Scientific Realism and Quantum Theories

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Introduction

This dissertation centers on some themes in scientific realism and non-relativistic quantum theories, including both standard quantum mechanics and Bohmian mechanics. I take scientific realism in its most general sense to be a view that concerns beliefs about the unobservable aspects of the world. This dissertation aims to provide some new insights into realism about quantum mechanics, recognizing that physicists often take quantum mechanics at an instrumental level for making correct predictions while leaving out discussions on metaphysical and ontological questions. A realist position within the general background of the philosophy of science must respond to some traditional arguments against scientific realism, such as the pessimistic induction problem and the problem of underdetermination. This dissertation focuses on addressing whether a realist position of quantum theories is truly tenable by investigating some ontological issues surrounding quantum physics within the context of the traditional realism/anti-realism debate, using Bohmian mechanics as a test case. Overall, Bohmian mechanics is a defensible realist quantum theory, and in particular, a wave function ontology of Bohmian mechanics is preferable over a primitive ontology of Bohmian mechanics, from both metaphysical and empirical considerations.

There are two major components of the dissertation: scientific realism and quantum theories. These two projects collide when we debate whether a scientific theory should be taken as a realist theory or an anti-realist theory. There are various positions to take in the realism/anti-realism divide, ranging from anti-realist positions, such as instrumentalism, to Van Fraassen's constructive empiricism, to selective realism, and to theory realism. This dissertation engages predominately with selective realism and aims to construct a selective realist approach to quantum theories, specifically

Bohmian mechanics. In general, the thesis of scientific realism has three dimensions which Psillos (2005, 2006) explicates:[1]

The Metaphysical Thesis: The world has a definite and mind-independent structure.

The Semantic Thesis: Scientific theories should be taken at face-value.

The Epistemic Thesis: Mature and predictively successful scientific theories are well-confirmed and therefore (approximately) true of the world. The entities posited by them, or, at any rate, entities very similar to those posited, inhabit the world.

Throughout the dissertation, these three dimensions of scientific realism are discussed extensively. And they all conform to the general theme that scientific theory leads to a belief in unobservable entities. For example, the theoretical claim that Bohmian particles follow a determinate trajectory is taken to have a truth value according to the semantic dimension. Or, theoretical terms such as 'particles' in Bohmian mechanics refer to some physical entities that inhabit the world according to the metaphysical thesis and the epistemic thesis. These dimensions of scientific realism face various criticisms from the anti-realist camp, such as the underdetermination argument (two or more theories are consistent with given data) and the pessimistic induction argument (current theories are false because past theories which are empirically successful are false). A tenable realist interpretation of quantum mechanics or realist quantum theory will need to offer some approaches to resist such criticisms. I argue against these anti-realist arguments in the dissertation and come to conclude that Bohmian mechanics is defensible.

In this dissertation, I consider only non-relativistic versions of quantum theories because they suffice to make my arguments against anti-realists and to avoid technicalities we might encounter in

[1] See Psillos, S. (2005). Scientific realism and metaphysics. *Ratio*, *18*(4), 385-404.

the relativistic versions. Relativistic quantum theories are complex and will need further investigations. Unless otherwise noted, Bohmian mechanics or standard quantum mechanics refer to non-relativistic versions of them. In a nutshell, Bohmian mechanics is a hidden-variable theory and sometimes is called the pilot wave theory. It is a deterministic theory in which particles have positions and follow determinate trajectories. Standard quantum mechanics is an indeterministic theory, and it is a wave function collapse theory (i.e., when a measurement is performed on a system, the system is in a definite state). These two theories have many variants, which in fact lead to different realist commitments, and this dissertation makes clear what these variants amount to and what their implications are. One notational clarification about these two theories is that standard quantum mechanics and Bohmian mechanics are different quantum theories, unlike some literature that takes Bohmian mechanics to be an interpretation of quantum mechanics. Standard quantum mechanics and Bohmian mechanics are different theories because they differ in ontology, structure, principles, and postulates. (A more explicit discussion of the postulates of these two theories can be found in Chapter 2).

A specific experimental investigation of Bohmian mechanics that I discuss in various places of the dissertation is a modified double-slit experiment conducted by Cardone et al. (see Chapters 2, 3, 4; section 2.1 of Chapter 3 for the usual double-slit experiment) and it is often called the box experiment. This experiment offers valuable implications on realism about Bohmian mechanics because it supports a wave function ontology of Bohmian mechanics, which is a version of Bohmian mechanics and commits to realism about the wave function (in addition to realism about particles). The rival version of Bohmian mechanics, primitive ontology, takes the wave function to be a nomological entity (i.e., it represents a law) rather than the same sort of physical entity as particles. The metaphysical status of the wave function in this "wave function ontology vs. primitive ontology" debate and an underdetermination between these two versions of Bohmian mechanics are explored.

Another main theme in this dissertation is causality. One version of Bohmian mechanics, in particular, the version David Bohm defends, is a causal version. We should keep the causal version of Bohmian mechanics separate from a causal realist account of Bohmian mechanics. The causal version of Bohmian mechanics refers to the metaphysical thesis of scientific realism in the Bohmian model, which introduces a force term that is derivable from the quantum potential when we rewrite the wave function in a polar form. This force appears when we describe how the wave and particles interact, such that the wave guides and pushes particles around in the universe. An account of causality in this sense is explored in section 5 of Chapter 3. On the other hand, a causal realist account purports to offer an epistemic justification of realism about Bohmian mechanics. This notion of causality *qua* selective realism is one in which involves experimental interventions with entities under consideration, such as the pilot wave and the particles, etc. This epistemic notion of causality is addressed in Chapter 4 in the context of the box experiment.

The main conclusion of the dissertation is that Bohmian mechanics is a defensible realist quantum theory, and in particular, a wave function ontology of Bohmian mechanics. To arrive at this conclusion, we rely on explanatory considerations to determine how to take a realist attitude towards a theory. The most appropriate realist position about Bohmian mechanics is selective realism. In this view, we should commit to some but not all of the unobservable parts of a theory, such as the pilot wave, the particles, and theoretical claims about these entities. An implication of realism about Bohmian mechanics sheds light on a question of theory continuity between classical mechanics and quantum theories (including

Bohmian mechanics and standard quantum mechanics). A continuity between classical mechanics and Bohmian mechanics cannot be established for both ontological reasons (given that the wave function does not have a classical counterpart and Bohmian particles differ conceptually from classical particles) and empirical reasons (given that they make different predictions such as in the double-slit experiment). In addition to that, classical mechanics and quantum theories differ in principles (see Chapter 1) and ontology and mathematical formalism (see Chapter 5). This discontinuity further implies that structural realism is problematic, or it at least does not capture realism about quantum theories fully (see Chapter 1 and Chapter 4).

Chapter summary

Chapter 1 lays down the foundation for the arguments in later chapters that a realist position about quantum mechanics is worth pursuing. If quantum mechanics is false as the pessimistic induction argument (hereafter PMI) suggests, then realism about quantum mechanics is not an interesting project. PMI is a challenge to the epistemic dimension of scientific realism. PMI is the thesis that *most* of our past theories were empirically successful, such that they provide explanations and predictions of natural phenomena that occur in the world, but they turn out to be false due to the progress of scientific knowledge. Our current best scientific theories are also empirically successful, so by inductive reasoning, our current theories, such as quantum mechanics, will turn out to be false and will be replaced by future theories. I argue in this chapter that PMI does not support anti-realism towards quantum mechanics, nor can it appropriately guide our realist understanding of quantum mechanics. Instead, we need to take a *selectivist realist* position towards quantum mechanics, and this realist position commits to some parts of a theory but does not always make a further commitment that these parts are inherited from its predecessors or will be retained in its successors (if there are any). Suppose that a successor theory is conceptually different from a previous theory. For instance, classical mechanics might be true about the existence of particles, and the theory does refer to real entities. In contrast, a successor such as standard quantum mechanics (but not Bohmian mechanics) denies the existence of entities. This can be a case where some part of a previous theory was true but was not retained in a successor theory. In particular, PMI is not a good inductive argument because the inductive basis, which consists of past theories, is unreliable. When we take into consideration factors in inductive arguments, we conclude that PMI should not lead us to infer that quantum mechanics is false.

In **Chapter 2**, I address an underdetermination that is seemingly present between the realist interpretation of quantum mechanics and Bohmian mechanics. It is important that we specify which realist interpretation of quantum mechanics we are working with given the complexity and ambiguity in interpreting quantum mechanics. The realist interpretation of quantum mechanics considered in this chapter is a version of standard quantum mechanics. In this chapter, I clarify the difference between empirical equivalence (namely two or more theories make the same empirical predictions) and underdetermination. And in particular, I show that the two theories are not empirically equivalent, and this implies that they are not underdetermined. I argue for a *domain-sensitive* approach to underdetermination. Domain sensitivity with respect to theories' predictions plays a role in determining whether two or more theories are empirically equivalent and underdetermined. I first consider two experiments to show that Bohmian mechanics and the realist interpretation of quantum mechanics are not empirically equivalent when we consider their predictions within their own domain of application. Furthermore, I argue that BM and RI are not empirically equivalent when we consider their predictions for domains outside their application, using the relativistic domain as an example. I do not suggest that a solution to an underdetermination addressed in this chapter should be generalized to all cases of underdetermination in scientific theories.

Chapter 3 addresses the debate between wave function ontology and primitive ontology, which are two main formulations of Bohmian mechanics, and I defend a tenable version of Bohmian mechanics using a wave function ontology. In particular, this chapter engages with the ontological status of the wave function. Unlike the primitive ontologist who suggests that the wave function is a nomological entity that supervenes on the motion of the particles, we can regard the wave function as a physical entity in a 3-D world. I argue that in order for the Bohmian to explain quantum phenomena adequately, a wave function ontology, which has both the wave function and the particles as part of the Bohmian ontology, is necessary. Although among wave function ontologists, there are various ways of interpreting the wave function, I show that the wave function possesses energy, and this feature is important for any scientific theories that obey the law of energy conservation. Given this feature of the wave function, the wave function is a deformed spacetime (which is the same as a field) that possesses energy and causally affects the trajectories of the particles. The wave function ontology defended in this chapter is an instance of the causal version of Bohmian mechanics and fits naturally with the conserved quantity theory of causation.

Chapter 4 goes further to explore the philosophical implications of the box experiment for Bohmian mechanics. In particular, I investigate how selective realism of some kind is appropriate to characterize realism about Bohmian mechanics. The box experiment supports a version of Bohmian mechanics, which takes the wave function to be a real physical entity in the 3-dimensional world in addition to particles. I use the box experiment as a working example to argue that a causal realist account (in the sense of selective realism, such as entity realism) that is applicable to Bohmian mechanics has to be supplemented with the use of Inference to the Best Explanation (IBE).

In **Chapter 5**, I unpack the nature of particles. Although it is not controversial that Bohmians believe in the existence of particles (in contrast with standard quantum mechanics that denies the existence of particles), it is puzzling how to understand the nature of the particles in comparison to our classical description of particles. In particular, I investigate the implications that the Bohmian interpretation of particles has for realism about Bohmian mechanics and whether Bohmian particles are different in kind from classical particles. A Bohmian interpretation of particles shows that particles are conceptually different from what we have traditionally known about particles. In fact, Bohmian particles are essentially different from particles under the description of classical mechanics, despite the fact that particles under both descriptions have positions. Particles' dynamics and behavior are essentially different under both descriptions. This is to say, the Bohmian description of particles picks up a new referent that is different from that of classical mechanics. This implies that a theory-continuity between classical mechanics and quantum mechanics at the ontological level cannot be established. And it further implies that structural realism and mathematical formalism, in general, are not sufficient for realism about Bohmian mechanics.

NOTE. Main conclusions

1.There is a discontinuity between classical mechanics and (standard) quantum mechanics/Bohmian mechanics. Continuity of ontology cannot be established between classical mechanics and Bohmian mechanics (see Chapters 1 and 5), and continuity of formalism is not necessary for realism (see Chapter 5).

2. To infer that unobservable entities such as viruses, genes, bacteria, and in our contexts, the wave function and the particles exist, we have to rely on the use of Inference to the Best Explanation. That is to say, for instance, upon our observations of some phenomena such as interference patterns in a double-slit experiment, we can rely on explanatory considerations to infer that some unobservables such as the wave function exist and are the best explanation for what we observe. Hence, whether one should make commitments to a quantity such as force in Newtonian mechanics and quantum potential in some versions of Bohmian mechanics, depends on whether this realist commitment is needed to give adequate explanations for phenomena. (See Chapter 5)

3.A Humean conception of laws of nature, which takes laws to supervene on particular local facts or in the context of this dissertation the spacetime points of particles, cannot provide adequate explanations for quantum phenomena. Primitive ontologists of Bohmian mechanics often adopt this conception of laws of nature. (See Chapters 3 and 4)

4.A successful reference of theoretical terms of a theory to physical entities which inhabit the world depends on both theoretical and experimental/causal descriptions of the entities, such as the wave function and the particles. Neither alone is sufficient. (See Chapters 3, 4, and 5)

5.To be a realist about a theory involves adopting a specific formulation or interpretation of the theory because different formulations or interpretations of the theory describe the world differently and have different ontological commitments. For example, a wave function ontology formulation of Bohmian mechanics differs in various aspects from a primitive ontology of Bohmian mechanics. Even if these two formulations are mathematically equivalent and make the same predictions, they do not describe and explain quantum phenomena in the same way. Therefore, a more abstract representation of the mathematical formalism, as in the semantic approach to theories where different linguistic formulations/versions of a theory may be mathematically equivalent or inter-translatable, does not seem to capture realism about the theory accurately. Instead, the level of specific formulations/versions of a theory better addresses the realism question and is the more appropriate level of description. (See Chapters 1, 3, and 5) In addition, structural realism is not an appropriate realist position about Bohmian mechanics because this position does not fully capture the ontological status of the wave function and the particles. (See Chapters 3 and 5)

6. In some cases, where it is controversial whether two theories are underdetermined, we should look at their predictions in domains outside their intended application, such as the one between standard quantum mechanics and Bohmian mechanics. If two theories do not make the same predictions in those domains, then it implies they are not underdetermined. Different cases of underdetermination might require different solutions, depending on the specific cases engaged. (See Chapters 2, 3, and 4)

CHAPTER 1

Quantum Mechanics, Realism and The Pessimistic Induction

Some scientific realists accept a form of the pessimistic induction argument (an argument against scientific realism) and take this as a motivation to identify theory-preserving parts of past theories and current theories. Realism about quantum mechanics is under the threat of the pessimistic induction.[2] I argue in this chapter that the pessimistic induction argument (hereafter PMI) does not support anti-realism towards quantum mechanics nor can it appropriately guide our realist understanding about quantum mechanics. Instead, we need to take a *selectivist realist* position towards quantum mechanics, and this realist position commits to some parts of the theory but does not always make a further commitment that these parts are inherited from its predecessors or will be retained in its successors (if there are any). My defense of selective realism about quantum mechanics has two steps. (1) PMI is a bad argument when it is formulated as an inductive argument, because it has an unreliable inductive basis. In particular, I elaborate on Mizrahi's criticism to show that relevant similarities between theories in the inductive basis are important to constructing a reliable basis. (2) Regarding realism, a realist position of theory-continuity from classical mechanics to quantum mechanics is not well motivated in order to resist PMI because classical mechanics and some realist interpretations of quantum mechanics operate on different and contradictory principles. And this fact is important for determining whether PMI is permitted to render quantum mechanics false. In a more general sense, there are various accounts of realism which strive for theory-continuity in response to PMI, but they

[2] Valia Allori (2017) has one such account.

are far from reaching a consensus. On the other hand, selective realism requires us to access individual theories and take each of them seriously on its own right. So, selective realism is the most tenable realist position about quantum mechanics, given its complexity. In short, my argument is three-fold. In Part 1, I argue against an anti-realist position by weakening PMI. In Part 2, I argue against a form of selective realism that commits to a theory-continuity during theory changes by analyzing a case of theory transition from classical mechanics to quantum mechanics. In Part 3, I show that the fact that PMI fails and the fact that there is a theory discontinuity between classical mechanics and quantum mechanics imply that PMI should not lead us to infer that quantum mechanics is false.

In Part 1 of the chapter, I argue for (1) by showing that pessimists cannot fulfill the condition of relevant similarities between theories in the inductive basis, so they do not have a reliable inductive basis to generalize the falsity of past successful theories to currently successful theories. This part aims to weaken the threat of PMI on the truth or approximate truth of our current best theories, including quantum mechanics. Part 2 will defend (2). In particular, I argue that there is a discontinuity in the transition from classical mechanics to quantum mechanics. Due to their contradictory essential features, a theory-continuity of the two theories cannot be obtained. I also discuss the primitive ontology of Bohmian mechanics which is a realist quantum theory and is taken as a promising account to resist PMI according to some Bohmians by establishing a theory-continuity between classical mechanics and Bohmian mechanics.[3] I argue that even this version of quantum mechanics cannot adequately account for the challenge of PMI. A form of selective realism that makes this extra commitment to a theory-continuity does not fit the realism about quantum mechanics. (3) In Part 3, I will connect Part

[3] Bohmian mechanics is a deterministic theory of quantum mechanics. Although it is often regarded as an interpretation of quantum mechanics, it ought to be taken as a theory in its own right because it differs from standard quantum mechanics in various ways, such as ontologies, principles, mathematical equations, and descriptions of unobservable entities, etc.

1 to Part 2, by showing how the fact that PMI is a bad argument and a defense of a selective realist account come together through the discussion of incompatible features of classical mechanics and quantum mechanics. The fact that these two theories have contradictory essential features is relevant to *whether PMI can be applied to deny the truth of quantum mechanics*. In particular, for PMI to be applicable, we need to take into consideration the details or background information of how theories relate to each other. To support this conclusion, I will show that the two theories consist of contradictory essential features, and this fact explains why past successful theories being false does not guarantee that quantum mechanics is also false.

To avoid confusions in this chapter, for those realists who resist PMI by identifying some theory-continuity parts in theory transitions, such that the essential parts of past theories are retained in current theories, I refer to them as *selective realists* (SR*)*. Defenders of this position include Kitcher (1993) and Psillos (2005), and also Allori (2018) who argues that primitive ontology will survive PMI (and I will discuss her account in Part 2). Alternatively, for those who defend realist commitments of parts of theories but do not *always* accept the further claim that these realist contents are inherited from its predecessors or will be retained in its successors, I call them *selective realists (SR)*. The aim of this chapter is to defend a weaker (compared to SR*) position, SR, about quantum mechanics.[4]

Introduction

PMI

Psillos (2006) has taken three theses, The Metaphysical, The Semantic and The Epistemic, as

[4] A specific version of selective realism about Bohmian mechanics is defended in a later chapter of the dissertation.

constitutive of scientific realism.[5] PMI is an objection to The Epistemic Thesis.

> *The Epistemic Thesis:* Mature and predictively successful scientific theories are well-confirmed and therefore approximately true. So entities posited by them, or, at any rate entities very similar to those posited, inhabit the world (Psillos, 2006, p. 135).

The PMI argument has a historical nature and it runs like this. Pessimists argue that *most* of our past theories were empirically successful, such that they provide explanations and predictions of natural phenomena that occur in the world, but they turn out to be false due to the progress of scientific knowledge. Our current best scientific theories are also empirically successful, so by inductive reasoning, our current theories, such as quantum mechanics, will turn out to be false and will be replaced by future theories. PMI as an objection to scientific realism depends on the empirical success of theories. More precisely, this argument is intended to refute the *epistemic* dimension of realism that empirically successful theories are (approximately) true. To be a realist about quantum mechanics, we not only need to overcome the more general anti-realist tendency that this theory is valuable only in so far as it makes correct predictions (e.g. Copenhagen interpretation), but as one of the best current scientific theories, we also need to consider it under the light of PMI. PMI concludes that our best current scientific theories and even future theories are false or will turn out to be false. *Prima facie*, accounts of a realist position about theories that take empirically successful theories to be (approximately) true about the world is under the threat of PMI.[6]

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[5] The Metaphysical Thesis: The world has a definite and mind-independent structure. The Semantic Thesis: Scientific theories are truth-conditioned descriptions of their intended domain. Hence, they are capable of being true or false. The theoretical terms featuring in theories have putative factual reference. So if scientific theories are true, the unobservable entities they posit populate the world.

[6] In fact, PMI targets a specific scientific realist argument called the No-Miracles Argument, which is the view that the predictive success of science would be difficult, if not impossible, to account for unless mature scientific theories were approximately true (Psillos, 1996). Scientific realism in a sematic sense, such as statement realism, takes realism about theories to be the view that theories have truth-values, either true or false. So statement realists can accommodate theories that are false. One should be careful that PMI denies the epistemic dimension of scientific realism.

*A reply to PMI from SR**

For those realists who acknowledge the challenge of PMI, they are called on to accommodate this difficulty if they want to remain realists towards scientific theories. To respond to PMI they, instead of committing to all parts of a scientific theory, selectively commit to some claims or descriptions of theories. This approach shields realism from the challenge of PMI, because what is preserved through theory change are some contents of the theory but not all. In fact, "successful past theories were in fact only partially abandoned whilst the essential parts are, in one form or another, contained in current successful theories. According to this view, the theoretical entities that are *responsible for the success* of a theory are preserved throughout the changes of theories, whereas the other constituents are abandoned" (Muller, 2015, p. 394).[7] That is, we should commit only to "the truth of those aspects of theories that have shown marked stability over the history of science" (Lipton, 2000, p. 199). A paradigm case is Worrall's argument for structural realism using theories of light. There is a "transition in nineteenth-century theories of light, from Fresnel's wave optics to Maxwell's electromagnetism. Fresnel believed in a luminiferous aether, but Maxwell's theory was ultimately accepted in the context of a non-aetherial physics. As Worrall notes, however, certain mathematical equations (concerning the intensities of incident, reflected, and refracted light at the interface of two media) are endorsed by both" (Chakravartty, 2008, p. 155-156). The mathematical equations or structures that survive theory change, together with structural relations in the world described by those equations, are what the structural

[7] Worrall (1989) argues for an epistemic structural realism and assumes that it is the mathematical structure which is retained in the successors' theories and which explains the success of (past) theories. Kitcher (1993) differentiates between 'working posits (the putative referents of terms that occur in problem-solving schemata)', which generate the success and are retained through theory shifts, and 'presuppositional posits (those entities that apparently have to exist if the instances of the schemata are to be true)' (Kitcher 1993, 149), which are suspect and had to be superseded. Psillos (1996, 1999), instead, distinguishes between those theoretical constituents that essentially contribute to the success of a theory and are retained over time, and other parts of theories, which have to be rejected (Muller, 2015, p. 394).

realist commits to. Other parts of the theory which have to exist to make a full explanation or prediction, such as aether in Fresnel's account, are taken as idle and do not deserve realist commitments. In the context of quantum mechanics, it seems that the realist about quantum mechanics uses the same argument to overcome the threat of PMI by identifying the theory-continuing part between classical mechanics and quantum mechanics which explains why classical mechanics is only partially abandoned and why both theories are successful. As I will show in Part 2, such theory-continuity parts do not seem to be present, at least not in any obvious sense.

Lipton (2000) argues that selective realism that commits to a theory-continuity (i.e. SR*) concedes too much to PMI, because of "its retreat to the least common denominator is a form of conservatism that is epistemically indefensible. Suppose we could divide our current theory into an old (i.e. stable) part and a new part. What reason do we have to place more trust in the old part? The old part has not therefore been better tested, and the new part is supposed to mark the epistemic advance on what has come before" (Lipton, 2000, p. 1999). I agree with Lipton that we were not yet in a position to identify an old part in both old theory and new theory, but I don't think that realism about some parts of theories is not defensible. My reason for agreeing with Lipton is that if a selective realist* buys into PMI by identifying theory-continuity realist parts of theories, she will have to commit to the view that our future theory is also partly false and some parts of past and present theories will be retained in future theories. This attitude towards current theories and future theories is too pessimistic. Park (2019) points out that our present theories have not yet turned out to be false and most of our past theories in the twentieth-century, such as the oxygen theory or the germ theory, are still accepted. Also, we are not in the epistemic position to conceive or predict what our future theories will be like. If the progress of science is heading in the right direction, we will be able to approach true or approximately true theories. By presupposing that our future theories will be partly false and if scientists do not believe that they are making progress, the project of scientific research will become quite unappealing to many. This is to say there is a pragmatic reason to believe that we are making progress to approximate truth in scientific theories. Otherwise, the project of scientific research will not be worth pursuing. If a selective realist* concedes too much to PMI, it seems that her position forces her to accept some kind of uninteresting position of realism. Her position will be uninteresting because SR* presupposes that future theories will not be radically different in their entirety from present theories, but more importantly it implies that future theories are partly false. Given the fact that most current theories and most theories produced in the last century as Mizrahi (2013) shows have not yet turned out to be false, SR*'s implication that future theories will be partly false makes it an unattractive position. However, SR is defensible because it does not imply that future theories will turn out to be false or partly false. For instance, it is a safer position for a structuralist to commit to the view that Maxwell's equations are all that she believes in Maxwell's electromagnetism, but not to commit to the view that a future theory necessarily retains Maxwell's equations instead of some novel equations. SR makes sure that we don't make unwarranted assumptions about things we haven't yet have the epistemic stance to judge.

Although it is the selective realist*'s job to specify what theory-continuity parts of theories will survive through theory transitions, I suggest that the theory-continuity parts are those that are responsible for explanations, so they contribute to the explanatory success of theories. For selective realists*, a theory-continuity can be a continuity about theoretical contents, such as ontologies, structures, principles or whatever essential features a theory might have for it to be successful. For instance, the theory-continuity part for a structural realist is structure, such as mathematical equations of a theory. Unlike selective realists* who are guided or motivated by PMI to search for theory-continuity contents and being constrained by past theories, selective realists may have more freedom to say how we ought to be realists about quantum mechanics if they can weaken PMI rather than concede to it. In fact, PMI does not carry enough metaphysical significance in its own right to force an anti-realism on quantum mechanics. I will now turn to weakening PMI.

Part 1. Weakening PMI

In this part of the chapter, I argue against an anti-realist argument, PMI. In particular, if PMI is formulated as an inductive argument, pessimists cannot establish a reliable inductive basis. Specifically, I argue that relevant similarities in theories in the inductive basis cannot be established. The fact that PMI fails implies that PMI does not render some of our best current theories, such as quantum mechanics, false.

One should not ignore the metaphysical problems in PMI before it gets applied to theories in general. My argument that the PMI argument does not undermine quantum mechanics is as follows:

1. If the PMI is a bad argument against scientific realism, then it does not threaten our current theories, including quantum mechanics.
2. The PMI is a bad argument.
3. The PMI does not threaten quantum mechanics.

This part is devoted to defending premise 2. PMI has two important features. (a) The first is that it rejects the empirical success of a theory as a reliable indicator of its truth. (b) The second is that it rests on an inductive inference from the falsity of most past empirically successful theories to show current empirically successful theories are also false.[8] These two features correspond to two ways PMI can be formulated. Feature (a) corresponds to a deductive argument by *reductio ab absurdum* against The Epistemic Thesis. This deductive argument assumes that 'the success of a theory is a reliable test for its truth,' and concludes that 'the success of a theory is not a reliable test for its truth' (Lewis, 2001, p. 372; Mizrahi, 2013, p. 3210). The argument constructed by Lewis (2001, p. 372) is this:

(1) Assume that the success of a theory is a reliable test for its truth.[9]

(2) Most current scientific theories are successful.

(3) So most current scientific theories are true.

(4) Then most past scientific theories are false, since they differ from current theories in significant ways.

(5) Many of these false past theories were successful.

(6) So the success of a theory is not a reliable test for its truth.

Mizrahi argues that PMI formulated as a deductive argument is invalid. He shows that premises (3) and (4) do not entail that most past theories are false because the fact that theories are significantly different do not mean that they have different truth values, otherwise the argument will be circular.[10] The circular argument which assumes that 'radically different' means 'different truth values' is the following argument:

(3) Most current scientific theories are true.

[8] One may argue that the inductive basis of the PMI is not large and/or not representative enough to mount an attack against the No Miracle Argument, which is the argument that what explains the empirical success of scientific theories is that they are true, otherwise it is a miracle that they are successful (Psillos, 1999, 105).

[9] One might think that the notion of reliability is not appropriate in deductive arguments. One way to argue premise (1) is through the Inference to the Best Explanation by saying that the fact that a theory is true is the best explanation for why it is successful. But it is possible that the theory is false. Indeed, one may be using a specific notion of reliability in premise (1) to mean that other possibilities are less favorable.

[10] If two theories are significantly different means that they are contradictory, then this will imply that they cannot both be true. But most past theories and current theories that premise (4) engages with are often not incompatible in an obvious way.

(4’) Most past scientific theories differ from most current scientific theories in their truth value (i.e., most past scientific theories are false).

(C) Most past scientific theories are false.

In (4’), the pessimist assumes ‘differ significantly’ means ‘have different truth values.’ But to establish (4’), the pessimist already assumes that most past scientific theories are false. So this argument is circular (Mizrahi, 2013, p. 3212-3213). I think it is true that the truth of a theory is not entailed solely by its success, so realists need not take success to be a proof of its truth. In fact, we might need to look into the content of a theory and its ontology for whether it is true or false. This is to say, whether a theory is true or false depends on whether its unobservables (e.g. theoretical claims or entities) latch on to something in the world. I take scientific realism in its most general sense to be a view that concerns beliefs about unobservable aspects of the world.

I think the more serious problem of PMI is feature (b), the inductive argument. Pessimists face two major challenges of this form of PMI. The first is whether the inductive basis is a reliable one. The second is if pessimists have a reliable basis, whether an induction always carry through. In our context, this second challenge is whether pessimists can apply PMI to argue that quantum mechanics is false. This is to say that given past empirically successful theories that are false, whether one cannot infer our current theories which are successful are also false. I think to determine whether PMI will render quantum mechanics false depends on the relevant background information about theories in the inductive basis and the theory the pessimist wants to make an inference from the inductive basis. A naive induction that ignores these details can lead to a false conclusion. I will argue in Part 3 the fact that classical mechanics and quantum mechanics consist of rival features is relevant information for induction, and it explains why PMI fails to render quantum mechanics false. Here I argue that the *inductive basis* of PMI is problematic: Theories in the basis are not relevantly similar enough to count as a reliable sample. I will defend this point after discussing Mizrahi's argument.

Consider Mizrahi's reconstruction of the inductive argument in (b), which I call PMI*:
(b1) Most past successful theories are false.
(b2) Therefore, most successful theories are false.

Mizrahi has dismissed this argument because premise (b1) relies on a biased sample of past successful theories, and does not license the generalization of falsity to most successful theories (Mizrahi, 2013, p. 3219). In particular, Mizrahi argues that Laudan's (1981) list of successful but false theories does not provide a good basis for a pessimistic inductive generalization because Laudan's list is not a random sample and the examples were selected precisely because they are considered to be successful but strictly false (Mizrahi, 2013, p. 3219-3220). Laudan's list is this:

-the crystalline spheres of ancient and medieval astronomy;
-the humoral theory of medicine;
-the effluvial theory of static electricity;
-"catastrophist" geology, with its commitment to a universal (Noachian) deluge;
-the phlogiston theory of chemistry;
-the caloric theory of heat;
-the vibratory theory of heat;
-the vital force theories of physiology;
-the electromagnetic aether;
-the optical aether;
-the theory of circular inertia;
-theories of spontaneous generation. (Laudan, 1981, p. 33)

In contrast, Mizrahi's own list of successful theories shows that 72% of randomly sampled theories from *Oxford Reference Online* are currently accepted theories and hence considered true.[11] Mizrahi's conclusion is not surprising because the majority of scientific theories have been produced in the last

[11] Mizrahi (2013) also thinks that the No Miracle Argument is not a good argument for scientific realism (Mizrahi, 2013, p. 3223).

century and they should go into the inductive basis of PMI in addition to Laudan's list. According to Park, "the number of recent past theories far exceeds the number of distant past theories" (Park, 2019, p. 2). Fahrbach (2011) says that "at least 95% of all scientific work ever done has been done since 1915, and at least 80% of all scientific work ever done has been done since 1950s" (p. 148). These are taken to be recent past theories, while Laudan's list is considered to be about distant past theories. If we randomly select a sample from these past theories, including both recent past theories and theories in Laudan's list, then it is likely we select a theory that hasn't yet shown to be false. This is because the number of more recent past theories haven't yet shown to be false far exceed the distant past theories in quantity. The fact that most theories ever been produced are not yet shown to be false is a reason to think that our current theories are not false. It is possible to go further to challenge the pessimist, on whether it is sensible to talk about a random selection of sample theories from an incomplete inductive basis. To see what this objection means, consider a random sampling in intelligence tests. Suppose that a psychologist wants to test the level of intelligence in the age group of 18 years old. Theoretically, a complete inductive basis from a population of 18-year old adults can be made available to her by collecting all data from the target age group. Her job is to select a random sample from this population rather than wait for more members to be added to the population basis at the time she conducts the test. Unlike this example, given the fact that scientific theories are developing over time, we do not yet have a complete set of theories available to the pessimist. It seems that it will be problematic to select a sample randomly from the unfinished set of scientific theories in order to make a generalization about the next theory comes up.

Moreover, Laudan's list consists of theories that even realists will believe to be strictly false as

Mizrahi points out, but strictly false theories are abandoned completely and often have no use to us today. However, there are some false theories that are still useful for making predictions and explaining in some limited domain of application. Laudan's list and in fact pessimism in general are not explicitly about this feature of theories in the inductive basis. Pessimists have not made their inductive basis as reliable as it can be. We still use these false but useful theories not because we mistakenly believe that they are true, but because they may be easy to understand and can still make some right (although limited) predictions. For instance, Bohr's model of the atom is simple enough to explain the behavior of the hydrogen atom which makes it accessible for beginners in physics. But this model is false because it can make incorrect predictions, such as that it provides incorrect values for the ground state orbital angular momentum and it does not explain the Zeeman effect. Classical mechanics is another well-known theory that is believed to be false but still useful. It is clear that pessimists will only take these theories to have instrumental values, but selective realists might find room to defend. The reason is that, for instance, some realists might argue that some claims of classical mechanics have truth values. And I discuss in detail how selective realists can defend this in Part 2. In fact, if the pessimists' inductive basis includes these past successful but false theories which are still useful today, it will be a stronger and relevant inductive basis. The reason is that past theories that are false but still useful to us resemble our currently successful theories more, because our current theories are also useful. For some defenders of quantum mechanics, such as advocates of the Copenhagen interpretation of quantum mechanics, they accept the theory in so far as it is useful for them to make correct predictions. However, this distinction between false but useful and false but useless distinction has not received enough attention among pessimists.

In the rest of this part, I will take the pessimists' view as a starting point to test if theories can form a reliable basis by considering how a pessimist could try to defend the PMI through relevant similarities in theories but fail. And I conclude the pessimist's attempt cannot rescue the PMI.

Relevant similarities

So far, pessimists in general have not provided a reliable basis. If Laudan cannot fulfil the condition of randomness as Mizrahi argues, it seems that the alternative approach to construct a reliable inductive basis is to look for relations that theories in the inductive basis stand with each other. Laudan's list consists of theories that are of different kinds which are too diverse to be similar with each other except that they are strictly false. So we can narrow down theories to just physical theories in the inductive basis and test whether they are relevantly similar. Mizrahi (2013) makes the point that a successful induction requires that the instances in an inductive basis are uniform to make a generalization to the next instance. For example, we can infer from the fact that all observed copper rods can conduct electricity to the claim that the next copper rod can also conduct electricity. It is because of the relevant similarity of copper rods in the inductive basis that we can be confident about our conclusion. But in scientific theories, it is not obvious that if we know all past theories that are successful are false, then current theories will also be false, because we need to specify what counts as relevant features for them to be similar so an induction can take place. Unlike in the case of copper rods, where they all share a similar chemical structure and physical structure, such as having an atomic number of 29, scientific theories are not uniform in that sense. But it seems that if the advocates of PMI can find that theories are similar in some relevant senses, then they may be able to argue in a similar way as in the copper rod case. One might challenge the pessimist to identify what is responsible for the falsity of past theories in the inductive basis, except the fact that they are false. It is not reasonable to look for a common reason why past theories in the inductive basis are false, because the reason why a theory fails to make correct predictions and explanations might have to do with some specific features of the theory. But it seems that the pessimist can still try to specify some relations between these theories so that they are similar enough in some way that they will have the same truth value.

By specifying the relevant similarities in theories, the pessimist can not only argue that they have an inductive basis which consists of theories that are relevantly similar with each other (beside the fact that they are successful) and have the same truth value, but also to infer that the next theory that shares similar features will also have the same truth value. Here I suggest some possibilities for relevant similarities in theories. (1) Theories apply to a specific domain of application. Pessimists may argue two theories are relevantly similar if they concern the same domain of application. This possibility fails immediately, because we can have two empirically equivalent theories that make the same predictions for the same domain, but they make incompatible claims about actual states of affairs outside that domain. So they cannot have the same truth value. This implies that being able to make the same successful predictions (or being consistent with the same amount of evidential support) does not entail that the two relevantly similar theories have the same truth value. (2) Two theories are relevantly similar if they are both coherent with background theories. But it is possible that we can modify theories, by modifying auxiliary assumptions of these theories, so that they are both consistent with the background theory without denying that they remain as rivals if they have incompatible essential features. Even if the two theories are rivals because of their contradictory essential parts, which define the theories, they can be consistent with the background theory. For instance, the caloric theory of heat takes heat as a substance and the mechanical theory of heat denies that heat is a substance. They are rival theories but both are consistent with the law of energy conservation. They cannot be viewed as relevantly similar in any significant way. (3) Theories have the same origin, such that they were built up on the same model, so they are relevantly similar. For instance, Sommerfeld's model of atoms was built upon Bohr's model of atoms, and Sommerfeld's model can explain more phenomena than Bohr's model does, such as the Stark effect. These two models are similar and they both turned out to be false. (Pessimists might infer that Pauli's model that replaces these two models will also turn out to be false.) However, a realist can deny that these are two different models, because they have the same origin and one is merely a refined version of the other. It is not surprising that both of them are false, because they are variants of a single model. One can continue to name the ways that theories might be relevantly similar, but a further problem arises.

Even if we can make two theories relevantly similar along some dimensions, they may be significantly different along some other dimensions, and this can result in different truth-values. One may argue that theories may be relevantly similar if they have the same internal structure. Fresnel's theory of light and Maxwell's electromagnetism, where the structure under consideration is a mathematical structure, might be an instance of relevant similarity. However, one can argue that the two theories are in fact not relevantly similar in their ontologies, because Fresnel commits to an ether but Maxwell does not, even though their theories share the same mathematical structure. In fact, the success of Fresnel's theory seems to depend partly on its supposition of an ether because Fresnel derived his equations from premises that posit the existence of an ether. Fresnel makes assumptions that "the molecules of the elastic *ether* were taken to have mass, so that in oscillation they obtain a mixture of kinetic and potential energy presumably very much like a harmonic oscillator. They also obtain some momentum. The key assumption is that the maximum velocity of the oscillating *ether* molecules is directly proportional to the amplitude of light, which in turn is proportional to the square root of intensity" (Saatsi, 2005, p. 523). And the fact that the non-existence of ether was later proved in the Michelson-Morley experiments implies that even if Fresnel's theory is successful, it does not have anything to do with whether it is true or false with respect to the ontology. Despite the fact that two theories share the same mathematical structure, it does not imply that they have the same truth value. Nonetheless, even if we can make sense of the claim that Fresnel's theory of light and Maxwell's electromagnetism have a relevant similarity in some other way, this kind of similarity may not be found in other physical theories.

Connecting to the idea of sameness in mathematical structure in the derivation of mathematical equations in Fresnel's theory and Maxwell's electromagnetism is the concept of constructing a mathematical model from different kinds of modeling strategies. The Lotka-Volterra model involves two differential equations of prey-predator populations and can be applied to different systems, such as biological, chemical or social systems. But Lotka and Volterra constructed their model with different methods, such that "Volterra attempted to isolate the essential or "sufficient" components of the predator-prey system and their interaction in "sea fisheries", Lotka started from a very general perspective and applied his model template both to the analysis of biological and chemical systems" (Knuuttila & Loettgers, 2013, p. 8). Their construction of a model that applies to various domains is connected to Paul Humphreys' 'computational templates,' which are "genuinely cross-disciplinary computational devices, such as functions, sets of equations, and computational methods, which can be applied to different problems in various domains" (Knuuttila & Loettgers, 2013, p. 2-3). The approaches of Lotka and Volterra are different in that, "Volterra approached modeling from the perspective of the causal explanation of real mechanisms, Lotka approached it from the perspective of applying a general template to specific cases" which is a bottom-up and top-down difference. The basic idea behind the Lotka-Volterra model is in line with the goal of structural realists to capture the reality and phenomena with abstract models like mathematical models (Knuuttila & Loettgers, 2013, p. 25).

Pessimists might argue that if theories (although they may be of different kinds or belong to different disciplines) in the inductive basis can be abstracted to the same theoretical template or model, then they are regarded as relevantly similar to one another. But, if pessimists argue that theories are relevantly similar if they have the same template, they will have to make assumptions of idealization and simplification on the target theories. The concern is about at what level of abstraction the mathematical model can still appropriately capture the different theories. In addition, one may ask pessimists if the mathematical models or templates they obtain from theories (if there were any such models) in the inductive basis can be applied to the domain of quantum mechanics. That is whether theories in the inductive basis and theories pessimists want to make inference about exhibit some similarities at some level of abstraction. In fact, in the case of classical mechanics and quantum mechanics, there is a difficulty of obtaining a template across these two theories because the mathematical equations of these two theories do not seem to be abstract enough for relevant similarities to be shown, given the complexity of interpreting quantum mechanics. Next, I will argue why.

The modeling method we learn from the Lotka-Volterra model does not apply to all theories in theory transitions. This is the case between classical mechanics and quantum mechanics, where the Newtonian equations are not carried over to quantum mechanics, which is governed by Schrodinger's equation. So it seems that pessimists will need other arguments for relevant similarity, perhaps by going up the level of abstraction or structure. In classical mechanics, there are three different mathematical formulations, so to capture the more abstract structure of classical mechanics, we need some abstractions of the three formulations. Also, given that quantum mechanics has many interpretations and their mathematical formulations are different, such that Bohmian mechanics has a guiding equation that the realist interpretation of quantum mechanics does not have, to capture the structure of quantum mechanics, we nonetheless need some abstract formulation. In fact, Laudan's list of theories do not have this kind of abstract form. In particular, defenders of relevant similarities in terms of abstract formulations of theories in the present context face two challenges. *One* is whether some abstract formulation can be established in quantum mechanics. *Second* is whether there could be an abstract formulation that applies to both classical mechanics and quantum mechanics, or whether there is any 'computational template' at some level of abstraction that applies to these two theories. Abstracting classical mechanics may be achieved because its three mathematical formulations are translatable. But the same strategy cannot be used in the case of quantum mechanics, because it requires interpretations rather than merely that it is a theory formulated in multiple ways. Although Bohmian mechanics is often called an interpretation of quantum mechanics, it is in fact a theory in its own right.

One possibility of abstracting standard quantum mechanics is to take a Hilbert space formalism of it, such that the state space of some interpretations of quantum mechanics, such as the Copenhagen interpretation, is Hilbert space. But can a Bohmian abstract Bohmian mechanics as a theory by taking Hilbert space formalism to be essential to Bohmian mechanics just like in standard quantum mechanics? Arageorgis and Earman argue that "although BQM [i.e. Bohmian mechanics] helps itself to the technical apparatus of Hilbert spaces, it is not a Hilbert space theory in the sense that its ideology and ontology differ markedly from that of SQM [i.e. standard quantum mechanics and they often refer to the collapse-type quantum mechanics, such as the Copenhagen interpretation] which takes the Hilbert space formalism seriously (all too seriously according to the Bohmians)" (2017, p. 2). They argue that the state space of Bohmian mechanics is not Hilbert space but some space of wave functions that are sufficiently smooth so that Schrodinger's equation and the guiding equation make sense and Bohmian mechanics favors "a radically instrumentalist interpretation of the Hilbert space operator formalism" (Arageorgis & Earman, 2017, p. 5). The Hilbert space formalism uses state vector collapse to characterize the wave function collapse when measurements are performed on the system to yield determinate outcomes, but Bohmian mechanics as a non-collapse theory doesn't need such characterization. So it seems that it is the pessimist's burden of proof to show that Hilbert space formalism can be taken to have an equal metaphysical significance in different of quantum theories, such as in standard quantum mechanics and Bohmian mechanics. If Arageorgis and Earman are right about the two quantum theories, then to construct an abstract formulation that is common to both standard quantum mechanics and Bohmian mechanics seems unappealing. However, an abstract formulation is possible within the different formulations of standard quantum mechanics. Whether an abstract formulation can be established between classical mechanics and standard quantum mechanics seems to depend on whether classical mechanics can have its state space in a Hilbert space. Or with regard to Bohmian mechanics, if one argues that both classical mechanics and Bohmian mechanics operate on a second-order Hamilton-Jacobi equation, exceptthat Bohmian mechanics introduces a quantum potential term, then one has to say whether these are in fact the same formulation of the two theories. In fact, as Sengupta et al. (2014) show when the quantum potential term vanishes, a classical behavior of particles is not observed, so it is puzzling to take the Hamilton-Jacobi as an abstract formulation of both classical mechanics and Bohmian mechanics. If PMI requires that theories exhibit relevant similarities to share the same truth value, the strategy to look for similarities at more abstract levels has not yet been achieved, and realists will simply deny PMI.

For a realist who rejects PMI, she may wonder whether there is anything valuable about upholding a selective realist* account even though it was initially proposed to resist PMI. It is possible that some realists still want to maintain some sort of theory-continuity during theory transitions. For such selective realists*, they might believe that even if PMI is untenable, the progress of science indicates that some successive theories develop to accommodate the problems that their predecessors not able to account and they may be built upon these predecessors. They, such as Psillos, argue that there are essential constituents of theories that will be preserved in successive theories, while idle constituents will be abandoned in a theory transition. In Part 2, I argue that a selective realist* account of quantum mechanics is untenable.

Part 2. From classical mechanics to quantum mechanics

The fact that classical mechanics and quantum mechanics have contradictory essential features has an implication for SR* and SR. The contradictory essential features of the two theories will mean that a theory-continuity that selective realists* regard as stable part in theory transitions cannot be maintained in this case.

The classical mechanics to quantum mechanics transition

First of all, there is a continuity question in the transition from classical mechanics to quantum mechanics. It seems that if our current quantum theory is continuous with classical theories in some sense as the selective realist* argues, we may wonder how can they be continuous despite quantum mechanics being incompatible in certain respect with classical mechanics. In the famous double-slit experiment, we know that the classical theory cannot correctly predict and explain the results. In this experiment, classical particles will pass through either one of the two slits and simply fall behind the slits on the screen rather than creating an interference pattern. Quantum mechanics, whether it is standard quantum mechanics or Bohmian mechanics predict there is an interference pattern. The quantum interference pattern indicates we have moved to the domain of quantum mechanics for explanations. Even Bohmian mechanics which shares some similar characteristics with classical mechanics, such as that particles have trajectories, should not be considered as a classical theory because particles behave differently according to the Bohmian description and the description according to classical mechanics (A more detailed discussion about the nature of Bohmian particles and classical particles can be found in Chapter 5). One example is that Bohmian mechanics will predict that particles form an interference pattern in the double-slit experiment as other quantum mechanical accounts do, which differs from that of the classical prediction. Particles, according to Bohmian mechanics, exhibit tunneling effects such that they have some probabilities that they will tunnel through potential wells, while classical mechanics will not give such predictions of particles. It is important that we do not treat Bohmian mechanics as a classical theory even though it resembles classical mechanics in some aspects. If it is true that we have entered a different realm of physics, the transition from classical mechanics to quantum mechanics seems to need different treatments and understanding as in the transition from Fresnel's theory to Maxwell's electromagnetism.

In what comes next, I use a realist interpretation of quantum mechanics to understand the relation between quantum mechanics and classical mechanics and its implication for PMI. The realist interpretation takes some theoretical claims to have truth value but not all, unlike the Copenhagen interpretation that takes all claims about unobservables to be construed in an instrumental sense. For instance, the realist interpretation can believe in the truth of the claim that a quantum system has an indeterministic dynamics. Classical mechanics consists of classical concepts of nature which differ greatly from that of the realist interpretation of quantum mechanics. They have different and in fact *contradictory* central claims and descriptions of reality. According to Karakostas, "quantum features such as non-commutativity, non-separability and the generalized phenomenon of quantum entanglement have been forcing us to revise radically the intuitive classical ideas about physical reality" (Karakostas, 2012, p. 46). And he argues that "a viable realist interpretation of quantum theory, the concept of realism must not be associated with ideas taken over from classical physics, such as atomism, localizability, separability, or similar philosophical preconceptions such as strict subject-object partition, mechanistic determinism and ontological reductionism" (Karakostas, 2012, p, 46). In particular, classical physics describes the world "in terms of analyzable, separately existing but interacting self-contained parts" and it is also reductionistic (Karakostas, 2012, p. 47). So classical physics is non-holistic, such that compound systems are analyzable fully in terms of the features of its parts. Karakostas considers two principles of classical physics: the Separability Principle and the Definite Values Principle.

> *Separability Principle:* The states of any spatiotemporally separated subsystems S1, S2,…,SN of a compound system S are individually well-defined and the states of the compound system are wholly and completely determined by them and their spatiotemporal relations (Karakostas, 2012).

An example of a classical system that clearly demonstrates separability is the fall of a stone. "The fall of a stone is similarly spatiotemporally separable in a space-time region that contains it. For the stone consists of atoms, each of which has a *space-time trajectory [emphasis mine]* on which various *intrinsic mechanical properties* are defined at each point, and each atom is acted on by various *force fields*, importantly including the gravitational field due to the earth, which are also defined at each point on its trajectory" (Healey, 1991, p. 406). Notice that trajectories of classical systems exist in classical theories. As mentioned earlier, the three formulations of classical mechanics all rely on the fact that we can measure variables, such as positions and velocities, precisely at the same time. There is no inherent uncertainty in the measurement of these quantities, as long as we can minimize measuring errors, we can get precise measurements. And there is no dispute that we can describe trajectories of classical systems, since we can specify their position and velocities at any given time. This way of describing a system's motion seems rather intuitive and unproblematic at the macroscopic level.

However, the realist interpretation of standard quantum mechanics denies the existence of trajectories of particles. According to Santos (2015), "The Heisenberg principle becomes an obstacle for a realistic interpretation of quantum mechanics when the empirically found practical difficulty (or impossibility) of simultaneous knowledge of position and velocity is elevated to the category of an ontological statement: "Trajectories of quantum particles do not exist"" (Santos, 2015, p. 365). This realist interpretation of quantum mechanics violates the following principle:

> *Definite Values Principle:* Any classical system is characterized, at each instant of time, by definite values for all physical quantities pertaining to the system in question.

The Definite Values Principle takes classical properties (values of physical quantities) to be intrinsic to the system and independent of whether or not any measurement is performed on them. The *Separability Principle* and the *Definite Values Principle* are essential to classical mechanics because they allow classical mechanics to describe our ordinary perceptions of the macroscopic world in an adequate way. For our everyday experience in the world, these two principles provide us with correct predictions and explanations of most physical phenomena. For instance, the definite values principle allows us to measure the definite speed we drive at a given time.

However, the realist interpretation of quantum mechanics overturns the classical conception of nature and denies the *Separability Principle* and the *Definite Values Principle*. The realist interpretation of quantum mechanics violation of the Separability Principle is best demonstrated in terms of quantum entanglement. In the paradigm entanglement system of two spin-1/2 particles, the compound system has properties that cannot be determined by intrinsic properties and spatio-temporal relations between its two parts. The reason is that when they are entangled, only the compound system is in its eigen-state, but each of the two parts is not. And this nonseparability reveals a holistic feature of entangled systems. The slogan of holism is that 'the whole is more than its parts.' But there is no classical analog of such a phenomenon. Moreover, when the two particles are entangled, each of them is not found to have a definite spin value until measurement is performed. And measurements always reveal them being anti-correlated, such that if one particle is measured to have +1/2ħ, the other particle is guaranteed to have -1/2ħ, and vice versa.[12] But in the classical counterpart, there is no such correlation between noninteracting distant subsystems, otherwise one subscribes to 'action at a distance.' However, in the quantum world under the description of the realist interpretation, this correlation can be blamed on nonseparability. A violation of the *Separability Principle* is essential to the realist interpretation of quantum mechanics because it relies on it to make correct predictions and explanations of the quantum world. Likewise, the violation of *Definite Values Principle* is essential because Heisenberg's uncertainty principle prohibits canonically conjugate variables of quantum systems from having definite values at any given time before measurements are performed, and this is important for collapse theories like the realist interpretation of quantum mechanics.

*Implications for selective realism**

An implication of the fact that classical mechanics and quantum mechanics possess essential rival features is that it denies a theory-continuity between these two theories, so a selective realist* position about quantum mechanics is not preferable. However, selective realists* may argue that there might be some other ways to construct a theory-continuity project between classical mechanics and quantum mechanics, so her SR* is still an appropriate characterization of the two theories. This line of thought

[12] In addition, prior to measurement, there is a probability that particle 1 will have value +1/2ħ and particle 2 will have value -1/2ħ. Only after measurement can we be certain about what value each particle has. This differs from classical mechanics because quantities of classical systems do not depend on our measurement on them. However, in quantum physics, "there is a simple explanation for the frequent inexistence of properties independent of measurements (some particular properties do exist, for instance the rest mass of particles). We may assume that the measured properties are contextual, that is they depend not only on the state of the system but on the whole experimental context" (Santos, 2015, p. 366).

is natural for those who adopt Bohr's correspondence principle (which I will discuss later), by interpreting classical mechanics as a limiting case of quantum mechanics.

Initially, a motivation for a theory-continuity is to accommodate the threat from PMI. Only those realists who accept the pessimistic induction, such as selective realists*, will have to worry about what the theory-continuity parts of theories from past to current theories are. They will have to explain that past theories are successful yet false, yet current theories are both successful and true, by arguing that there are some theory-preserving parts of past and current theories. However, one can still be a realist, in a general selective realist sense, about both classical mechanics and quantum mechanics (despite the fact that they have incompatible essential features), and about theories in general, which I am about to argue next.

Selective realism (SR)

SR on its own is attractive because we have independent reasons to believe in parts of theories. Among the collection of past theories in the inductive basis, classical mechanics was considered to be one of the most successful past theories. I argue that the three formulations of classical mechanics, Newtonian, Lagrangian, and Hamiltonian, provide an independent reason for realism. A closer examination of classical mechanics will get us back to a realist position but without committing to everything each of the three formulations claims. First of all, the three formulations of classical mechanics are mathematically equivalent but not ontologically equivalent (French, 2011).[13] According to French, "under an appropriate transformation, the Lagrangian yields the Hamiltonian and indeed, this forms the basis of the claim that the two formulations are inter-translatable" (2011, p.

[13] This feature of classical mechanics is also discussed in Chapter 5.

209). Each formulation is useful depending on what kind of systems we are working with. For example, when we are dealing with a system with many constraints, say a harmonic oscillator, the Lagrangian might be preferred over the Newtonian. In the familiar form, Newtonian mechanics, the motion of classical systems can be specified by positions, forces, masses, etc. The Lagrangian and Hamiltonian formulations, unlike Newtonian formulation, do not explicitly specify *force,* an unobservable, but specify positions and velocities, which are observable quantities. "In the Lagrangian formulation, the state of a system is specified by its position and velocity. In the Hamiltonian formulation, the state of a system is specified by its position and momentum. But this is normally taken to be a nominal difference. The two theories may be formulated in different languages, but they are still equivalent" (Barrett, 2014, p. 802). The point is that the three formulations make the same commitment with regard to observables, but not to the unobservable, force. For one to view the three formulations consistently, one can deny the existence of force, which is a claim about our knowledge of the unobservable.

One might draw an opposite conclusion: that the fact that Lagrangian and Hamiltonian don't commit to force, but all three formulations give the same prediction, is a reason for an anti-realist position, instrumentalism for example. In particular, claims about force, an unobservable, should not be interpreted literally and its postulation does not provide us any knowledge. However, realist interpretations of the three formulations can claim that denial of the existence of an unobservable is a realist claim, with the unobservable, force, being a presuppositional posit. More specifically, it seems that one can still take a Psillos-type (2005) or Kitcher-type (1993) of realist position towards classical mechanics. Psillos' account divides a theory into two components: idle constituents of a theory and the essentially contributing constituents. Psillos' distinction between idle constituents and essential constituents often gets treated more or less the same as Kitcher’s (1993) distinction between working posits and presuppositional posits. Psillos points out that his distinction is meant to capture how the successes of a theory can differentially support its several theoretical constituents (Psillos, 1996, p. 311). Kitcher's distinction between presuppositional and working posits, however, is meant to capture the difference between referring and non-referring terms. Working posits are said to be "the putative referents of terms that occur in problem-solving schemata," while presuppositional posits are "those entities that apparently have to exist if the instances of the schemata are to be true” (Psillos, 1996, p. 311). A Newtonian realist may take a force as a presuppositional posit or an idle constituent for the derivation of the right result only under the Newtonian formulation. Point particles which have position, velocity and momentum are taken as working posits or essentially contributing constituents, and they are required to work out the calculations, predictions and explanations, but force is posited for the sake of deriving the right result in relevant cases.

With regard to SR about quantum mechanics, there are various interpretations of quantum mechanics that can be interpreted in terms of SR. Bohmian mechanics, as a quantum theory, has various versions. Some versions commit to the existence of a quantum potential, while some other Bohmians might take the potential to be a mathematical artifact, so they can be selective realists about the quantum potential. Also, defenders of the realism of quantum mechanics can believe in the claim of non-existence of particle trajectories, while taking the wave function to be a mathematical construct for calculations.

Objection: An alternative account - Bohmian mechanics

One might argue that if we have a theory of quantum mechanics that is compatible with classical mechanics and if this quantum theory contains elements that survive a theory transition, then we have a clear case of quantum mechanics that can resist PMI as selective realists* argue. Allori argues that primitive ontology of Bohmian mechanics can achieve this.

According to Allori, a primitive ontologist, the primitive ontology (PO) approach "can provide what explanationism needs to defeat the PMI argument in the classical-to-quantum transition. The PO, and not the wave function, can be identified with the working posits of quantum theory, and as such: (1) it is primarily responsible for the success of both classical and quantum mechanics; and (2) it is (suitably) preserved in the classical-to-quantum theory change" (2018, p. 69). PO is defined as "some variable in three-dimensional space (or four-dimensional space-time) that represents physical objects" (Allori, 2018, p. 71). For classical theories, the PO is point-particles. In Bohmian mechanics, PO is particles. The rival version of Bohmian mechanics to primitive ontology, *wave-function realism*, takes a wave-function to represent a real physical entity (a detailed discussion of primitive ontology and wave function realism can be found in Chapter 3 and some part of Chapter 4). It takes the wave function to be part of its fundamental ontology in addition to Bohmian particles. Allori argues that "since the wave function does not have any classical analog, if wave function realism is true it is hard to see how the working posits are preserved in the transition from classical to quantum mechanics" (2018, p. 69). However, she has not sufficiently argued why the wave function is not a working posit even if she anticipates this criticism. Indeed, a Bohmian might still want to be a realist about the wave function, because taking the wave as a physical entity, such as a field (such as in Hubert and Romano 2018), can explain well how an interference pattern is formed in a double-slit experiment. Also, to account for conservation of energy, it seems that the wave has to exist as a physical entity in order to allow energy exchange with particles. Riggs (2008) argues that "the quantum potential facilitates the transference of energy from wave field to particle and back again which accounts for energy conservation in isolated quantum systems," such that the wave field can also store energy (p. 21; p. 33). Any plausible physical theory will have to obey the conservation law. The wave function takes part in the explanation of certain phenomena, unlike primitive ontologists suggest.

For Allori's primitive ontology to resist PMI, she seems to assume something she is not entitled to or at least she has not justified. She assumes that classical particles are the same as particles in Bohmian mechanics and are retained in the ontology through theory change. It is controversial whether classical particles are the same sort of particles as quantum particles (In fact, I argue in Chapter 5 that Bohmian particles and classical particles are essentially different). For instance, a classical particle, when no gravitational force acts on it, travels in a straight line, but a Bohmian particle guided by a wave will follow a curved trajectory. The point here is that classical particle dynamics are different from Bohmian particle dynamics, such that there is an essential difference in their trajectories because Bohmian particles are under the guidance of the wave function where classical particles are not. Furthermore, Allori claims that primitive ontology in other interpretations of quantum mechanics can be continuous fields or flashes which behave like particles but are not particles. This just makes it more obvious that the working posits which were supposed to be responsible for the success of classical mechanics are different from working posits in quantum theories. So far, primitive ontology of Bohmian mechanics has not yet successfully resisted PMI. But one should not take this to suggest that

Bohmians should give up primitive ontology. This only suggests that some sort of theory-continuity between classical mechanics and quantum mechanics cannot be established.

The correspondence principle

The fact that classical mechanics endorses the *Separability Principle* and the *Definite Values Principle*, but quantum mechanics denies them seems to be worrisome for those who accept Bohr's correspondence principle. Just like in Newtonian mechanics and relativity, although they differ greatly, the former is taken to be a limiting case of the latter, say when the system is moving at extremely low speed, a theory correspondence principle applies to classical mechanics and quantum mechanics.[14] Bohr argues that past classical theories can be taken to be limiting cases of quantum theories. The simple idea is that later theory is a better approximation to truth than earlier theory, since it can reproduce the results of earlier theories and can accommodate cases that are not accounted for by earlier theories.

Initially, one may worry that since the correspondence principle sought to reestablish the link between classical mechanics and quantum mechanics, my argument on the discontinuity of the two theories will undermine the correspondence principle. This is a genuine worry. However, even if the correspondence principle interprets classical mechanics as a limiting case of quantum mechanics, this does not mean that my argument against theory-continuing parts and SR* undermines the correspondence principle. The reason is that the correspondence principle is not to be understood as a principle about any theory-continuity parts or ontological continuity between theories, rather it should

[14] One way this may happen is when we have large quantum numbers, we can recover the result of classical mechanics.

be viewed as a principle of mathematical equivalence, *at some limit*. For instance, the defender of wave function realism might hold that the wave function is a real physical entity although there is no classical analog. She might think that the wave function is responsible for why quantum mechanics is successful. Even if she might maintain that particles have charge and mass just like how classical mechanics describes particles, she does not commit to a continuity of ontology even if she believes that classical mechanics is a limiting case of quantum mechanics.

To further see how the correspondence principle should be separated from a theory-continuity, consider another case. In classical mechanics and theory of relativity, it is widely agreed that they coincide in a formal way at the low speed limit.[15] But, this should not lead us to assert that there are some theory-continuity parts or common essential parts underlying the two theories. In fact, these theories also make very different assumptions, for example classical mechanics assumes Galilean transformations and absolute space, but relativity assumes Lorentz transformations.[16] The idea that a correspondence principle does not latch on to any ontological connection between classical mechanics and theory of relativity but that they merely coincide at the mathematical level is supported by Feyerabend's claim on incommensurable terms of classical mass and relativistic mass. According to Feyerabend, classical mass is an intrinsic property of a particle and independent of its motion, but relativistic mass depends on a particle's motion (Feyerabend, 1981, p. 81). In other words, the term 'mass' refers to different conceptions of a particle in two theories. It is only when one takes a low

[15] Although I have been primarily concerning low speed limit, similarly, large distance is also a limiting case. Steven Weinberg (1972, Ch.7) talks about the Newtonian limit of Einstein's field equations too, and in (1989, pp. 14-15) he repeats that "Einstein's theory of general relativity ... reduces to Newton's theory at large distances and small velocities." Also Misner, Thorne and Wheeler (1973, ? 17.4) explore the mathematical reduction of general relativity to Newton's theory of gravity "in the 'correspondence limit' of weak gravity and low velocities".

[16] Lorentz transformations are a set of linear transformation from a coordinate frame to another one that moves at a constant speed. Galilean transformations are a set of transformation between reference frames which differ only by constant relative motion within a Newtonian framework. Galilean transformations are useful approximations for systems moving at low speed.

speed limit that relativistic phenomena, such as time dilation, disappear (Rivadulla, 2004, p. 418). But one should be careful whether taking a classical limit of the quantum counterpart will recover classical results. When Bohmian mechanics is written as a second-order Hamilton-Jacobi equation which is similar to that of the classical second-order Hamilton-Jacobi equation (except the Bohmian includes a quantum potential term), Poland (1993) suggests that taking the classical limit of Bohmian mechanics by taking the quantum potential to zero will recover the classical result (Brown et al. 1996, p. 313). This is a manifestation of the fact that classical mechanics is a limiting case of quantum mechanics, but this makes no indication whether a continuity of ontology is maintained or should hold between the two theories. However, one should be careful whether the classical result will be regained in experiments rather than in theory. In the simulation of Sengupta et al. (2014), they did not observe classical behaviour of particles when taking the quantum potential to zero. If taking the classical limit does not reproduce the classical result in Bohmian mechanics, this just means that a correspondence principle does not hold between classical mechanics and Bohmian mechanics. It does not imply whether such correspondence principle cannot hold between classical mechanics and other quantum theories. The point is, defenders of the correspondence principle should not confuse the correspondence principle with a theory-continuity. The conclusion to draw, I think, is that the correspondence principle is a principle of mathematical equivalence, at some limit, but nothing else.

Part 3. Bridging Part 1 and Part 2.

The fact that classical mechanics and quantum mechanics have contradictory essential features has an implication for pessimists. There is a lack of relevant similarity of the essential features (due to contradictory essential features) between classical mechanics and quantum mechanics needed to permit the pessimist's inference that quantum mechanics is false given that past theories are false. This is different from saying that we cannot infer from the falsity of classical mechanics to that quantum mechanics is false. The point is rather that the additional information about members of theories, in particular classical mechanics and quantum mechanics being discontinuous, confirms that PMI is a bad argument as shown in Part 1. The rival features of classical mechanics and quantum mechanics show that pessimists are not allowed to infer that quantum mechanics (which is one of our best current theories) is false, in addition to the implication that a selective realist* account of quantum mechanics and classical mechanics is not plausible as I argue in Part 2.

Because of the additional information of the incompatible essential features of classical mechanics and quantum mechanics, PMI does not render quantum mechanics false. This background information of their incompatibility is important for generalizing the features of the theories in the inductive basis to the next theory. The point is that PMI as an induction is not always permitted if there is relevant background information about theories that prohibits an induction from past theories to the next theory. Background information often plays a role in determining the conclusion in an inductive process. In a general case of induction, suppose person A encounters a virus and gets sick, persons B encounters the same kind of virus and gets sick, and the same thing happens to person C, D, E, F, G…. Now person x also encounters the same sort of virus. But unbeknown to the pessimists, person x caught the virus before and produced anti-body to fight the virus. In her second encounter with the same virus, she will have a quicker anti-body response to the virus. But lacking this background information of person x's medical history, the pessimist given her sample of person A, B, C… will conclude that person x also gets sick. But person x may not get sick because her quick anti-body response to the virus this time.

In the case of PMI, it seems that the transition from classical mechanics to quantum mechanics is relevant background information that pessimists need to take into consideration, but they have failed to, and mistakenly infer that quantum mechanics is false, given that past theories that are successful have turned out to be false. These two cases exhibit some similarities. Similar to making an induction from theories in the inductive basis, the inferred member, persons x in the medical case, should be also relevantly similar to the members in the inductive basis. For instance, person x has similar biological functions and biological reactions to virus as other human persons A, B, C and so on. Also, in a temporal sense, both inductive cases involve using some historical records. Most people in the past who encountered virus were sick, and most empirical successful theories in the past turned out to be false. Nonetheless, there is a stronger connection between the two cases. In the medical case, pessimists need a story about why people who encounter the virus are sick (note that when one gets a virus she is not always sick). The reason might be that most people have weak immune systems or haven't yet got vaccines. Likewise, pessimists need a story about why successful theories are false or what is responsible for that most successful theories are false. Pessimists might argue that these empirically successful theories (were once successful because they can explain some phenomena) cannot account for newly discovered phenomena and they give an inaccurate description of the world.

In addition, we can find similar examples in scientific theories that shows that PMI is not always permitted, at least not in a superficial way that ignores details of these theories. In thermodynamics, the mechanical theory of heat denies that heat is a substance, unlike the caloric theory (and the phlogiston theory) of heat that takes heat as a substance, caloric, which flows from hotter objects to colder objects. Instead, the mechanical theory of heat treats heat as equivalent to mechanical work.

According to William Thomson, "heat is not a substance, but a dynamical form of mechanical effect, we perceive that there must be an equivalence between mechanical work and heat, as between cause and effect (Thomson, 1851). Also, Maxwell specifies that heat "*cannot be treated as a material substance*, because it may be transformed into something that is not a material substance, e.g., mechanical work" (Maxwell, 1872). The caloric theory has turned out to be false, but the mechanical theory of heat has been accepted for a long time. So this discontinuity in the conceptual change of heat during theory transition suggests that a simple induction from past theories to the next theory may fail if the pessimists ignore such background information.

For PMI to be a powerful argument or for an inference to be permitted at all, pessimists have to take into consideration the relations between past theories and current theories, because such information can play an important role in determining whether an induction can be made. Given that classical mechanics and quantum mechanics cannot be similar enough along multiple dimensions and in fact they make rival claims, the falsity of past empirically successful theories does not transfer to our current empirically successful theories. However, one should note that if two theories differ significantly but do not suppose contradictory essential features, they may still have the same truth value.[17]

Conclusion

To summarize, I argue against the anti-realist argument PMI and a selective realist* account of

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[17] Mizrahi argues that "from the fact that past and current theories differ in "significant ways," it does not necessarily follow that past and current theories must have different truth values. Past theories and current theories can differ in significant ways, and yet have the same truth value" (2013, p. 3212).

quantum mechanics (and classical mechanics). Realism about quantum mechanics involves taking a selective realist attitude towards a version of quantum mechanics. The incompatible features of classical mechanics and quantum mechanics is consistent both with the Part 1 conclusion that PMI fails and the conclusion in Part 2 that a theory-continuity cannot be established between them. The theory transition from classical mechanics to quantum mechanics connects these two main conclusions. On the one hand, a selective realist* position ignores the fact that these quantum theories, unlike classical theories, require interpretations before we take realist commitments toward them. On the other hand, realists about quantum mechanics also have to resist the challenge from PMI which denies the truth of quantum mechanics based on the falsity of past theories. But as I have shown in this chapter, PMI constructed as an inductive argument is a weak argument, and pessimists have not yet provided a reliable inductive basis to permit an inductive inference that quantum mechanics is false. Not only that PMI fails as an inductive inference in general that I argue in Part 1, but also that pessimists did not take into considerations of background information about the relation between classical mechanics and quantum mechanics. Also, the fact that quantum mechanics needs interpretations makes it difficult for selective realists* to rely on the standard solution to resist PMI, by searching for some theory continuity between classical mechanics and quantum mechanics. This standard solution overlooks how complex the transition from classical mechanics to quantum mechanics is. If selective realists* were to revolve their realism about quantum mechanics around resisting PMI and looking for some deep connections with classical mechanics, they maybe misguided about how they should be realist about quantum mechanics. It seems unappealing and unnecessary to seek a continuity with classical theories. SR, as a weaker position than SR*, can accommodate the realism about quantum mechanics better.

CHAPTER 2

Underdetermination and Empirical Equivalence: The Realist Interpretation of Quantum Mechanics and Bohmian Mechanics

The problem of underdetermination in general is that if two or more different theories are empirically equivalent, that is they make the same empirically testable predictions, then we have no empirical reasons to believe one but not the other. I take that two or more theories or formulations are empirically equivalent with respect to *all possible data*.[18]An underdetermination is seemingly present between the realist interpretation of quantum mechanics (hereafter RI) and a non-local hidden-variable theory, Bohmian mechanics (hereafter BM).[19] Both are non-relativistic theories. Here, the realist interpretation of quantum mechanics is the theory that upholds the same postulates and principles as the Copenhagen interpretation without taking all unobservables to have only instrumental values. I called RI the realist interpretation of quantum mechanics, but it should not be taken to be the only realist interpretation of quantum mechanics. Although sometimes BM is also called an interpretation of quantum mechanics, it is in fact a theory in its own right. It is widely accepted that both of them have the same predictive power (Allori and Zanghi 2004; Bostrom 2015; Gisin 2018; Goldstein 2010). For instance, according to Allori and Zanghi, "Bohmian mechanics makes the same predictions as does orthodox quantum theory for the results of *any experiment* [emphasis mine]" (2004, 1947). Goldstein (2010) also argues that "Bohmian mechanics is empirically equivalent to orthodox quantum theory

[18] It is possible to define empirical equivalence with respect only to currently available data. Under this definition, it is a matter of time that two currently empirically equivalent theories may turn out to be not equivalent.

[19] There are various versions of Bohmian mechanics. An underdetermination can also be found among different versions of Bohmian theories, such as a minimalist account and a causal account. See Mauricio Suarez's (2015) "Bohmian Dispositions."

provided we accept the quantum equilibrium hypothesis" (p. 345).[20] But, it is agreed that they have different ontologies, in fact opposed ontologies, so they cannot both be correct theories. For example, RI obeys indeterministic laws and claims a nonexistence of particle trajectories, while BM obeys deterministic laws and claims an existence of particle positions and trajectories (Cushing 1994, p. 203). Their different conceptual apparatuses will show how they describe the world differently and may or may not account for certain phenomena. In addition, they have different mathematical formalisms even if both have employed a wave-function that evolves in accord with the Schrodinger equation. BM injects a pilot wave with a guiding equation that describes particles' trajectories at any given time. There is thus a way to distinguish the two theoretically and ontologically. If they are empirically equivalent but are rivals, they cannot be both correct. It is questionable whether the two theories are in fact empirically equivalent, but if they are, it seems that we will face a problem of underdetermination.

In this chapter, I use BM and RI, which are often believed to be empirically equivalent and underdetermined (see Allori and Zanghi 2004; Goldstein 2010; Saatsi 2019), to show that it is possible to offer a solution to underdetermination in some local cases, by specifying what counts as relevant empirical evidence in empirical equivalence and underdetermination. I argue for a *domain-sensitive* approach to underdetermination. Domain sensitivity on theories' predictions plays a role in determining whether two or more theories are empirically equivalent and underdetermined. One should however be careful about generalizing this strategy to all cases of underdetermination in

[20] Bohmian mechanics "accounts for all of the phenomena governed by nonrelativistic quantum mechanics, from spectral lines and scattering theory to superconductivity, the quantum Hall effect and quantum computing" (Goldstein, 2017). But note that this is not sufficient to claim that BM and RI are empirically equivalent. Instead, we need a stronger claim that the two theories make the same predictions for all experiments and observable phenomena they apply to.

scientific theories. I provide two experiments to show that BM and RI are not empirically equivalent when we consider their predictions within their own domain of application. To further support my argument for the denial of the empirical equivalence between BM and RI, I argue that BM and RI are not empirically equivalent when we consider their predictions for domains outside their application, using the relativistic domain as an example. The main conclusion is that there is no given set of empirical data that BM and RI are both consistent with, so they are not underdetermined. By showing that BM and RI are not empirically equivalent, it follows that the underdetermination between BM and RI is merely *apparent*. In section 1, I present the background of underdetermination in the context of non-relativistic quantum mechanics. In section 2, I will consider predictions within the domain of non-relativistic quantum mechanics, and show that the two theories are not empirically equivalent. In section 3, I will show that the predictions for domains outside quantum physics are relevant if they are derived from the fundamental part (or the hard core) of a quantum theory and those predictions may be also confirmed or disconfirmed by theories or empirical findings in other domains. The two theories, BM and RI are not empirically equivalent when extending our discussion to the relativistic domain.

1. Preliminary

First of all, we need a clear characterization of empirical equivalence and underdetermination. Although underdetermination is a general philosophical problem, I restrict the scope to underdetermination in scientific theories. In particular, underdetermination is the situation that given the available empirical evidence, there are always at least two theories that are consistent with it.[21]

[21] This is what sometimes called contrastive underdetermination. Also note that here I define underdetermination as the case that given available empirical evidence, there are at least two theories consistent with it. Here 'available empirical evidence' should be taken to mean whatever evidence is under consideration. One can consider a given set of empirical data where two theories are

The available empirical evidence equally supports these theories. In our context, Bohmians, such as Allori and Zanghi (2004), claim that "all the experimental evidence confirms Bohmian mechanics as well as quantum mechanics" and so is an instance of underdetermination (p. 1748). Note that the definition of underdetermination here raises an epistemological issue about theory choice. And there are different criteria to theory choice, such as epistemic criteria on non-predictive empirical evidence or practical criteria such as simplicity. Empirical equivalence is the thesis that two theories are empirically equivalent iff they make exactly the same empirically testable predictions. With respect to the scope of the empirical predictions, I consider *all possible data from empirical predictions*, rather than merely what is currently empirically testable and available to us. This is to include the possible data that the progress of science might provide us in the future and also data that may never be tested in practice due to the limitations of scientific inquiry. Empirical equivalence and underdetermination are different in that underdetermination implies empirical equivalence, but not vice versa. If two theories are not empirically equivalent, then they cannot be underdetermined, because they cannot both be consistent with the given empirical data. This point is essential for the rest of the chapter because by arguing that RI and BM do not make the same predictions either within or outside their domains of application, they are not underdetermined. On the other hand, if two theories are not underdetermined, it does not imply that they are not empirically equivalent (using the definition above). This is because there might be empirical evidence that are not empirical predictions of these two theories, such as

consistent with, but not all, data. For example, one might say the orbital velocities in the galaxy are consistent with both the dark matter theory and Modified Newtonian dynamics. Concerning this piece of empirical evidence, these two theories are both consistent with respect to these data (and this implies that the two theories make the same predictions in the orbital velocities and hence are empirically equivalent), but there might be other empirical evidence (which are not predictions) that one theory can account for but not the other. The definition of underdetermination is not in conflict with my consideration of all possible data in this chapter because I take all possible data to be what is under consideration, although some of them are not yet detected or could never be detected due to the limitation of the technology.

background theories, which can empirically distinguish one theory from the other, so they are not underdetermined even if they might make the same predictions (Laudan and Leplin, 1991). In this case, even if two theories are not underdetermined, they may still be empirically equivalent. Namely, they make the same empirically testable predictions. This point is discussed in Laudan and Leplin (1991). And my discussion of this chapter will focus on the entailment that if two theories are not empirically equivalent, then they are not underdetermined.

It is often not made clear what a relevant piece of empirical evidence is involved in underdetermination, that is whether the only relevant empirical evidence is what is predicted by the theories and whether two or more theories are empirically equivalent with respect to certain domains of theory application. I argue that BM and RI are not empirically equivalent by showing what counts as relevant empirical evidence for confirming or disconfirming a theory. This implies that there are empirical data that one theory is consistent with but not its rival, so there is no underdetermination between BM and RI. More specifically, an item of empirical evidence can be a prediction (i.e. evidence entailed by or derivable from a theory) which has empirical consequences, or evidence that is not predictive, but serves as a confirmation or disconfirmation or empirical support for a theory. In particular, I adopt Worrall's definition of prediction which draws the distinction between predictions and empirical evidence that can be accommodated by a theory. According to Worrall (2011), "prediction properly understood is simply the opposite of accommodation. A piece of evidence e is accommodated within a theoretical system T based on a core theory C by tailoring specific and/or auxiliary assumptions exactly so as to produce such a system that entails e. A datum e′ is predicted by a theoretical system just in case it is deductively entailed by that system but was not accommodated within it" (p. 163). In other words, predictions of a theory are empirical claims or hypotheses that are deductively derivable from the theory. On the other hand, there is non-predictive empirical evidence that might support a theory but not its rival(s). For instance, in fluid mechanics, macroscopic systems called walkers exhibit quantum-like phenomena. A walker system, which consists of a water droplet and the wave it creates, is a macroscopic system that resembles the Bohmian model of particles and waves, but is not direct evidence for BM. However, by studying the walkers and how they behave, we can understand the Bohmian model and its behavior in a relatively intuitive way. Another main point I address in this chapter is that empirical evidence for a theory can be evidence we find in other domains of application. I devote section 3 to address this point.

1.1 The basics of RI and BM

Next, I give an overview of the leading postulates or principles of RI and BM. I extract them from the formulations of Suarez (2015) and Maudlin (2002). These postulates tell us some fundamental features (or essential features) of the two theories. But they shouldn't be taken to include all of the hard core features of the theories. For instance, postulates 1 and 2 do not tell us that particles do not have trajectories because we cannot simultaneously measure positions and momentum precisely in the framework of RI (due to Heisenberg Uncertainty Principle). Although BM is sometimes said to be defined in terms of postulates 1'-5', one should not take these postulates to be exhaustive features of BM either. For instance, these postulates do not tell us how to understand the wave function, and they do not say that it is defined in a high-dimensional *configuration space* which causes many difficulties in accepting BM.[22] A configuration space is a mathematical space. And for a quantum system with N particles, the configuration space of the system is 3N-dimensional. According to Bricmont, the *configuration space* of the system consists of the set of all possible positions of all the *N* particles, where *N* is arbitrary and could in principle include all the particles in the universe (2016, p. 52). According to Lewis, in Bohmian mechanics, one can understand that "the state of a quantum system at a time is specified by the distribution of wavefunction properties over the possible values of 3N coordinates" (2004, p. 726). But these postulates give some senses of how the two theories differ and why they are scientifically and philosophically interesting.

The realist interpretation[23]

1. The State Postulate: The wave-function is complete, i.e., the physical state of a system is entirely captured by the wave-function.

2. The Dynamical Postulate: (1) The wave-function usually develops in accord with Schrodinger's equation, but it sometimes 'collapses.' (2) The complete dynamics is stochastic rather than deterministic. The stochastic element of the standard interpretation appears in the wave collapse since the Schrodinger evolution is deterministic.

Bohmian mechanics[24]

1'. The State Postulate: The wave-function is incomplete. The physical state of a system is not entirely captured by the wave-function. BM ascribes to all particles positions at all time, where such physical properties are not encoded in the wave-function. These positions of particles are hidden variables. (The state of a physical system is given by a wave-function and particle positions.)

2'. The Dynamical Postulate: (1) The wave-function always develops in accord with Schrodinger's equation. There is no wave collapse (not even when measurement interactions take place or under any other circumstances). (2) The dynamics is deterministic, since the wave-function is always governed by Schrodinger's equation. The hidden variables also evolve deterministically.

[22] A configuration space is an abstract high-dimensional space, such that the configuration space for a quantum system with N particles is 3N-dimensional. The *configuration space* of the N-particle system consists of the set of all possible positions of all the *N* particles, and could in principle include all the particles in the universe (Bricmont 2016, p. 52).

[23] This formulation of the realist interpretation of quantum mechancis is from Maudlin (2002 p. 116-117).

[24] See Suarez (2015 p. 2-5) and Maudlin (2002 p. 117) for this formulation of Bohmian mechanics.

3'. The Equilibrium Postulate (or The Distribution Postulate): The quantum equilibrium configuration probability distribution ρ for an ensemble of systems each having quantum state ψ is given by: $\rho = |\psi|^2$.[25] (The Born-rule distribution for positions (assumed to hold at *t* = 0) will hold for all *t*. And this assumption reproduces the same predictions as the standard interpretation.).[26]

4'. The Guidance Postulate: Particles move on trajectories given by their positions and velocities which are determined by Bohm's equation (the guidance equation). This equation describes a velocity field associated to each particle, in terms of its position, as a function of the quantum wave-function.[27]

5'. The Quantum Potential Postulate (endorsed by the causal version of BM): The force acting on each particle at position k with velocity v is given by the quantum potential, which is a quantity definable from the wave-function.[28] The quantum potential was supposed to influence the particles and guide their trajectories.[29]

1.2 Motivating realism

In order for the underdetermination problem to be a genuine worry for the realist, we need to investigate whether we can hold a realist position towards both RI and BM. We need to be clear whether the theoretical claims both theories make should be interpreted literally, otherwise the underdetermination is not really a problem. *Prima facie*, if we take the wave-function to be a merely mathematical tool for making predictions, then we have no reason to believe in the truth of either theory. The underdetermination problem is supposed to attack the claim that empirical data give reasons to believe in the truth of one theory over the other. But if both theories are empirically

[25] The wave function is universal wave function, not for ensemble of subsystems of the universe.
[26] I take this postulate as an auxiliary assumption of BM to recover the predictions of RI, because I take theories to consist of essential parts and auxiliary parts.
[27] Some argue that this guidance equation is not a postulate, because it can be derived in several ways, see Durr, Goldstein and Zanghi (2013).
[28] "It has been pointed out how these two versions of Bohmian mechanics differ minimally in ontology. This difference is indeed minimal, since neither version by itself describes how the world is ultimately furnished ontologically, but to the contrary leaves the fundamental ontological options wide open" (Suarez 2015, p. 4). For instance, the two versions haven't said if the wave-function is a physical object.
[29] One should note that not all Bohmians adopt this postulate, but David Bohm does. This postulate does not appear in the formulations of some other Bohmians such as, Durr, Goldstein and Zanghi.

equivalent, then we don't have an epistemic reason to believe in one theory but not its rival. Suppose that we agree that the two quantum theories are empirically equivalent (under the characterization introduced above), then whether empirical equivalence leads to a underdetermination will partly depend on whether we are entitled to take realist positions towards both theories. On an instrumentalist position, such as the Copenhagen interpretation, there is no concern regarding whether one theory is true or false. In what follows, I will take realism to be the thesis that theoretical claims of a theory have truth values, such that they are either true or false.[30] In other words, theoretical claims are to be interpreted literally.[31] This contrasts with the instrumentalist who thinks that theoretical claims are useful for deriving the right predictions and calculating, but shouldn't be taken at face value nor having any literal meaning. The problem of underdetermination will be a genuine worry for both quantum theories which have incompatible ontologies and postulates only if it is reasonable to take realist positions towards each of them.

It is generally believed that BM is a realist theory. Given the dynamical postulate 2' of BM, which is a deterministic theory, it is possible to specify particles' positions at any given time. And postulate 4' determines a velocity field of a particle at each time. For instance, a Bohmian can take the claim that 'a particle follows a determinate trajectory' to have a truth value. But there is more we can say about it, and attribute fewer realist commitments to Bohmians. The dynamics described by the minimalist version of BM (accepting postulates 1'-4', but denying 5'), fits well with a Humean picture of distinct existences of entities. In the present context, there is no necessary connection between a particle's distinct existence at different times. The positions of a particle can be specified at each given

[30] I leave multivalued logic aside and restrict to two-value logic, so a statement is either true or false. And this realism construed as a semantic thesis is one Michael Dummett (1982) defends.

[31] This is often referred to as the semantic dimension of scientific realism.

time and one can commit to only its existence at a time. Regarding the dynamics of a particle, the Bohmian adopting a Humean account does not have as heavy a realist commitment as one might envision. However, the causal version of BM (accepting postulates 1'-5'), David Bohm's version, does not fit well with the Humean picture, because on the causal account there is a "dynamical equation describing the 'force' that 'causes' particles to accelerate in or out of inertial constant motion" (Suarez, 2015, p. 6). The causal version explicitly commits to something over and above distinct existence at each moment. Some causal force is pushing the particles and grouping all the distinct existences at different times.[32] There can be more or less realist commitments in BM depending on how we understand it.

In contrast, according to RI which is a realist interpretation of quantum mechanics, the quantum dynamics is indeterminsitic. It thus seems natural to say that the realist will deny that the dynamics is deterministic. And this suggests that the advocate of RI can take some theoretical claims to have truth values. Not all advocates of postulates 1 and 2 take them in just an instrumental sense because they deny that the dynamics is deterministic to distinguish their position from other positions, such as BM. Furthermore, with regard to particle dynamics, RI can even accept claims about wave collapses (as in postulate 2(1)), even if the wave function is a mathematical construct for calculation in this interpretation. RI should not to be confused with the Copenhagen interpretation. RI is a realist interpretation of quantum mechanics, and RI and BM should be taken as two distinct quantum theories. Some literature seems to take BM as a realist interpretation of quantum mechanics when it is, in fact, a theory in its own right because it has its formalism, ontology, and postulates, which give a

[32] The minimalist will not describe the relation between the wave and particles in terms of some quantum force mediating them. The minimalist can say that the wave is associated with particles, but do not commit to any other unobservables that describe their interactions or relations.

deterministic conception of the reality.

Worrall (2011) argues that for an underdetermination situation to be truly threatening to the scientific realist, two conditions have to be satisfied. (i) "For any accepted scientific theory there is always another that is 'equally empirically successful'" and (ii) "the alternative cannot plausibly be regarded as equally 'approximately true' as the accepted theory" (Worrall 2011, p. 161). (ii) is straightforward when we are dealing with two theories that are contrary in their 'deep structure.' The pair, BM and RI is a common example of (ii), where the former is a deterministic theory, endorses particles trajectories, identifies the wave function as representing some physical object, and mathematically introduces a guiding equation, etc. while the latter endorses the opposites. What we are about to investigate is whether the two theories satisfy (i), that is whether they make the same predictions.

1.3 The Equilibrium Postulate

BM and the RI are often believed to be underdetermined because BM can reproduce the same predictions as RI. According to Allori and Zanghi, "Bohmian mechanics makes the same predictions as does nonrelativistic ordinary quantum mechanics for the results of any experiment, provided that we assume a random distribution for the configuration of the system and the apparatus at the beginning of the experiment given that the probability density is equal to the wave function squared" (2004, p. 1746). This is the Equilibrium Postulate (postulate 3'). This is to say, " a Bohmian universe, though deterministic, evolves in such a manner that an appearance of randomness emerges, precisely as described by the quantum formalism and given, for example, by "$\rho = |\psi|^2$" (Durr, Goldstein & Zanghi, 1992, p. 1). Dürr, Goldstein and Zanghi (1992) argue that the choice of the square of the wave-function as the initial probability distribution can be justified without any stochastic processes by a close consideration of the notion of universal typicality (Maudlin 2002, p. 119).[33] It is common to assume that the two theories make the same predictions and they are empirically equivalent. However, one may be skeptical whether the two theories, RI and BM, can make the same experimental predictions at all, as one can challenge the equilibrium assumption that Bohm makes to reproduce the predictions of RI. If these assumptions are problematic, we have a reason not to accept that the two theories are empirically equivalent even in their own domain of application.

According to Valentini, the predictions of quantum theory are recovered if one assumes that an ensemble of systems with the wave-function begins with a 'quantum equilibrium' distribution of configurations at t = 0 in BM (2002, p. 2-3). But BM also allows one to consider arbitrary 'nonequilibrium' initial distributions, where the probability density is not identical to the wave function squared, which violate quantum theory (Valentini 2002, p. 2-3).[34] And Valentini thinks that we often ignore non-equilibrium states because "a huge amount of 'subquantum information' is hidden from us simply because we happen to live in a time and place where the hidden variables have a certain 'equilibrium' distribution" (2002, p. 9). From a practical point, Colin and Valentini point out that "in the context of inflationary cosmology, quantum non-equilibrium at very early times could leave an observable imprint today on the cosmic microwave background. It has also been shown that, in certain conditions, relaxation [from non-equilibrium states to equilibrium states] can be suppressed for long-

[33] According to Durr, Goldstein and Zanghi (1992), "a crucial ingredient in our analysis of the origin of this randomness is the notion of the effective wave function of a subsystem, a notion of interest in its own right and of relevance to any discussion of quantum theory" (p. 1).

[34] Notice that Valentini (2014) states explicitly that De-Broglie (1927) dynamics assumes only equilibrium states, but Bohm's dynamics (1952) allows assumption of both equilibrium and non-equilibrium states.

wavelength field modes in the early universe, and it is possible that low-energy relic particles could still exist today that violate the Born rule. Apart from these cosmological *possibilities*, however, if we focus on the physics of ordinary systems in the laboratory, then according to de Broglie's dynamics equilibrium [i.e. accepting the Equilibrium Postulate] today is to be expected" (Colin and Valentini 2014, p. 3).[35] This is to say, it is possible to observe those non-equilibrium states that are naturally created, but not in experiments.[36] This is a reasonable conjecture because the progress of science might tell us whether the equilibrium postulate will be rejected or not. From a theoretical point of view, "if de Broglie's pilot-wave theory [that only assumes equilibrium states as the initial conditions] is taken seriously it must be admitted that departures from the Born rule are in principle possible—just as departures from thermal equilibrium are obviously possible in classical dynamics" (Colin and Valentini 2014, p. 2). The non-equilibrium states will lead to predictions that differ from that of RI, including violating the uncertainty principle.[37] Although the non-equilibrium state still lacks empirical evidence, if it is true, one should rethink whether we can make the assumption of equilibrium distribution without hesitation.

We ought to acknowledge the fact that we lack empirical evidence of non-equilibrium states due to the limitations of science, but not to see it as a vice of empirical research or a discouragement to pursue scientific projects. There are some empirical data that are hard to detect but should be taken as

[35] One possible reason why we do not see quantum non-equilibrium today is that there is relaxation from non-equilibrium to quantum equilibrium: if some non-equilibrium distributions existed in the past, they are quickly driven dynamically to quantum equilibrium (Colin 2011, p. 1117).

[36] Although experimentally non-equilibrium states have not yet been created, according to Colin, there have been simulations of the evolution of non-equilibrium distributions for two-dimensional systems (e.g. the two-dimensional Dirac oscillator and the Dirac particle in a two-dimensional spherical step potential) (2011, p. 1116).

[37] According to Colin and Valentini, "it has been shown that non-Born rule distributions in pilot-wave theory can give rise to a wealth of new phenomena. These include non-local signalling—which suggests that the theory contains an underlying preferred foliation of space–time—and 'sub-quantum' measurements that violate the uncertainty principle and other standard quantum constraints. On this view, quantum physics is a special equilibrium case of a much wider non-equilibrium physics" (2014, p. 2).

relevant and important in our scientific reasoning. For instance, dark matter is inferred to exist to account for the orbital velocities in galaxies, but we haven't yet detected it because we think it does not interact with observable electromagnetic radiation. The point is that it is difficult to detect either dark matter or non-equilibrium states in practice, but this should not prevent us from taking them as relevant evidence for confirming a theory. It seems reasonable to include such empirical data in assessing underdetermination in the present context even if they are difficult to detect in practice. In a word, all possible data include data that are not yet detected in practice but may be detected in the future and data that may never be detected in practice due to the limitations of science. Riggs (2009) also stresses this point. Riggs (2009) considers a case where we can use Atomic Optics to empirically distinguish BM and RI, by testing whether an atom trapped in a well is in motion (p. 144). He concludes that "ideally, if the Causal Theory [aka. Bohmian mechanics] prediction is correct, one would expect to detect no phase shift in the reflected laser light (i.e. no motion of the atom)," and he thinks that in this case BM makes a different *theoretical* prediction from that of RI (p. 145). This experiment is very difficult to conduct in practice, but we nonetheless think the predictions for this experiment is relevant (Riggs, 2009, p. 146). Riggs' point is that we should acknowledge the limit of science and the problems it creates for drawing conclusions about whether BM and RI are empirically equivalent.

The advocate of BM is not defending their interpretation simply because it produces the same experimental predictions as RI. They have more genuine motivations to defend BM because it can accommodate the measurement problem and recovers some classical conceptions, such as determinism and trajectories of particles. But one should remain skeptical on whether the two in fact are empirically equivalent within the domain of quantum physics. If it is true that other assumptions, such as non-equilibrium states, are legitimate to make, this will mean that the predictions derivable from BM and RI need not be the same, in a principled way. This means there is no empirical equivalence to begin with. However, we will have to wait for the verification and testing of such assumptions to tell us the answer. For Laudan and Leplin, theories make the same prediction only temporarily because it will depend on scientific progress for us to know whether the assumptions we are making are in fact correct. "As a consequence of scientific progress the class of auxiliary assumptions which are suitable for the derivation of observational consequences from theoretical hypotheses may get enlarged by the introduction of new well-confirmed theoretical hypotheses (and this may include theories outside the domain of non-relativistic quantum mechanics, as I will show in section 3) or newly discovered facts, or it may get reduced through the rejection of theoretical hypotheses which were previously accepted" (Acuna & Dieks, 2014, p. 7). It might be due to the limitation of science that we misbelieve in an empirical equivalence between the two theories at the current stage.

2. Empirical evidence within the domain of application

However, we should remain optimistic about searching for empirical distinguishability between the two quantum theories. In the rest of this section, I will discuss why there might not be an empirical equivalence between the two theories (hence they are not underdetermined), and restrict the discussion in this section to the domain of non-relativistic quantum mechanics. When we restrict ourselves to the non-relativistic quantum domain, it is important for us to see within this domain what the relevant empirical data are for accepting one theory but not its rival(s). The two theories, BM and RI, make the same empirical predictions in statistical correlations, tunneling, interference, etc. To give a specific case, BM predicts that there is an interference pattern in a double-slit experiment because there is a wave associated with particles when the system passes through a double-slit device and the particles go where the wave reinforces. On the other hand, RI predicts there is an interference pattern because the probability wave creates such a pattern. But the two theories are not necessarily empirically equivalent even within their own domain of application. Since BM has endorsed the ontology of particles and the pilot wave, the starting point is to look at evidential supports from experiments concerning these two sorts of entities.

Kocsis et al. (2011) show that they can measure average trajectories of a quantum particle, where they reconstructed these trajectories by performing a weak measurement of the particle's momentum.[38] In particular, they "sent an ensemble of single photons through a two-slit interferometer and performed a weak measurement on each photon to gain a small amount of information about its momentum, followed by a strong measurement that postselects the subensemble of photons arriving at a particular position…. This weak momentum measurement does not appreciably disturb the system, and interference is still observed. The two measurements must be repeated on a large ensemble of particles in order to extract a useful amount of information about the system. From this set of measurements, we can determine the average momentum of the photons reaching any particular position in the image plane, and, by repeating this procedure in a series of planes, we can reconstruct trajectories over that range. In this sense, weak measurement finally

[38] In the experiment, Kocsis et al. "sent an ensemble of single photons through a two-slit interferometer and performed a weak measurement on each photon to gain a small amount of information about its momentum, followed by a strong measurement that postselects the subensemble of photons arriving at a particular position. We used the polarization degree of freedom of the photons as a pointer that weakly couples to and measures the momentum of the photons. This weak momentum measurement does not appreciably disturb the system, and interference is still observed. The two measurements must be repeated on a large ensemble of particles in order to extract a useful amount of information about the system. From this set of measurements, we can determine the average momentum of the photons reaching any particular position in the image plane, and, by repeating this procedure in a series of planes, we can reconstruct trajectories over that range" (Kocsis et al., 2011, p. 1171).

allows us to speak about what happens to an ensemble of particles inside an interferometer" (Kocsis et al. 2011, p. 1171). In fact, "the trajectories measured in this fashion reproduce those predicted in the Bohm–de Broglie interpretation of quantum mechanics" (Kocsis et al., 2011, p. 1173). This prediction is within the domain of application of non-relativistic quantum mechanics, and is confirmed by experiments. This empirical evidence about average trajectories directly supports the Bohmian model. On the other hand, RI rules out particle trajectories. It seems that if an advocate of RI interprets the data of particle trajectories in this case, she has to bite the bullet and argue that a weak measurement on a photon's momentum without disturbing the system cannot be done. She might say that because there is a principled reason, which is that "any information gained about the quantum particle's position irrevocably alters its momentum (and vice versa) in a way that is fundamentally uncertain" (Kocsis et al., 2011, p. 1170). In other words, there is a detectable empirical difference between the two theories if we look at those empirical consequences of a theory, which are empirical data we obtained in experiments. So, BM and RI cannot be consistent with the experimental results. This challenges the common impressions that RI is sufficient for making correct predictions, and the thinner our realist commitment is, the safer our theory is.

In addition to the experiment of Kocsis et al. which reproduces the results about particle trajectories (particle features) predicted in Bohmian theory, we are also interested in results that support the existence of the pilot wave, since it gives rise to peculiar characteristics of BM, such as nonlocality. Cardone et al. (2004) conducted a double-slit like experiment which shows that the pilot wave has to exist in order to account for an anomalous interference effect. I will focus on explicating this experiment as an instance of empirical differences between BM and RI, because it presents a clear case of how the two theories make different predictions.

I will first give a brief description of the experiment. In several similar experiments carried out by Cardone et al., they infer the existence of the wave function and consider their results to be “the first direct evidence for the Einstein-de Broglie-Bohm waves” (2006, p. 1116).[39] Their primary box experiment consisted of a Plexiglas box with wooden base and lid. As shown in Fig. 1, the box (thoroughly screened from those frequencies which might have affected the measurements) contained two identical infrared (IR) LEDs, as (incoherent) sources of light S1 and S2, and three identical photodiodes, as detectors A, B, C (In replicated experiments, the experimenters replaced photodiodes with phototransistors.). The two sources, S1, S2, were placed in front of a screen with three circular apertures (i.e. slits) F1, F2 and F3 on it. The apertures, F1 and F3, were lined up with the two LEDs, so that the IR beams from S1 and S2 propagated perpendicularly through each of them. The geometry of this equipment (e.g. size of the box and locations of the lighting sources, detectors and slits) makes sure that the detector C and S2 are lined-up in a proper way (distance between them matters as suggested by experiments on the breakdown of LLI), such that F2 is outside the emission cone of S2, so photons from S2 will be eliminated at C and no photons can pass through F2. Similar to the usual double slit experiment, we have two slits, F1 and F2, which are designed to produce interference effects. “The experiments just consisted in the measurement of the signal of the detector A (aligned with the source S1) in two different states of source lighting. Precisely, a single measurement on the detector A consisted of two steps: (1) Sampling of the signal on A with source S1 switched on and source S2 off; (2) sampling of the signal on A with both sources S1 and S2 switched on. Analogous measurements

[39] See also Cardone et al. (2004, 2007); Mignani et al. (2012).

were taken on the detectors B and C. A possible *non-zero difference* Δ A = A(S1 on S2 off) - A(S1 on S2 on) in the signal measured by A when source S2 was off or on has to be considered as evidence for the searched anomalous effect" (Mignani et al. 2012, p. 3).[40] ΔA is a measure of a change in energy in the two states of source lighting. Classical or quantum electrodynamics fails to predict a non-zero Δ A (Cardone et al. 2006, p. 1110). Cardone et al. conclude that the non-zero energy gap is a manifestation of an anomalous interference effect, and they interpret this change as an anomalous interference involving the pilot waves associated with photons.

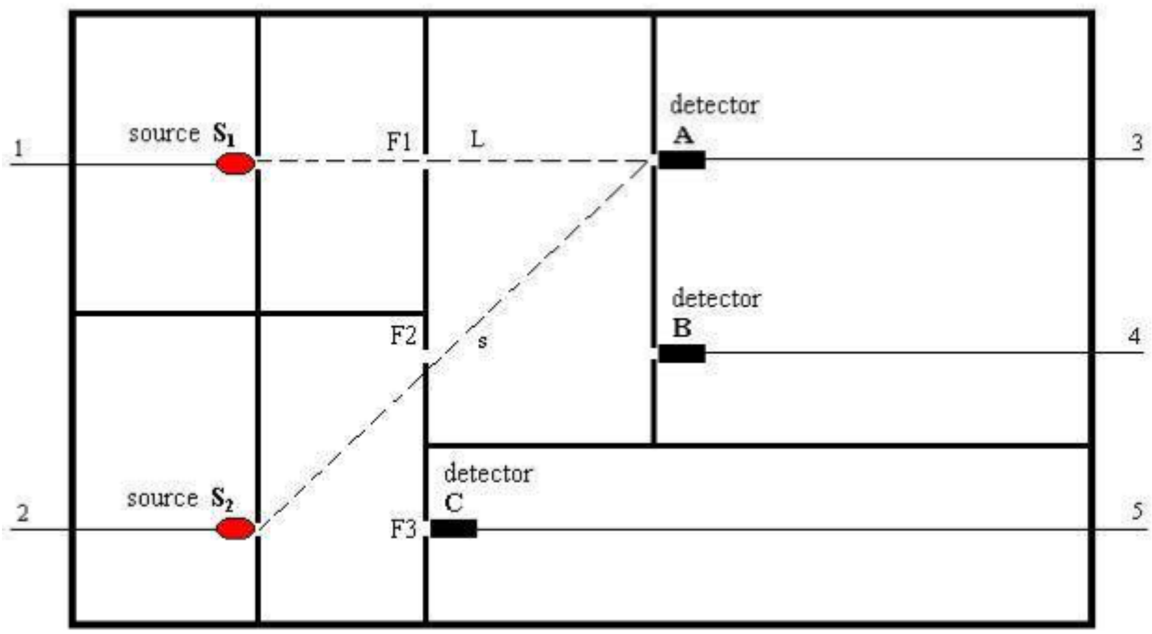

Fig. 1 The top view of the box experiment (From Cardone et al. 2004). Numbers 1-5 represent the five devices (two sources S1 and S2 and three detectors A, B and C) used in this experiment. Dash lines represent the straight-line path of putative entities. The horizontal line L represents the distance between source S1 and the detector A, which is the shortest distance photons passing through slit F1 and detected at detector A. The diagonal dash line s represents the shortest distance between the (putative) pilot wave and detector A (no photons could pass F2), which is the path the pilot wave passing through slit F2 and arriving at A. But it does not represent any physical trajectory of photons from S2, because C is situated at the place to ensure no photons from S2 go through F2 (For a more detailed description of the setup see Cardone et al. 2004).

The geometry of the box experiment plays an important role in drawing the conclusion of the

[40] The anomalous interference effects of photons were also observed when using microwave and infrared laser beams. One with microwaves emitted by horn antennas, at IFAC — CNR (Ranfagni and coworkers), and the other with infrared CO2 laser beams, at INOA (Meucci and co-workers). See Cardone et al. (2006, p. 1113-1114).

existence of the pilot wave and that RI and BM make different predictions. The experimental set-up was designed according to the results of two experiments, the Florence experiment and the Cologne experiment, which manifest a threshold behavior of the breakdown of Local Lorentz Invariance.[41] In particular, the box is designed in analogous geometry of the Florence experiment not just because it is analogous to the usual double-slit experiment, but also because the energy (measured at detectors) and spacing of the box are critical to bring about the anomalous effect (Cardone et al. 2004, p. 6). The values of energy and spacing indicated by the Florence experiment and the Cologne experiment allow Cardone et al. to conclude that the pilot wave is a deformation of spacetime, which connects BM with deformed special relativity. For our argument here, the crucial point is that the experiment set-up manifests a change in energy. Another important geometrical feature is that "the apparatus was determined by the requirement that the slit F2 lies outside the opening cone of the source S2," so no photons from S2 can possibly passes through F2 (Cardone et al., 2004, p. 6).

The Cardone et al. experiment presents a case where BM makes a correct prediction while RI fails to do so (In fact, the experiment supports some versions of Bohmian mechanics but not all. In this chapter I will just refer to BM without making distinctions between different versions of it. Later on, in Chapter 3 and 4, I argue that the Cardone et al. experiment supports a wave function ontology of Bohmian mechanics rather than a primitive ontology version of Bohmian mechanics). The postulation of the pilot wave allows one to make sense of an anomalous interference effect, reflecting in a change of energy level. But RI does not predict this change because the wave function will collapse at a

[41] The Cologne experiments is about superluminal sub-cutoff propagation in waveguide and the Florence experiment is about superluminal propagation in air. For details see Nimtz et al. (1994); Heitmann and Nimtz (1994); Ranfagni et al. (1993); Cardone and Mignani (2004).

detector so it does not make any impact on the result. "The central part of Quantum Mechanics is the wave function, along with its probabilistic interpretation and its instantaneous collapse in one of the eigenstates as the quantum system is measured. The photons emitted by S2 are detected and hence measured by the detector C. In this sense the wave function, that describes the quantum system of these photons and that, before the measurement, represents the probability to find them in any place of the universe (in the sense of Feynman path integrals), collapses in C and reduces to zero the probability to find them in any other point of the box. This quantum mechanical prediction is against the results of the experiments that indicate that the turning on of the source S2 influences both the reading of the detector C, of course, and that of the detector A although, *by design* [emphasis mine], there should not be any correlation between S2 and A" (Mignani et al., 2012, p. 6). This is a case where BM exhibits both explanatory power and predictive power towards the anomalous effect. We have a reason to accept the truth of one theory but not the other not only due to theoretical virtues but also empirical support, so the underdetermination does not arise here.

For the conclusion that RI and BM are not empirically equivalent in the case of the box experiment, we anticipate two criticisms. One is that the two theories both make incorrect predictions, that is they both do not predict there is a change in energy level at the detector A. The other one is that one may argue that both theories make correct predictions. In either case, one argues that we cannot distinguish them empirically using this experiment.

Some might argue that BM will make the same but *incorrect* predictions as RI. The reason is that if a Bohmian accepts the conditional waves (associated with sub-systems in the world) version of BM, an anti-realist can challenge her that conditional waves associated with each particle from S2 will also collapse at C in the same way the wave function collapses according to RI. So this version of Bohmian mechanics will not predict a change in energy level in the box experiment. However, the conditional wave function view, as opposed to the universal wave function view (i.e. there is a wave function, the pilot wave), needs scrutiny. The conditional wave function view is that there is a conditional wave function associated to every particle in the three-dimensional space instead of a universal wave function that lives in the configuration space. One major problem of the conditional wave function view is that it does not recover all the predictions of BM, because "they cannot describe entangled states between particles" (Hubert & Romano, 2018, p. 6). The reason for failing to account for entanglement states is that "the information about entanglement gets lost in the definition of conditional wave-functions—that's the same for the reduced density matrix in an EPR experiment, where it merely gives us the statistics for one particle irrespective of what happens to the other particle" (Hubert & Romano, 2018, p. 6). To recover quantum entanglement, Norsen (2010) adds additional local fields to the conditional wave-functions (Hubert & Romano, 2018, p. 7). But Hubert and Romano argue that "Norsen's theory of exclusively local beables makes the very same empirical predictions as the de Broglie–Bohm theory—it even predicts the very same trajectories—, but the price to be paid is a more contrived law for the evolution of all those local fields" (Hubert & Romano, 2018, p. 7).[42] There is no convincing reason for accepting the conditional waves view. My point here is that the conditional wave function view is a less defensible version of Bohmian mechanics and it does not undermine the conclusion that the box experiment supports the universal wave function view, and in

[42] Hubert and Romano has two objections for Norsen's approach. "First, it turns out that there are infinitely many such interacting fields since the evolution of the interaction fields requires further interaction fields. . . a never ending recursion. And it's not clear yet that one can get satisfactory results with only a finite set of these fields. Second, each conditional wave-function follows a modified Schrödinger equation, in which the other interaction fields are included. And these interaction fields themselves have their own evolution equation. This makes the theory mathematically very complicated and almost impractical for calculating empirical predictions" (Hubert & Romano, 2018, p. 7).

particular the existence of the pilot wave.

Another worry is that one may argue that both RI and BM make the same correct predictions which is that they both predict there is a change in energy level at the detector A. To reply to this concern and to argue that RI does not predict a change in energy level, it is important that we emphasize the design of the experiment. The experimental set-up and an elimination of S2 photons do not allow photons to pass through slit 2. This feature is ensured because "when the lighting condition changes from (S1on S2 off) to (S1 on S2 on) the signal on A increases a little bit, although this cannot be imputed to the passage of photons from F2 since *the detector B is always underneath the maximum dark voltage established experimentally* [emphasis mine]" (Mignani et al. 2012, p. 6). It is worth stressing that that the experiment is set up in a way that RI does not predict a change in energy level. What this means is that on the RI account, in the setting when S1 and S2 are both on, when photons from S2 are detected at C, the wave function associated with these photons will also collapse (this is the wave function collapse postulate). Because of the wave function collapse, no photons and any other unobservable entities can pass through slit F2 to contribute a change in energy level. In either settings, S1on-S2off and S1on-S2on, RI predicts that there is no change in energy level because what happens to photons from S1 is not influenced by anything that originates from S2.

Using the empirical evidence of the pilot wave to undermine the underdetermination charge is related to Allori and Zanghi's comment.[43] Allori and Zanghi argue that the decision of what is the right theory should be taken on the deeper level of the ontology of the theory—what the theory is about

[43] The orthodox solution is to prefer a theory that is simpler and has more explanatory power. But one can argue that it is subjective of what counts as simple and whether a theory has enough explanatory power.

(Allori & Zanghi, 2014, p. 1747-1748). Ontologies merely tell us what a theory is and what ontological commitments it can make, but it does not automatically confirm the truth of that theory unless it is empirically supported. For a correct theory, its ontology should also be verifiable on an empirical ground, otherwise it is idle. As we can see, this is the case in Cardone et al.'s experiment, and it is the postulation of the existence of the pilot wave that allows the Bohmian to make the right prediction. This does not require direct observation of the pilot wave since most unobservable entities we are realist about are inferred. For instance, the existence of electrons is inferred by Hacking (1983) in his entity realism, because we can use electrons to manipulate other unobservable entities. (A detailed discussion of applying Hacking's criterion to the wave function and the particles can be found in Chapter 4.) Hacking's entity realism is that we use unobservable entities to investigate other parts of nature by relying on their well-understood causal properties (which we gain by interacting with the entities) to build devices. We know how to get the entities to behave in such and such a way, and when we do this, we should believe in the existence of these entities (Hacking 1983, p. 263). Likewise, one can argue that the pilot wave is inferred to exist in the experiment of Cardone et al. under Hacking's criterion by saying that we can use the pilot wave to manipulate something else. And the existence of the pilot wave explains why Cardone et al. observed an anomalous interference effect.

However, a more serious worry about these two experiments arises from another sort of underdetermination. Resulting from the Duhem-Quine thesis which states that "a hypothesis can entail observable consequences only with the help of auxiliary assumptions", "one should generally expect that if a hypothesis H—along with the class of auxiliary assumptions A—entails the observational consequence e, there exists another hypothesis H' that can also entail e by introducing a suitable class of assumptions A'" (Acuna & Dieks, 2014, p. 2). In short, this sort of underderdetermination is one about whether both T+AH1 and T'+AH2, where 'T' and 'AH' stands for a theory and auxiliary hypotheses of theories respectively, are consistent with the empirical results. And this calls into question of whether T+AH1 and T'+AH2 are empirically equivalent. An implication of this underdetermination is that if T'+AH2 makes a false prediction in an experiment, this experiment does not tell us whether T or one of AH2 is wrong because we can always choose the auxiliary assumptions to make the right predictions according to the implications of the Duhem-Quine thesis. So in an experiment where a theory T makes a correct prediction and a theory T' makes an incorrect prediction, the experiment cannot determine if T' is wrong.

Applying this objection to Kocsis et al. where the experiment confirms BM, but not RI, one argues that the experiment cannot tell us whether RI is wrong. In response to that, it seems that it is not always uncertain what to blame for making the false predictions. The degree of blame may be placed more heavily on one hypothesis of RI than its auxiliary assumptions in Kocsis et al. Indeed, we have a stronger reason to condemn the hypothesis of RI that particles do not have trajectories, because it is clear that the experimental result of Kocsis et al. is inconsistent with this hypothesis of RI. In their experiment, Kocsis et al. produce the average trajectories of a quantum particle. But according to RI, there is no such concept of particle trajectories, so it does not make sense to say particles have trajectories regardless of whether they are average trajectories or exact trajectories. RI cannot describe the result of the Kocsis et al., namely the average trajectories of particles. The reason that RI cannot invoke the concept of particle trajectories is because it violates the Heisenberg Uncertainty Principle mentioned in section 1.1. On the other hand, a Bohmian claims that particles have trajectories, so she can easily account for the empirical result that particles have trajectories. In other words, a Bohmian can argue that the best explanation for the existence of the average trajectories of particles is that particles in fact have trajectories as BM describes them. Although predictions and explanations of theories might come apart in some cases, here we have a case where the fact that a theory cannot explain the phenomena because it lacks the conceptual apparatus is connected to its inability to make the right predictions. Likewise, in the Cardone et al. experiment, an anti-realist might argue a similar point that the experiment cannot tell us whether RI is false even if it makes an incorrect prediction about the change in energy level. But unlike the Kocsis et al. experiment, the error does not obviously lie in RI. The Cardone et al. experiment results in a change of energy levels, and this does not contradict any essential features of RI in any obvious way. In the Cardone et al. experiment, we are not confident that the error in empirical prediction is caused by RI rather than RI's auxiliary assumptions.

The reason that we think the progress of science can offer a way to distinguish the two theories empirically, total data considered, is because auxiliary assumptions are themselves subject to changes over time. This is to say, since we can always change auxiliary assumptions of a theory, science will be able to tell us whether certain auxiliary assumptions should be given up. BM and RI seemingly constitute a case of underdetermination in practice that requires us to consider the empirical evidence that scientific research provides us. So far, the two experiments discussed above haven't yet gained many supports just like BM itself, and this is the case due to many factors such as the fact that the ontological commitments involved in accepting BM are more substantive than RI. In fact, the literature of realist interpretations of quantum mechanics and the empirical testing of BM was only revived more recently. Not only that we need to approach the underdetermination here from a practical point of view, but also that we should realize the limit of science of its descriptive power to describe the world. The point is that we need to take restrictions of the scope of underderdetermiantion seriously. Whether or not we can generalize the reasoning from the progress of science and the limit of scientific research to underdetermination in principle is another issue. Although it might not be obvious whether underdetermination in principle can ever be solved, there is a possibility to solve a practical case of underdetermination. The issue of underdetermination (at least underdetermiantion in practice) is to be settled by the progress of science. For instance, it can tell us whether RI is wrong or its auxiliary assumptions are wrong as shown in the Kocsis et al. experiment where the experimental result disconfirms the non-existence of particle trajectories in RI while there is no obvious contradiction with its auxiliary hypotheses. Furthermore, despite confirmation holism, which is the thesis that a theory or a hypothesis can never be tested in isolation but only together with other hypotheses, if a theory together with auxiliary assumptions makes a false prediction, it is not the case that where the error lies is completely unknown to us. This can be more easily shown in the Kocsis et al. experiment than in the Cardone et al. experiment.[44] In Kocsis et al., it is clear that RI does not have the concept of trajectories to account for the empirical evidence of average trajectories reconstructed in the experiment. It follows that it is more likely that RI fails to make the correct prediction rather than its auxiliary assumptions, such as the assumption of how the experimental apparatus operates or how things interact, etc. RI lacking the concept needed to account for the experimental predictions is the reason why the Kocsis et al. experiment can help us distinguish it from BM. If, in addition to Kocsis et al. and Cardone et al. experiments, we have more experiments that falsify RI conjoined with

[44] Although Andersen et. al (2015) provide a computer-simulated case where they show BM and RI do not make the same predictions (only RI makes the right prediction) when there is a long splitter plate between two slits in a double-slit experiment, there is no actual experiment done on that.

auxiliary assumptions, it is more likely that the error lies in the hard core of RI, rather than its auxiliary assumptions.

3. Empirical evidence from other domains of application

3.1 Background and motivation

In the discussion of empirical equivalence and underdetermination in theories, the sort of relevant empirical evidence under consideration lacks specification. But oftentimes, it seems that if we consider non-relativistic theories, we should consider only empirical evidence within its domain of application to be relevant for its confirmation or disconfirmation. But our sensitivity to predictions outside the domain of theory application may lead to different conclusions of underdetermination. And this is related to a compatibility problem that is often raised between quantum mechanics and the theory of relativity. The theory of relativity requires that there is no objective fact about simultaneity (to be explained later), but BM requires an absolute simultaneity because the guiding equation requires that particles that are spatially separated, no matter how far, affect each other instantaneously. *Prima facie*, one might object that the compatibility problem between quantum mechanics and the theory of relativity is a conceptual-ontological one rather than an empirical one. This objection misses the point I am raising here. The point of the argument is not to solve the compatibility problem, instead the point to look for empirical evidence outside a theory's domain of application and see if it is relevant for its confirmation. In fact, the relativity of simultaneity is empirically supported whereas absolute simultaneity is not. But it is correct that addressing this question involves offering some solution to the compatibility problem. To show that predictions a theory makes for domains outside its general application are relevant, it is worth mentioning Laudan and Leplin's (1991) treatment of underdetermination. They think there is *background knowledge that can count as empirical evidence* which will enable us to prefer one theory over the other. So an empirical equivalence of the two theories explicitly considered does not necessarily lead to a problem of underdetermination. Also, Acuna and Dieks (2014) argue for this same point, and like Laudan and Leplin, not in the context of the two quantum theories under consideration.

Acuna and Dieks' point is that although two theories are empirically equivalent, confirmation theories or background knowledge of science can offer a way out of the problem of underdetermination.[45] Acuna and Diek's emphasis is not on a theory's predictions for domains outside its general application, but the fact that a theory makes predictions that contradict background theories. What I am about to argue next is to challenge if there is empirical equivalence in the first place given that a theory can make predictions for domains outside its own application. Nonetheless, my argument is rooted in Acuna and Diek's idea (and also Laudan and Leplin's).

It is possible that there is a way out the underdetermination between RI and BM that depends on scientific development and its relations to theories that concern other domains of application. Lewis (2016) has put the dispute between BM and the theory of relativity in terms of objective facts. Relativity denies any objective facts about simultaneity given that there is no preferred reference frame in the universe and the speed of light is a constant across all frames of reference. According to Lewis,

[45] It seems that if one were to appeal to empirical reasons that Dieks (and Laudan and Leplin) suggests, then one might argue that there are also other empirical considerations to prefer Bohmian mechanics, rather than RI. According to Allori and Zanghi, "there are in fact a variety of experimental issues that don't fit comfortably within the standard operator quantum formalism, such as dwell and tunneling times, escape times and escape positions, scattering theory, but are easily handled by Bohmian mechanics" (2014, p. 1748). The fact that one theory is better at accounting for some phenomena is not the same as saying that it is correct. Just like in the various formulations of classical mechanics, for instance, Hamiltonian formulation can better account for the dynamics of a harmonic oscillator compared to Newtonian mechanics, but this practical virtue does not necessarily mean that one formulation is correct while the other is wrong. All it shows is that one theory or formulation fits more naturally with some empirical data. This empirical difference is superficial and does not amount to anything deep.

“whether two events are simultaneous is a matter of conventional choice, not objective fact. So the value of a distant property right now is simply undefined according to special relativity. *The motion of a particle here and now cannot depend on distant states of affairs*, not because such instantaneous action at a distance would be “spooky,” but because there is no objective fact about which distant states are simultaneous with here and now (2016, p. 111). BM as a non-local version of hidden variable theories runs against the well-confirmed claim that nothing can travel faster than the speed of light and that there is no absolute simultaneity. BM contradicts the theory of relativity which precludes non-locality, hence we seemingly have a reason to give up BM, if we believe the theory of relativity is correct. RI easily avoids non-locality by viewing the two particles in the Bell-type experiments as a whole when entangled. On the other hand, entanglement is explained in terms of nonlocality in BM. According to Bricmont, in BM “there is a genuine action at a distance here, since choosing the orientation of the magnetic field that measures the spin of particle *A* will affect the motion of that particle, but also of particle *B*, no matter how distant the two particles are from one another” (2006, p. 169).

3.2 Separating domains of application

The main idea is that BM makes a prediction for the relativistic domain that differs from that of RI. This leads some people to question whether BM and RI as *non-relativistic* theories can have implications for the domain of application that the theory of relativity concerns. In a general sense, the question is how to separate domains of application in theories. To justify a domain separation between non-relativistic BM and the theory of relativity and how they are separated and related requires us to address whether non-relativistic BM and relativistic BM are coherent theories. In fact, we need to answer two questions. (1) Given that nonlocality of non-relativistic BM is at odds with the theory of relativity (at least in an apparent sense), is non-relativistic BM a coherent theory? (2) Can we reconcile BM with relativity? Specifically, how do we account for nonlocality of BM so that it is not a problem for construing a relativistic version of BM? It takes some effect to answer (2) because the answer is not obvious.

For (1), nonlocality cannot be avoided in BM, because it is a result of the wave function defined in a higher-dimensional configuration space (Riggs 2009, p. 14). In non-relativistic BM, nonlocality does not make BM more acceptable or less acceptable, because it is a constituent feature of BM. The worry about nonlocality appears when we access both BM and relativity together or when we look at their relation with each other. For those who hold that theories cannot be made independent of background assumptions or cannot be tested in isolation, the relation between BM and relativity becomes important. We wonder what sort of constraints relativity can place on BM. The question now is how to construct a relativistic version of BM despite nonlocality. This is what (2) tries to answer. What it means for a theory to be relativistic is to say this theory can describe, explain and predict the behavior of the relativized entities, such as particles that move at a speed close to the speed of light, with a relativistic version of mathematical formalism and structure. But whether or not we can relativize BM depends heavily on whether we can reconcile nonlocality in BM with relativity.

Riggs points out that nonlocality cannot be rectified in a non-relativistic theory, but he does not provide a solution to reconcile nonlocality in BM with special relativity (2009, p. 115). Fortunately, there are attempts to construct a relativistic version of BM. Here I mention briefly two accounts to show that it is possible to have a relativistic BM although it will need further justifications.[46] Nikolic (2005) argues for a Lorentz-covariant Bohmian interpretation of relativistic quantum mechanics for particles without spin, by giving a Bohmian interpretation of the Klein-Gordon equation, which is a second-order relativistic wave function (p. 549). In his account, "the equations for Bohmian particle trajectories are nonlocal, but they can still be naturally written in a Lorentz-covariant form without a preferred Lorentz frame" (Nikolic 2005, p. 560). In fact, he argues against the common belief that the principle of Lorentz covariance forbids superluminal velocities and superluminal velocities lead to causal paradoxes (Nikolic 2005, p. 550). Although the nonlocality (and hence absolute simultaneity) is part of Bohmian mechanics, Nikolic argues that we can have a relativistic version of Bohmian mechanics by relativizing the wave function without ruling out absolute simultaneity. Goldstein and Tumulka (2003) propose an alternative approach to construct a relativistic version of BM. According to them, the drawback of reconciling BM with relativity is that "in order to account for quantum nonlocality, one employs—contrary to the spirit of relativity—a time-foliation, i.e., a foliation of space-time into 3-dimensional spacelike hypersurfaces, which serve to define a temporal order for spacelike separated points, or one might say simultaneity-at-a-distance, and hence simultaneity surfaces along which nonlocal effects propagate" (Goldstein and Tumulka 2003, p. 3). This foliation is often taken as "an additional element of space-time structure existing objectively out there in the universe" (Goldstein and Tumulka 2003, p. 3). Goldstein and Tumulka present a model that uses backward causation to achieve nonlocality in a Lorentz invariant way, so this model does not involve an additional space-time structure (Goldstein and Tumulka 2003, p. 1). In their relativistic universe,

[46] I am presenting the two possible accounts here, but don't intend to endorse both of them because they need further scrutiny.

“quantum nonlocality originates in a microcausal arrow of time opposite to the thermodynamic one,” such that the microcausal arrow of time is one in which entropy decreases as time evolves (Goldstein and Tumulka 2003, p. 12). Basically, what Goldstein and Tumulka suggest is that a relativistic version of Bohmian mechanics, which is a nonlocal theory, does not presuppose a concept of absolute simultaneity that is directly at odds with the theory of relativity. Even if the model of Goldstein and Tumulka is restricted to systems of entangled particles but no particle interactions allowed, we should remain optimistic in building a relativistic version of BM.

Nikolic argues that his version of relativistic BM makes measurable predictions on particle positions even when the conventional relativistic quantum mechanics does not make such predictions (2005, p. 549). A caveat is that whether relativistic BM and relativistic RI are underdetermined is a separate issue (although not wholly separated) from the underdetermination in non-relativistic BM and non-relativistic RI. Nikolic’s relativistic BM theory and Goldstein and Tumulka’s account suggest that pursing a relativistic version of BM is promising. When we look beyond the domain of non-relativistic BM and RI, we might conclude differently about whether they are empirically equivalent than we may otherwise have. In assessing underdetermination of BM and RI, we should make clear not only if we mean the non-relativistic versions or their relativistic counterparts, but also the scope of their applications, either within their domains of application or outside their domains of application. Our discussion on non-relativistic BM and RI’s relations to the theory of relativity is located on the middle ground between non-relativistic quantum mechanics and relativistic quantum mechanics.

Now, we can proceed to the criterion for separating domains of application of theories. In some cases of specifying the domains of application, the criterion is quite straightforward. For instance, the domain of classical mechanics extends as far as when a system is moving at a low speed (compared to that of the speed of light) and does not cover systems moving at a speed close to the speed of light. This is because objects moving at a very fast speed will require us to change our conception of space-time. On the other hand, relativity not only governs the dynamics of systems moving at a very fast speed, but can also recover the predictions of classical mechanics when taking a classical limit of velocity. The case of classical mechanics and relativity and the case of BM and relativity involve different criteria for separating domains of applications. In the classical mechanics and relativity case, the criterion for domain separation lies in taking a classical limit in the mathematical formalism. However, in the case of BM and relativity, it makes no sense to say one theory is the limiting case of the other. Indeed, the separation of domains of application is even more obvious here because we can pinpoint exactly where the incompatibility arises. The point of contact of the two domains of application is this feature of nonlocality in BM. Dürr et al. (2014) have suggested that regardless of whether we relativize Bohmian mechanics, that is whether or not the usual Schrodinger wave equation is replaced with a relativistic wave equation (such as the Dirac equation), it contains nonlocality. Nonlocality creates a gap between non-relativistic BM and relativistic BM. To jump from non-relativistic BM to relativistic BM requires us to find a way to account for nonlocality in relativistic BM. Nikolic (2005), Goldstein and Tumulka (2003) and Durr et al. (2014) have shown we can have a relativistic version of BM despite its nonlocal feature.

In the rest of section 3, I will argue why empirical equivalence should take into account predictions these BM and RI make for other domains of physics. In particular, I will elaborate on why nonlocality in BM runs against the theory of relativity and what predictions for the relativistic domain are relevant.

3.3 Relevance of predictions for other domains: Nonlocal interactions

Now, there are various kinds of non-locality physicists and philosophers of physics refer to in quantum theories. And it is true that non-locality is part of quantum theories, as demonstrated in the Bell-type experiments of entangled states.[47] But it is important that we keep these various kinds of non-locality separate, and be clear that it is non-locality as action at a distance that is at odds with the theory of relativity. There are two categories of non-locality: Non-locality as action at a distance and non-locality which is not action at a distance (e.g. nonseparability). To use Healey (1997)'s formulations of two locality principles (then non-locality principles are violations of these two locality principles):

> Local Action: If A and B are spatially distant things then an external influence on A has no immediate effect on B (Healey 1997, p. 23).
>
> Separability: Any physical process occurring in spacetime region R is supervenient upon an assignment of qualitative intrinsic physical properties at spacetime points in R (Healey 1997, p. 24).

The kind of nonlocality that RI has to deal with in entangled systems is not non-locality as action at a distance, which is a violation of the principle of Local Action. In this interpretation, the non-locality in entanglement "takes the form of 'nonseparability' (Belousek 2005, p. 671). Given that spatially separated parts are statistically correlated and they are not in their eigen-states when they are

[47] In fact, Tim Maudlin in "Quantum Non-Locality and Relativity" puts the point more assertively. He thinks that non-locality is unavoidable in any theory which recovers the predictions of quantum theory (2002, p. 121).

in an entangled state, they do not each have a definite state as in the classical case. But, instead of thinking that entanglement forces us to accept 'action at a distance,' RI provides an explanation for those statistical correlations between spatially separated particles, by connecting it with a joint state of a whole which is composed by these two parts in the entangled state (given that each of the two objects, which are spatially separated, is not in a definite state when they are entangled, but the whole is at a given state). There is no 'action at a distance' in the Bell-type experiment according to this interpretation. The non-locality in the Bell-type experiments, under RI is understood as *nonseparability*.

On the other hand, according to Belousek, "in Bohmian mechanics, in which "entanglement" takes the form of 'nonlocality', while again the individuality of particles is not at stake, one can interpret 'nonlocality' in terms of the action of either basic, nonlocal, many-bodied forces, or in terms of the dynamics of a 'pilot wave' in configuration space, or in terms of many-particle nonsupervenient relations, depending upon one's interpretation of the 'wave function,' choice of particle dynamics and specification of particle properties" (2005, p. 671). In fact, non-locality is an inherent feature of BM, rather than a unique feature of the Bell-type entanglement experiments. The non-locality of BM originates from the guiding wave it postulates. According to Bell, "that the guiding wave, in the general case, propagates not in ordinary three-space but in a multidimensional-configuration space is the origin of the notorious 'nonlocality' of quantum mechanics. It is a merit of the de Broglie-Bohm version to bring this out so explicitly that it cannot be ignored" (Dürr et al. 1995, p. 4). So the fact that the wave-function is defined in a configuration space and the introduction of Bohm's equation entail the non-locality in BM. A more straightforward way to understand this non-local feature is that *the velocity of any one of the particles, will typically depend upon the positions of the other particles* (Dürr et al. 1995, p. 4). This is to say, an external force acting on a particle at a certain position can immediately influence the trajectory of another particle, even if they are spatially separated (regardless of how distant the particles are from each other). So this feature of non-locality is a violation of the Local Action Principle. The fact that there is an objective fact about simultaneity due to nonlocality in BM is at odds with the theory of relativity.

But one worry is whether empirical equivalence should only be limited to the domain of non-relativistic quantum physics, or extends to other domains of application, such as the relativistic domain. Some empirical considerations are relevant, but not all of them. The prediction of non-local interactions by BM is not an idle prediction but a genuine one, namely those that the essential features of a theory entails, or *deductive consequences* of that theory. The most relevant empirical evidence for evaluating empirical equivalence will have to come from a theory's distinctive ontology or its essential parts, because those empirical equivalences reflect the significance and nature of that theory. The distinctive ontology in BM are the pilot wave and particles, which are subjects of empirical investigations. It is more obvious to think that particles are empirically detectable. For instance, Ian Hacking's (1983) entity realism tells us that some particles, such as electrons, exist because we can use them to investigate other parts of nature. However, we lack empirical evidence of the pilot wave at the current stage, and the justification of it often relies on the Inference to the Best Explanation to show that the pilot wave has to exist in order to explain certain quantum phenomena, such as an interference. If the empirical data of an inference pattern can only be explained by the existence of the pilot wave, then this implies that the pilot wave is empirically loaded, rather than have empty empirical content. If the distinctive ontology of a theory, at least in the case of BM, is empirical, then the predictions derivable from the distinctive ontology are empirical consequences. It is in this sense, one can argue that BM and RI are empirically nonequivalent. A theory not only consists of a set of propositions but also ontologies which are physical things in the world. The essential features of theories might vary from theory to theory. This idea of essential features is related to Lakatos' (1976) idea of the hard core of a research programme, such that the hard core of a sequence of theories remain irrefutable. For instance, BM and Newtonian gravitational law both exhibit action at a distance and particle trajectories, which are central claims of the two theories. However, the theory of relativity and BM do not seem to share such hard core features. In the case of non-locality, the introduction of hidden variables and the guiding wave in postulate 4' (part of the hard core of BM) guarantee a non-locality in BM. These predictions derivable from the hard core of a theory, such as that the world is nonlocal is derivable from BM, might be confirmed or disconfirmed by theories in other domains. So, here we need to distinguish the idle predictions a theory makes from genuine predictions that come from the essential characteristics of that theory. It is possible that a theory X that is empirically equivalent to another theory Y except that X makes a prediction for other domains outside quantum physics, and this prediction is not derivable from the essential part of that theory, but some auxiliary assumptions of that theory, then this prediction is idle. This is a definition of an idle prediction. For instance, some Bohmians, such as primitive ontologists who take the wave function as a nomological entity which does not play a role in explaining the quantum phenomena, might take the prediction of a change in energy level in the box experiment to be an idle prediction. The reason is that this prediction is derivable from the wave function, which is not a genuine part nor a primitive part of primitive ontology of Bohmian mechanics. (And as I will argue in more detail in Chapters 3 and 4, the box experiment supports some versions of Bohmian mechanics but not all.) This further implies that predictions derivable from the essential parts of *non-relativistic* BM is relevant for the relativistic domain. After all, it is not hard to come out with theories that are empirically equivalent, if one accepts an implication of the Duhem-Quine thesis - it is always logically possible to change the auxiliary assumptions in a way that two hypothesis H and H' are empirically equivalent. But the interesting ones are those that are seemingly empirically equivalent but are genuine rivals with incompatible ontologies. RI and BM are such a pair. The former is an indeterministic theory, while the latter is deterministic. It is more interesting to deal with contrary theories because we care about which one is true and which one is false. And we ought to look at the empirical evidence that can shed light on the truth of those theories. The realist often relies on empirical evidence to show that a theory is true, and the underdetermination problem is supposed to show that if both theories are empirically equivalent, then we do not have empirical reasons to accept one theory but not the other. When we take into consideration of a theory's prediction for domains outside of its application, we have more available data to determine whether it is empirically equivalent with its rival. Background knowledge can change over time, unlike the hard core of a theory. If it turns out that the theory of relativity is false and non-locality is a feature of the reality, it will not refute the conclusion that empirical evidence in other domains may be relevant for empirical equivalence.

4. Conclusion

BM and RI are not empirically equivalent when we extend our vision beyond the domain of their applications. This implies that there is no given set of empirical evidence where they can be both consistent with. Even if it is legitimate for Bohmians to make certain assumptions to reproduce the predictions of RI in some cases, we need to also take into account of different sorts of empirical evidence, outside their domain of application. It is often not made clear whether an empirical equivalence is always relative to some domains of application and what counts as relevant empirical evidence. I argue that BM and RI are not empirically equivalent either within the domain of non-relativistic quantum mechanics, or when we extend our discussion to their implications for the relativistic domain. I argue that not all predictions for other domains are relevant, but only those that are derivable consequences of the hard core of the theory. A prediction, such as non-local interactions, is not idle even if it is a prediction that may be disconfirmed by theories in other domains, because it follows from the fundamental part of BM. This prediction plays a role in determining whether RI and BM are in fact empirically equivalent. When we take into consideration of domain of application in empirical equivalence and underdetermiantion, we might draw different conclusions than when we were ambiguous about what count as relevant empirical evidence. A caveat to add to this conclusion is that we should be careful about generalizing this criterion to other cases of underdetermination. We are far from concluding that there is an underdetermination problem for the two quantum theories. The underdetermination problem should not be a reason for abandoning a realist interpretation of quantum mechanics. On the one hand, the two experiments, the Kocsis et al. and the box experiment, support BM. On the other hand, the extension to the relativistic domain and the prediction of nonlocal/local interactions seem to support RI. This contrast seemingly implies that we should give up realist positions to embrace a non-realist interpretation of quantum mechanics. One thing to clarify is that this chapter does not aim to decide which of the two theories is correct but to resist an apparent underdetermination by showing that there is more to consider on the empirical ground when we look beyond the domain of application of theories. It aims to provide a possible solution to real cases of apparent underdetermination but makes no further claim on which of the two theories is correct. And in fact, to decide on that matter, we might need further empirical evidence that is not made available to us. However, if one thinks that theories should explain rather than merely make predictions, then one might still want to resist the challenge of underdetermination even if one cannot yet determine which of the two theories is correct.

CHAPTER 3

Wave Function Realism

Introduction

This chapter aims to explore, from both theoretical and empirical perspectives, a tenable version of Bohmian mechanics using a wave function ontology, which is an alternative to primitive ontology. In particular, to defend a wave function ontology involves understanding the ontological status of the wave function. The background debate between primitive ontology and wave function ontology concerns whether only particles constitute the Bohmian ontology or there are additional entities in the Bohmian ontology. I argue that a wave function ontology is not dispensable by considering various interpretations of the wave function and show that the wave function has to be regarded as a real physical entity in the 3-D space. There are no conceptual problems regarding it in this way. The reason is that if a Bohmian wants to offer an explanation of quantum phenomena, such as interference in the double-slit experiment, only a version of Bohmian mechanics which takes the wave function to be a real entity can best fulfill this explanatory role. In order to articulate what sort of entity the wave function is and why it is part of the Bohmian ontology, I give an analysis of the philosophical implications of the box experiment, which is a modified version of the usual double-slit experiment (introduced in Chapter 2), by analyzing its implications for the ontological status of the pilot wave. I argue that the box experiment provides evidential support for realism about Bohmian mechanics. Specifically, it supports a version of Bohmian mechanics that views the pilot wave as a real physical entity which possesses energy.

In section 1, I present the debate between primitive ontology and wave function ontology and motivate why a wave function ontology is defensible. Section 2 shows that wave function ontology, in particular, leads us to think of the wave function as a real physical entity in the 3-D space as opposed to an entity in a higher-dimensional configuration space (e.g., Albert's configuration space realism) or a nomological entity (e.g., primitive ontology). This position is necessary to explain physical phenomena, such as interference in the usual double-slit experiment. I show that Hubert and Romano's (2018) multi-field account fulfills this role of adequate explanations. The double-slit experiment by itself does not tell us what the wave is except that it is a physical entity, but this gives a reason to pursue a wave function ontology. Hubert and Romano's multi-field is one of the many interpretations of the wave function as a physical entity. We need to go further to unpack the nature of the wave function. To do this, I present the box experiment and explicate how realism about the wave function is manifested in this experiment. I argue that Bohmian mechanics provides explanations for the produced anomalous effect in the box experiment, and Bohmians arrive at this conclusion through using the Inference to the Best Explanation (IBE). In sections 3 and 4, I argue that the box experiment favors a certain version of Bohmian mechanics, namely that the pilot wave is described as a field or a deformed spacetime that possesses energy. In section 5, I discuss the possibility of formulating a causal account of this version of Bohmian mechanics by applying it to the conserved quantity theory of causation.

1. Primitive ontology and wave function ontology

In what aspect should one be a realist towards Bohmian mechanics? According to Allori, there are two proposals: (1) One endorses a direct ontological interpretation of the wave function as representing a physical object. (2) Bohmian mechanics is not really about the wave function, but about the primitive ontology (Allori, 2013, Durr, Goldstein and Zanghi, 2013). For primitive ontologists, the wave function is not an irreducible entity in the Bohmian ontology and only the primitive variables, particles, live in the three-dimensional space.[48] According to Allori, "Bohmian mechanics is naturally a theory with a primitive ontology: there are particles (the primitive ontology), whose temporal evolution is governed by a Schrodinger evolving wave function (the nonprimitive variable)" (Allori, 2013, p. 69). The primitive ontology position "is that all fundamental physical theories, from classical mechanics to quantum theories," share some features, such as being able to account for the macroscopic objects in the three-dimensional world around us, and postulating entities living in three-dimensional space or in space-time, etc. (Allori, 2013, p. 60). For the Bohmian primitive ontologist, the wave function does not represent real entities. Some primitive ontologists take the wave function as nomological, such that it represents a law which describes the motion of particles in the 3-D space (Miller, 2014; Esfeld, 2014).[49] The central issue is whether particles, which are the primitive ontology of Bohmian mechanics, are by themselves sufficient to explain quantum phenomena or whether the wave function is an indispensable and irreducible entity in the Bohmian ontology. As I will show later, Bohmian particles by themselves cannot provide adequate explanations for quantum phenomena and particles' trajectories also need explanations.

In fact, a parallel debate is between the guidance view and the quantum potential view (or the

[48] The primitive ontology applies not only to Bohmian mechanics, but also GRW and many world interpretations (Allori, 2013; 2018).
[49] In section 5, I will say why the primitive ontologist takes a law to play a descriptive role rather than a governing role, and why this makes primitive ontology a non-causal version of Bohmian mechanics.

causal view). The guidance view is that a first-order equation, the guiding equation, is sufficient for Bohmian dynamics about the particles. On the other hand, the quantum potential view takes a second-order Hamilton-Jacobi equation (classical-like) as the most fundamental equation in Bohmian mechanics. Primitive ontologists fall in the camp of the guidance view because the guiding equation which determines the motion of particles is the fundamental equation. In this view, the wave function, which 'guides' particles in a nomological sense, is governed by the Schrodinger equation. On the other hand, if one accepts the quantum potential view, one commits to some sort of causal processes for the particles involved, and this requires some irreducible entities to causally affect these particles. Belousek (2003) defends a quantum potential view which takes particles and the quantum forces as the Bohmian ontology but not the wave function. Here I will use the distinction between primitive ontology and wave function ontology instead of that between the guidance view and the quantum potential view. The reason is that the former distinction directly concerns how we should analyze the wave function. The ontological status of particles is not the focus here because Bohmians all accept that there are particles which have trajectories. But there are further issues which concern Bohmian particles that will be addressed in Chapter 5.[50]

1.1 Primitive ontology: the nomological interpretation of the wave function

For those primitive ontologists who deny the wave function is a real physical entity, they regard the wave function as nomological (e.g., Goldstein and Zanghi (2013)). According to this interpretation,

[50] This feature about particles separates the Bohmian from defenders of standard quantum mechanics, who think that there are no particles that have trajectories throughout their dynamical history. There are no particles in a strict sense according to standard quantum mechanics, except there are particle-like entities when the wave function collapses.

the wave function represents a law – one that describes the motion of real physical particles in the 3D physical space via the Guidance Equation (Suarez, 2015, p. 11). The advantage of this view is that it fits naturally with our classical description of the motion of particles in terms of a law. For example, a charged particle is governed by Coulomb's law. A law governs particles' motion, but not vice versa.[51] In Bohmian mechanics, the wave function describes the motion of particles, but particles have no return action on the wave function. This differs from electromagnetic fields, which are generated by charged particles and can act on those particles. However, this interpretation faces a problem of time-indexicality: we typically understand physical laws as determining the time evolution of the objects in its domain but not as the subject themselves to any temporal evolution (Suarez, 2015, p. 13). This is to say, the wave function cannot be a law because a law is time-invariant, but the wave function described by the Schrodinger equation evolves through time.

In addition to the problem of time-indexicality, a more general issue in primitive ontology is that primitive ontology is not explanatorily adequate. In particular, it does not explain why things are the way they are. Belousek (2003) argues that particle trajectories themselves needed to be explained, which is to ask what accounts for the motion of these particles. According to Belousek, "while the *existence* of quantum trajectories in Bohmian mechanics is itself to be left unexplained – the existence of such trajectories is, after all, *postulated* rather than derived from first principles – the mere existence of those trajectories is by itself insufficient for an explanation. For example, to simply specify the motion of a body correctly with a certain mass and distance from the sun in terms of an elliptical space-time orbit is *not* to *explain* the earth's orbiting the sun but rather to *redescribe* that state of affairs in a

[51] One should note that in this case, there is a Coulomb force between charged particles due to Coulomb's law.

mathematically precise way. What remains to be explained is *how* it is that the earth revolves around the sun *in that way*, and within classical mechanics, Newton's law of universal gravitation and the second law of motion provide the explanation" (2003, p. 136). This is to say, postulating the existence of particles and particle trajectories merely re-describes the phenomena one wants to explain in terms of particles, but how such phenomena occur haven't yet been explained.

If the primitive ontologist's interpretation of the wave function as nomological is explanatorily insufficient, then one might still keep the hope up for a wave function ontology. Wave function ontology has many variants which offer radically different ontological pictures of the world. Two variants, Albert's configuration space realism and Norsen's local-fields interpretation, have received criticism in various aspects.

1.2 Configruation space realism[52]

Configuration space realism is the view that the wave function is real, and the wave function is defined in the 3N-dimensional configuration space, where N is the number of particles. The configuration space realism is endorsed by David Albert (1996) and John Bell (1987). Bell claims that "no one can understand [the de Broglie–Bohm] theory until he is willing to think of it as a real objective field rather than just a 'probability amplitude'. Even though it propagates not in 3-space but in 3N – space" (Bell, 1987, p. 128). Bell thus understands the wave function as a field in the configuration space. For Albert, "if the wave-function is a field, it has to be a field in configuration space" which he takes to be the fundamental space of physics (Albert, 1996, p. 278). On Albert's configuration space realism, the world consists of exactly two physical objects: the universal wave function and the

[52] For a definition of configuration space, see section 1.1 in Chapter 2.

universal particle (Albert, 1996, p. 278; Hubert & Romano, 2018, p. 8).[53] "The major reason for Albert to develop an ontology in configuration space is to have the wave-function as a local beable [i.e., something that has a precise localization in space at a given time]: the wave-function is determined by the local values it assigns to every point of configuration space. Hence, the motion of the universal particle is completely determined by the field value at its location, exactly as in classical electrodynamics, where the motion of a charged particle is determined by the value of the electromagnetic field at its location" (Hubert & Romano, 2018, p. 9). On the configuration space realist account, the wave function behaves very much like a classical field. But the pursuit of a resemblance with the classical field is not necessary because it is clear that the field described here is different from an electromagnetic field. For instance, the electromagnetic field is produced by a source and acts and is acted on by its source, but not in the field in the configuration space realist account. The most common objection is *the problem of perception*. That is, how do objects of ordinary perception emerge from a configuration space if the world consists of only the universal wave function and the universal particle? If the fundamental space is a configuration space, we will have a problem of explaining what we perceive in this 3-D space.

1.3 Norsen's local-fields account

An alternative wave function ontology account is Norsen's interpretation of the wave function, which postulates a multitude of *fields* in the 3D space, and each corresponds to a particle. Since each particle is assigned a local field by a conditional wave function in the 3D physical space (and there is

[53] And "the story of the world consists, in its entirety, of a continuous succession of changes of the shape of the former and a continuous succession of changes in the position of the latter. And the dynamical laws that govern all those changes – that is: the Schrödinger equation and the Bohmian guidance condition – are completely deterministic, and (in the high-dimensional space in which these objects live) completely local" (Albert, 1996, p. 278).

no longer a wave function in the configuration space), what happens to one particle has nothing to do with other particles. The conditional wave "merely gives us the statistics for one particle irrespective of what happens to the other particle," even if it is defined by the universal wave function (Hubert & Romano, 2018, p. 6).[54] The conditional waves prescribe the dynamics of subsystems of particles but not all particles in the universe. This means that "the one-particle conditional wave-functions, however, don't suffice to recover all the predictions of the de Broglie–Bohm theory, since they cannot describe entangled states between particles" (Hubert & Romano, 2018, p. 6). Because of this limitation, Norsen's account seems quite unappealing.

The problem of perception can be avoided by denying that the configuration space is fundamental, so one rejects configuration space realism. Another more general problem of the wave function ontology is the problem of communication. The problem of communication arises when the wave function is defined in a higher-dimensional space but particles are in the 3-D space. How can the wave function guide the particles if they are in different spaces? The problem of communication should sound familiar to the mind-body problem in Descartes' dualism. To solve the problem of communication, we need a way to characterize the wave function as a physical object in the 3-D space, even if it is defined in a configuration space. There are no logical or conceptual problems of having the wave function located in the 3-D space. In what follows, I argue that there is a need to regard the wave function as a physical entity for the sake of explanatory considerations. And in sections 4 and 5, I use the box experiment to show how we should understand the nature of the wave function.

[54] According to Hubert and Romano (2018), "The conditional wave-function $\psi_t(x)$ of a particle is defined by the universal wave-function , once the positions of all the other particles in the universe Y (t) are fixed: $\psi_t(x) := \psi\ (x, Y\ (t))$."

2. Wave function ontology and explanatory adequacy

Prima facie, most of those different versions of Bohmian mechanics can reproduce the same predictions in the quantum domain, so they are empirically on a par with respect to those predictions.[55] We will have to look at the metaphysical ground and how each of their ontological commitments with respect to the wave function (and particles) shed light on their explanations of empirical evidence. I show that a criterion to identify the right version of Bohmian mechanics and to understand the ontological status of the wave function depends on how a version of Bohmian mechanics can best explain quantum experiments and empirical data.

2.1 Bohmian mechanics and the double slit experiment

It is a virtue of Bohmian mechanics, compared to the Copenhagen interpretation of quantum mechanics, to explain the wave-particle duality and interference patterns in a double-slit experiment. In order to decide which version of Bohmian mechanics to accept, I suggest that we look at Bohmian mechanics within the context of this double-slit experiment. This experiment is widely discussed not just because it shows that classical mechanics fails but because it also contains some key features of quantum mechanics. According to Richard Feynman, the double-slit experiment for electrons is "a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery" (Feynman et al., 1963). This experiment "has been designed to contain all of the mystery of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature one hundred percent"

[55] As I will explain later, Norsen's view does not reproduce the same results as the standard interpretation of quantum mechanics.

(Feynman, 1967). Feynman might sound as though he is exaggerating since there are other experiments such as Bell-type experiments that also exhibit peculiar features of quantum theories, but the double-slit experiment does manifest some important features. Feynman does not think we can provide an explanation for it. But the Bohmian account is one that claims to provide an explanation for the double-slit experiment. A realist theory, such as Bohmian mechanics, provides the ontology and tools to explain why things are the way they are. An instrumentalist theory, such as the Copenhagen interpretation, has no equipment to do this. For the sake of understanding the reality, one might be tempted to accept a realist quantum theory. But why do we think that a mere description of the phenomena in the double-slit experiment is not enough, given that it allows us to make the right predictions? For the realist, the answer is to say more than how we can use a theory to make predictions – we also need to explain why things are the way they are. Bohmian mechanics is a realist theory that aims to accomplish this goal of adequate explanations. And there is a further question about which version of Bohmian mechanics is the best, and this is what this chapter tries to answer. Through these experiments, we can infer from them something interesting about physical reality. Due to this motivation, we might want to look for the best explanation of the empirical results in a double-slit experiment. We want to be able to tell a story about the dynamics of the particles passing through the slits and how they end up forming an interference pattern on the wall where they were detected. Some versions of Bohmian mechanics can trace particles' trajectories throughout their motion and coherently account for the wave-particle duality.

In order to see how the Bohmian can claim to provide an explanation for the double-slit experiment, we need to see what role the wave function plays in this experiment. A story told by a Bohmian, J.S.

Bell, is the following:

> "Is it not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave? De Broglie showed in detail how the motion of a particle, passing through just one of two holes in the screen, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored" (Bell [1989] 1987c: 191).

The waves propagate through the slits, and the particles that pass through the slits are attracted to where the waves cooperate. This implies that the particles and the waves both occupy some spacetime region in the physical space, even if the wave function is defined in the 3N configuration space. The mathematical representation of the wave function is defined in a 3N mathematical configuration space is compatible with saying that the entity it represents it is in a physical space (as I will show later in this section when I introduce the multi-field account). Physical interaction between the waves and the particles is possible because they are both physical entities in the same space. Also, according to Bricmont, in the double-slit experiment "each particle goes through one slit, but the wave function evolves differently when both slits are open than when only one of them is, and this, in turn, affects the motion of the particles via the guiding equation" (Bricmont, 2016, p. 135). And "the behavior of the particle is affected by the fact that the slit through which it does not go is open or not" (Bricmont, 2016, p. 135). If the wave function evolves differently when either or both slits are open, the change in slits has affected the wave function and hence the particles. If the wave function is not a physical object, then it need not be affected by the opening of slits at all. A slit is just a slit that is situated where it is, a particle either passes through it or doesn't (and one particle can only pass through one slit at one time), but the wave associated with the slit or slits can affect the motion of the particle. If the wave function is nomological, then there is a problem of interaction between it and the slits, which is similar to the interaction problem between it and the particles, because both slits and the particles are physical entities in the 3-D world. But if the wave function is a physical entity, then this explains why the slits can affect how the wave function behaves. The role the wave function plays in the physical world nonetheless rules out the option of the wave as a law, because a law does not occupy a spacetime region in physical space. And the fact that the wave that the wave function represents is in the 3-D physical world will also rule out configuration space realism, which takes a configuration space as the fundamental space.

If the wave function is some real entity in the 3-D physical space, then what would it be? Earlier, we have shown that it is problematic to think of the wave function as a field in the configuration space because this will leave the problem of perception and the problem of communication unsolved. But it is possible to conceive of the wave function as a physical entity in the 3-D space. One suggestion is that it is a multi-field. Hubert and Romano (2018) defend the multi-field realism account, which takes the wave function to represent a field in the three-dimensional physical space even if the wave function is defined in the configuration space. For Hubert and Romano (2018), there is only one field in the three-dimensional space, the multi-field, and this field is not the same kind of field as a classical field. For example, the multi-field is not produced by particles, unlike electromagnetic fields that are produced by charged particles.[56] The key features of a multi-field are: (1) it ensures energy and

[56] The multi-field view "is an interpretation of the wave-function as a new type of field in three-dimensional space. In particular, it does not require us to modify the definition of the wave-function, and so it does not require us to modify the mathematical formalism of the theory" (Hubert & Romano, 2018, p. 12). Someone, such as Belot (2012), might take this difference to be a reason to reject the field represented by the wave function.

momentum conservation; (2) it is an assignment of holistic intrinsic properties to particular N-tuples of points of three-dimensional space (Hubert & Romano, 2018, p. 4). What (2) means is that a multi-field specifies a precise value for the entire N-tuple of points in the 3-D space and determines the motion of all particles. Unlike a classical field which assigns intrinsic properties to a particle at each given point in space, the multi-field assigns intrinsic properties to all particles in space. The multi-field is holistic rather than decomposable, so it provides holistic features of N particles.[57] (2) is what distinguishes the field in the quantum domain from an electromagnetic field. It specifies that "given an N-particle system, a multi-field specifies a precise value for the entire N-tuple of points in three-dimensional space, thus determining, given the actual positions of N particles, the motion of all particles. Although the multi-field is *a* physical field in three-dimensional space, its mathematical representation is given by the usual wave-function in the configuration space" (Hubert & Romano, 2018, p. 6). To justify that the wave function is a field in the physical space rather than the configuration space, Hubert and Romano points out that "there is a difference between the mathematical structure that we use to define a physical object and the ontology of this object" (Hubert & Romano, 2018, p. 13).[58] The distinction between a representation and the ontology it represents is standard (see section 1.3 of Chapter 5 for more discussion). "The configuration space is the mathematical space that we

[57] A comparable way to understand (2) is to think of an entangled state of two spin-1/2 particles, such as electrons. In the entangled state, there is, for example, a property of spin-0 of the state which cannot be decomposed into the intrinsic properties of the two electrons.

[58] Hubert and Romano uses an example from classical mechanics can demonstrate this distinction. "Historically, the first formulation of classical mechanics was due to Newton. Newton's theory of mechanics was an ontological theory, that is, a theory with clear ontological commitments: particles moving in three-dimensional space accelerated by force acting on them. The same theory can be cast in the Hamiltonian formulation. Here, the system is represented by a particle moving in phase space with a trajectory described by the Hamiltonian function. Nevertheless, it is understood that the Hamiltonian formulation is just a mathematical representation of the ontological picture of classical mechanics given by Newton's theory. What we usually do in practice is to use both formulations simultaneously: the physical ontology of Newton's theory (that's what the world is built of) and the mathematics of the Hamiltonian formulation (which is often more convenient in doing calculations)" (Hubert & Romano, 2017, p. 13). Hubert and Romano seem to suggest a practical way of separating the representation of an object and ontology of an object. A worry of this is that the two formulations are underdetermined because they are both consistent with whatever empirical data classical mechanics concerns.

need to describe a function which generally depends on 3N degrees of freedom (where N is the number of particles of the system); three-dimensional space is the physical space in which the object represented by that function is defined" (Hubert & Romano, 2018, p. 13). One way to understand the wave function as a real entity in the 3-D space, even if it is defined in a configuration space, is in terms of different levels of abstraction. The theoretical formalism of a theory can be at various levels of abstraction of the theory even though different formulations of a theory might be mathematically equivalent. At a lower level of theory description, which is the level of specific formulations of theory, these different formulations might give different ontological commitments. So the wave function ontology of Bohmian mechanics and the primitive ontology of Bohmian mechanics, which are two formulations of BM, can both take the wave function to be defined in a configuration space, but whether the object which the function represents exist in the 3-D space is a different question.

We have noted that the mathematical representation of a theory and a description of its ontology can be at different levels of abstraction. One example of this can be found in classical mechanics, in which the mathematical formalisms of the Newtonian formulation and the Lagrangian formulation are equivalent because they are inter-translatable, but each of the two formulations bear different ontological commitments, where the Newtonian may commit to a force, and the Lagrangian denies such commitment because the force term does not arise in the mathematical formalism of the Lagrangian formulation. In comparison to Norsen's (2010) local-fields account, "the multi-field is specified not for one point but only for N-tuples of points in three-dimensional space. The multi-field thus explains what the quantum state is, and it instantiates a non-local beable" [i.e. no precise localization at each spatial point at any time] (Hubert & Romano, 2018, p. 12-13). In short, "the multi-field interpretation bears the advantages of Norsen's ontology (that is, having the wave-function physically as a field on three-dimensional space) and the simplicity of the standard formalism (that is, the wave-function as a mathematical object in configuration space)" (Hubert & Romano, 2018, p. 14).

On the multi-field account, there is a multi-field in the physical space, and this allows a real physical interaction between the field, which is determined by the wave function in a configuration space, and particles. Both the multi-field and the particles are in 3-D physical space, so no problem of communication arises. This view gives a natural explanation of the interference pattern and how the wave function influences the particles. "Having the wave-function as a multi-field, however, gives this intuition an ontological underpinning. The de Broglie–Bohm theory is hence a pilot-multi-wave theory, where the wave directly guides particles in three-dimensional space" (Hubert & Romano, 2018, p. 11). According to Hubert and Romano, "while the particle goes through one of the slits, the wave literally enters both slits, thereby determining the motion of the particle and accounting for the characteristic interference pattern on the screen" (Hubert & Romano, 2018, p. 11). It seems that to affect the particles in the 3-D space in a physical way, it is unavoidable that we have to posit something extra, such as a multi-field, into the Bohmian ontology. Although Norsen's local-fields interpretation can also explain the interaction between conditional wave functions and the particles, by assigning a field to each particle, this account is dispensed with because it does not reproduce all the results like its rivals.[59] This empirical inadequacy seems to be a good reason to abandon Norsen's local-fields view.

As mentioned earlier, Belousek argues that the primitive ontology account cannot adequately

[59] Bohmian mechanics reproduces the same empirical results in the quantum domain as standard quantum mechanics and hence is taken to be a genuine rival of the standard interpretation, so if there is a version of Bohmian mechanics that does not satisfy this condition, it is a rather unattractive position to take.

explain the interference phenomena because of its interpretation of the wave function as nomological. This is to say, particles by themselves are not sufficient for explaining quantum phenomena. According to Belousek, "assigning an ensemble of particles all with a certain initial quantum state and initial positions distributed according to the amplitude-squared of that state will yield via the guidance equation a set of trajectories that correctly reproduces (as guaranteed by the continuity equation) the expected quantum interference pattern appearing at the screen or photographic plate. To do so, though, is *not* yet to *explain* the interference pattern, but rather to *redescribe* this state of affairs in terms of mathematically precise space-time trajectories. For the question arises regarding *how* it is that those trajectories should produce a pattern at the screen *in that way*; or, in other words, *how* it is that particles having those initial positions and initial quantum state should follow trajectories that produce *just this pattern* at the screen rather than a different one. The 'how' here has *physical*, *not* merely *mathematical*, significance" (Belousek, 2003, p. 137). The nomological interpretation of the wave function and the primitive ontology of Bohmian mechanics can hardly explain how the wave function and the particles interact to produce diffraction and interference patterns.

2.1 Explanatory virtues

One might argue that it is *ad hoc* to infer that the wave function is a physical entity in the 3-D space, such as a multi-field, from the double-slit experiment. And we don't have independent empirical reasons to believe in the existence of this entity in addition to the particles. To reply to this, it is important to recognize the power of the Inference to the Best Explanation and explanatory considerations. "According to Inference to the Best Explanation, our inferential practices are governed by explanatory considerations. Given our data and background beliefs, we infer what would, if true, provide the best of the competing explanations we can generate of those data (so long as the best is good enough for us to make any inference at all) .... the core idea of Inference to the Best Explanation is that explanatory considerations are a guide to inference" (Lipton, 2003, p. 56). This method of inference is quite common in physics. For example, although scientists have not yet detected dark matter and it seems that its existence cannot yet be independently verified, we nonetheless believe in its existence because, without it, we cannot account for the orbital velocities in a galaxy. So, scientists believe that there is dark matter which we cannot or may not observe but when added to our theories is the best explanation of galactic motions. An alternative theory, Modified Newtonian dynamics (MOND) is inferior compared to the dark matter explanation because the former, for instance, does not adequately account for observations of galaxy clusters. In the present context, the inference of the existence of the wave function as a physical entity in 3-D space, if true, will best explain the phenomena in the double-slit experiment. There therefore are good reasons to be a realist about the wave function. We cannot explain the phenomena without it, even though we cannot independently verify its existence. The double-slit experiment forces us to accept that there is an object that exists in the physical world and that literally influences the particles passing through the slits.

But one may wonder why we should care about explanations if standard quantum mechanics can give a description of the phenomena in the double-slit experiment and makes correct predictions. Lipton has an answer to this. "One of the points of our obsessive search for explanations is that this is a peculiarly effective way of discovering the structure of the world. The explicit point of explaining is to understand why something is the case but, if Inference to the Best Explanation is correct, it is also an important tool for discovering what is the case” (Lipton, 2004, p. 67). In particular, Inference to the Best Explanation provides an effective tool to discover what the world is like, and this is compatible with the aim of scientific realism to understand the unobservables of the world. Although there are general problems of the Inference to the Best Explanation, this method has been used by scientific realists in a more general way. For instance, the No Miracles Argument is one which relies on Inference to the Best Explanation to show that the reason our scientific theories are predictively successful is that they are true or approximately true. Truth is the best explanation of their success. But as Lipton points out, “since Inference to the Best Explanation is a warranted form of inference, we have reason to infer that the theory is true. This is an inductive argument, so it does not prove that successful theories are true, but it does, according to its proponents, provide a good reason for believing that they are true, and so that the form of inference that leads to them, namely Inference to the Best Explanation, is a reliable guide to the truth” (Lipton, 2004, p. 185). In our present context, which is also an application of the Inference to the Best Explanation, the postulation of the wave function as a real entity is the best explanation that the particles and the wave function interact to produce the patterns we observed in the double-slit experiment. In contrast to primitive ontologists who suggest taking the wave function as nomological, if Bohmian mechanics is explanatorily adequate, it seems to require us to take the wave function as a real entity. In addition, unlike Belousek’s account, which takes the quantum force as part of the ontology but not the wave function has a problem of making sense of what is the source of the quantum force, the wave function ontology avoids such a problem.

3. The box experiment

To explain the interference effect in the double-slit experiment requires that a real physical entity acts on the particles. Still, this experiment alone tells us very little about what the wave function is. The wave function being a physical entity in the 3-D space is compatible with many descriptions of the wave function, such as a multi-field, a wave or a wave field, etc. One might wonder, what are the shared properties or shared characteristics of the wave function these different ways of identifying the wave function have? Or is there a way to unify these ways of understanding the wave function? Bohmian mechanics can provide some theoretical descriptions of the wave function, such that Schrodinger's equation determines it, and it determines the motion of particles. But these descriptions do not seem to offer a complete story of how it and the particles interact to produce certain effects. In fact, we need to descend to the level of causal properties and causal processes the wave function is involved in, thus acquiring more substantial descriptions of the wave function beyond the fact that it is a physical entity. The box experiment, which I introduced in section 2 of Chapter 2, is a modified version of the double-slit experiment that provides some insights about the wave function at an experimental and causal level. In particular, the box experiment is evidence for a particular form of Bohmian mechanics, where the wave function is a real physical entity that *possesses energy*. In fact, this feature of the wave function unifies different wave function realist positions, such as defenders of the multi-field or a wave field (as I will discuss in section 5).

The experimental result of the box experiment (refer to Figure 1 in Chapter 2) shows that there is a difference in energy level when the second light source S2 is on and off while S1 is on. And the experiment is designed in a way that no photons from the second light source pass through the second slit, namely F2, so the change in energy level cannot be contributed by photons from the second light source (checked by B and C). The experimenters, Cardone et al., conclude that the non-zero energy gap when the second light source is on and off is a clear signature of an anomalous interference effect. This means that a nonzero ΔA, can be interpreted as an anomalous interference involving the pilot waves associated with photons. According to Petrucci, one of the experimenters of the box experiment, "the box (double-slit) experiments not only provide direct evidence for the Einstein-de Broglie-Bohm waves by their effect on photon propagation, but also yield a measurement of the energy associated to them and indicate the space-time deformation as the physical entity hidden behind their synopsis" (Petrucci, 2019). There are two major points in Petrucci's conclusion. One is that the box experiment provides evidence for the existence of the pilot wave supposed in Bohmian mechanics because of the observed anomalous interference pattern, or a nonzero ΔA. The second point is that the pilot wave is a physical entity which carries energy (and also momentum), and this is reflected in that amount of energy change at A. This amount of energy is required to affect photons from S1, and this fact provides some ideas on how to understand the nature of the pilot wave and how it guides particles. I will now elaborate on the first point and leave the second point for section 4.

According to Petrucci, "a way to detect such quantum waves might be through their affecting the probabilities of events to which they superimpose in space–time (for instance, in interference phenomena)" (Petrucci, 2019, p. 1). This suggests that the experimenters infer the existence of the pilot wave through the observations of anomalous interference effects. The existence of the pilot wave is an unobservable that can explain the experimental results. Although Cardone et al. cannot directly observe the pilot wave, they think the existence of the pilot wave is the best explanation for the anomalous interference effect, because "the interactions of quantum objects with all the pilot waves present in a given space region, through their quantum potential" can affect the trajectories of the photons from S1 (Petrucci, 2019, p. 1). It is clear that they rely on the use of IBE to arrive at their conclusion. In the box experiment, the Bohmian explanation of the anomalous effect is that the pilot wave exists, and it interacts with particles (and its associated wave) from S1. In short, the experimenters, Cardone et al., argue that the change in energy level when the second light source is on and off "finds a natural explanation, in the Einstein-de Broglie-Bohm interpretation of quantum wave", in terms of the interaction of the first light source/photons (and their waves) with the pilot wave passed through the second slit (Cardone et al., 2006, p. 1115). The reasoning here is similar to that in the double-slit experiment. By taking explanatory considerations into account, one infers that the pilot wave exists. The energy difference observed at the detector A provides a reason to think that even if some alternative accounts of Bohmian mechanics, such as primitive ontology, make the same empirical predictions, they are explanatorily inadequate. The reason is that particle trajectories cannot by themselves explain why there is a difference in energy level in both lighting settings, although the wave function plays a nomological law in 'guiding' the particles. Our reason to infer the existence of the pilot wave is based on explanatory considerations.

4. The pilot wave and its possession of energy

Bohmians have different interpretations of the wave function. As mentioned above, some view it as a nomological entity, such as Goldstein and Zanghì (2013). And some others, such as Esfeld (2014) and Suarez (2015), take it as a dispositional property. Some, such as De Broglie and Bohm, take it to be a hollow wave that does not carry either energy or momentum (Petrucci, 2019, p. 1). Hubert and

Romano argue that the wave-function is best regarded as an objective physical field rather than a nomological entity because the wave function is in general time-dependent (Hubert & Romano, 2018, p. 11). One may wonder if the box experiment provides a more substantial description of the pilot wave. Or, do any of these proposed possible ontological interpretations of the wave function fit the descriptions of the wave function according to the box experiment? In particular, what causal descriptions or non-theoretical descriptions about the wave function can we learn from the box experiment? To answer this question requires us to say what properties the wave function possesses and how it affects the trajectories of the photons. Basically, we need to interpret the empirical data of the energy change detected at A.

The box experiment is more peculiar than it initially seems because it supports the wave function ontology of Bohmian mechanics. This experiment picks out a certain version of Bohmian mechanics, namely the one that takes the wave as a deformed spacetime that possesses energy. The question is how to link the idea of deformations of spacetime with the pilot wave. Cardone et al. designed the experiment according to the energy and space threshold of the breakdown of Local Lorentz Invariance (LLI). "LLI is broken when the energy exchanged during the process is less than 4.5 PeV, and the maximum distance, over which its non-Lorentzian effects can be still detected, is about 9 cm" (Petrucci, 2019, p. 2). And they found that the value of the energy gap they measured (~2. 3 μV) is less than the threshold energy value (~4. 5 μV) for the electromagnetic breakdown of Local Lorentz Invariance (Cardone et al., 2004, p. 9). The phenomenon obeyed the threshold behaviour of the LLI breakdown predicted by the analysis of the Cologne experiments (superluminal sub-cutoff propagation in the waveguide), the Florence experiment (superluminal propagation in air), and the other experiments of

Cardone and Mignani.[60] They "corroborate the hypothesis that LLI violation means indeed the existence of a locally deformed spacetime whose deformation stores some energy and is able to affect (pilot) the propagation of photons" (Petrucci, 2019, p. 2). The parallel descriptions of the anomalous interference effects in terms of deformed spacetime and the pilot wave led the experimenters to conclude that the quantum wave (in the interpretation by de Broglie and Bohm, as a pilot wave) and the breakdown of local Lorentz invariance, described by the formalism of Deformed Special Relativity (i.e., in terms of a modified Minkowski metric) are one and the same thing (Petrucci, 2019, p. 9).

As we can see, the box experiment provides an alternative way to understand the ontological status of the wave function, which differs from the accounts that have been proposed before. It suggests that the wave is a deformed spacetime that possesses energy. This feature of the pilot wave explains why the wave can guide particles throughout motion in a physical way. "In particular, with regards to the photon we can say that most of its energy is concentrated in a tiny extent (complying with electrodynamics, relativity and Minkowski space-time) and the rest of the energy is used to deform space-time surrounding it (violating electrodynamics, not complying with relativity and hence possessing real non-local and superluminal features). This second part of the energy is stored in the local deformation of space-time just as the Riemann curvature of space-time in General Relativity possesses its own energy momentum pseudo-tensor" (Mignani et al. 2012, p. 7). The experimenters interpret a nonzero ΔA as the energy absorbed by the space-time deformation itself. Energy is a conserved quantity. Understanding the wave as a physical entity that possesses energy raises the questions of whether a Bohmian who takes the wave as deformed spacetime can tell a story about how

[60] See Nimtz et al. (1994); Heitmann and Nimtz (1994); Ranfagni et al. (1993); Cardone and Mignani (2004).

Bohmian mechanics obeys the law of energy conservation. I will postpone this discussion to section 5.

So far, the pilot wave is identified as a deformed spacetime which carries energy, but we need a more in-depth grasp of it. The idea that the pilot wave possesses conserved quantities (and so do particles) such as energy is not an empirical result of the box experiment but finds its support in some other versions of Bohmian theory, such as Hubert and Romano's multi-field interpretation of the wave function. According to them, "the multi-field view starts from the idea to generalize a classical field, which specifies a definite field value for each location of three-dimensional space. A charged particle that is posited at a given location will feel the force generated by the value of the field at this location. The multi-field generalizes this concept to N-tuples. Given an N- particle system, a multi-field specifies a precise value for the entire N-tuple of points in three-dimensional space, thus determining, given the actual positions of N particles, the motion of all particles" (2018, p. 2). Here, Hubert and Romano arrive at their multi-field account from a different methodology as Cardone et al.'s experimental method, but by conceptual generalization from classical fields. According to Hubert and Romano, "energy conservation is an important factor to reify a mathematical function into a physical field, …, the multi-field permits to restore energy-momentum conservation in the de Broglie-Bohm theory" (2018, p. 4). They argue that interpreting the wave-function as a multi-field "permits to account for energy conservation in a natural way" because the classical potential and the quantum potential which comes from the wave function together contribute to energy conservation (and momentum conservation) (2018, p. 5).

One might wonder whether we have two incompatible descriptions of the wave function. On the one hand, we take the wave function as a multi-field, while on the other hand, as a deformed spacetime. Have we got an underdetermination of the wave function? Or are the deformed spacetime and the multi-field the same thing? According to Petrucci, the deformation "expands through aperture F2 and reaches the photons emitted by S1 and steers (pilots) their propagation before they are detected by A" (2019, p. 7). He compares this process with the curved spacetime around the Sun that curves the trajectory of the photons from a distant star (Petrucci, 2019, p. 7). In Hubert and Romano's characterization of the multi-field, the multi-field *directly* guides particles in three-dimensional space (2018, p. 5). And these particles evolve in time according to the guidance of the multi-field. Both descriptions of the pilot wave describe an interaction between the wave and the particles in the three-dimensional physical space, so when a Bohmian talks about particles being guided by the pilot wave, she doesn't speak metaphorically. In fact, Hubert and Romano point out that the multi-field is different from a classical field, such that the multi-field is not generated by the particles. This implies that multi-field should not be understood as what we normally take a field to be. And they both avoid the problems of perception. The deformed spacetime avoids the problem because it is not in a higher-dimensional space but in this 3-D space that persists through time so it can affect the particles that also exist in 3-D space. It is possible that the multi-field and the deformed spacetime might be *the same thing*. But what is the ground to regard the deformed spacetime and the multi-field as the same thing? The fact that both ways of referring to the wave function solve the problem of perception does not indicate that they are the same thing. Instead, we need a more robust connection between the deformed spacetime and the multi-field. Both the multi-field account and the box experiment take the wave function to be a physical object in the 3-D space and to possess energy. This is to say the energy unifies both interpretations of the wave function, even if it is not part of the Bohmian ontology. Without appealing to the concept of energy (and energy exchanges are discussed in section 5), a deformed spacetime and a field interpretation of the wave function will be distinct interpretations of the wave function. If a deformed spacetime is just the multi-field, one can think that a deformed spacetime represents a field, such that the field affects photons (or particles in general) just as a deformed spacetime affects photons (or particles). Representing a deformed spacetime as a field is not uncommon in physics. Another similar association of a physical field with deformed spacetime is found in general relativity. A gravitational field can be understood as a curvature of spacetime according to general relativity. A gravitational field in the theory of general relativity represents the curvature of spacetime caused by massive objects. This characterization of a gravitational field in terms of the curvature of spacetime can be used to understand the ontological status of the wave function in the present context. The pilot wave as a field can thus be understood as a deformed spacetime. The parallelism in the box experiment and Hubert and Romano's approach shows that wave function realism of Bohmian mechanics can avoid the problems of perception and the problem of communication, and is essential for explanations of quantum phenomena.

If a deformed spacetime is a multi-field, then the underdetermination mentioned at the beginning of the last paragraph is merely apparent. And the fact the wave function is a deformed spacetime is the best explanation for why we observe quantum phenomena, such as an anomalous effect in the box experiment. In particular, a deformed spacetime influences the trajectories of particles from S1, even if there are no particles from S2 traveling through slit F2. Alternatively, if one, such as a primitive ontologist, takes the wave function to be nomological, which describes the trajectories of the particles, then particle trajectories themselves are left unexplained. However, if one takes the wave function as a physical entity in the 3-D space, the explanation for particle trajectories is that they are pushed around by a physical entity, namely a deformed spacetime. The nomological interpretation of the wave function thus does not give an adequate explanation for the experimental result and hence is not the best explanation (In Chapter 4, I will address this problem of primitive ontology in the framework of Best System).

5. A causal account of Bohmian mechanics: The conserved quantity theory

In the literature of different versions or formulations of Bohmian mechanics, someone such as Belousek (2003) separates them into the guidance view and the causal view as briefly mentioned in section 1. It is important to note that the notion of causation here is used in the same way as Bohm's uses when he takes Bohmian mechanics to be a causal view in which the pilot wave guides the particles in a causal sense. Causation is taken in a realist sense of causation here. In this sense, a causal account of Bohmian mechanics is one that commits to the existence of the pilot wave and/or the quantum potential and its causal interaction with the particles (Most realists about the pilot wave also commit to the existence of the quantum potential, but Belousek (2003) is an exception because he denies the existence of the pilot wave but commits to a quantum force). This realist notion of causation in this chapter is to be distinguished from an epistemic notion of causation, which I address in Chapter 4. The guidance view is associated with accounts such as primitive ontology, which takes only particles to constitute the Bohmian ontology and only the first-order guiding equation as the fundamental equation.

If we take the primitive ontology account as a case of the guidance view, the wave function for a primitive ontology is often understood as nomological. This is a non-causal view because there are no other physical entities that causally push the particles around in the universe. Instead they follow certain trajectories according to a law, which is the wave function. There are two rival ways of understanding laws of nature. One is to take a law to play a governing role, such that "laws of nature do logically constrain objects to behave in accordance with them" (Beebee, 2000, p. 581). If a primitive ontologist takes the wave function to be nomological in this governing sense, then it seems that the law has to be regarded as realist in some sense. In fact, if the primitive ontologist wants to avoid a causal understanding of relation between the wave function and the particles and a realist interpretation of the wave function, this governing notion of law is not suitable for her to use. Fortunately, Beebee (2000) argues that it is optional that laws of nature have to be understood in the conception of *governing*. Alternatively, one can take a *descriptive* account of laws of nature, such as Humean conceptual of laws at which laws supervene on the distribution of particular matter of facts, in particular spacetime points of particles in the Bohmian universe. According to Esfeld (2014), "the Humean has to regard the law as supervening on the distribution of matter throughout the whole of space–time, that is, the entire mosaic of 'local beables' or local matters of particular fact" (p. 456). In fact, the more widely accepted conception among primitive ontologists is to understand the law in this Humean sense, which is to take the law as supervening on the motion of particles and understand it as a summary of the motion of particles that achieves the best and optimal state (Esfeld, 2014; Miller 2014). This is also called the best system framework. According to Beebee, Lewis's definition of law in a best system is that "a contingent generalization is a law of nature if and only if it appears as a theorem (or axiom) in each of the true deductive systems that achieves a best combination of simplicity and strength" (Beebee, 2000, p. 574). One way the primitive ontologist can make sense of how the wave function 'guides' the particles is by taking the wave function as part of the Best System. "The best system description of the physical world speaks in terms of it [aka. the wave function], and this description speaks in terms of it because it is part of an efficient and effective summary of what is fundamental: the positions of particles in space over time" (Miller, 2014, p. 580). So, on the primitive ontology account which is a form of the guidance view, the wave function plays a nomological and in fact a descriptive role to summarize the motion of particles, but no literal guidance as the causal view of Bohmian mechanics requires.

On the other hand, the causal view is associated with the second-order Hamilton-Jacobi equation, which is regarded as the fundamental equation and posits entities not reducible to motions of particles, namely the wave function and/or the quantum potential (the quantum force is derived by taking the gradient of the potential). Our understanding of the wave function as a physical entity that literally guides particles throughout their motions falls into the camp of the causal view. Hence, it is natural for us to formulate a causal account of Bohmian mechanics, and this is possible precisely because the wave function carries energy. The possession of energy of the wave makes a natural case for the conserved quantity theory of causation because energy is a conserved quantity. Before looking at the details of the conservation of energy in Bohmian mechanics, let's get clear on what the conserved quantity theory of causation is. The conserved quantity theory is a causal process theory of causation, which both Phil Dowe and Wesley Salmon defend.[61] Their versions of the theory do not differ greatly,

[61] Dowe notes that "the idea of appealing to conserved quantities has its forerunners in Aronson's and Fair's appeal to energy and momentum. (Aronson, 1971; Fair, 1979) But the first explicit formulation was given in a brief suggestion made by Skyrms in 1980, in

and the differences will not affect our application of the theory to Bohmian mechanics.[62] I will keep the explication of the conserved quantity theory brief here. I use Dowe's version (1992, p. 210) here, which is a more concise version:

> A *causal interaction* is an intersection of world lines which involves exchange of a conserved quantity.
> A *causal process* is a world line of an object which possesses a conserved quantity.

No explicit discussion of how energy is transferred between the wave and the particles is covered in Hubert and Romano (2018) nor Cardone et al. (2006). Instead, Riggs (2008) provides some insight into the process of energy transfer. Riggs also takes the wave function to be a wave field, which evolves in time according to the Schrodinger equation. A wave field is not physically separate from particles (they are associated with the particles although not produced by them) but can have limited, individual descriptions, such that they stand in certain relations, such as exchanging energy.[63] According to Riggs, the quantum field "is a physical process that propagates in three-dimensional Galilean space over time" and "a quantum particle is a point-like object localised in three-dimensional Galilean space with an inertial mass and a well-defined position at all times" (Riggs, 2008, p. 23). The motion of the quantum particle is causally governed by the wave field.[64] The quantum potential plays a role of facilitating the transference of energy from the wave field to particle and back again which accounts for energy

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his book *Causal Necessity* (1980, p. 111) and the first detailed conserved quantity theory by Dowe (1992). See also Salmon, 1994, 1998 and Dowe, 1995, 2000" (Dowe, 2008).

62 According to Dowe, "a process is the world line of an object, regardless of whether or not it possesses any conserved quantities. A process can be either causal or non-causal (pseudo). A world line is the collection of points on a space-time (Minkowski) diagram, which represents the history of an object. This means that processes are determinate regions, or 'worms', in space time. Such processes, or worms in space time, will normally be time-like; that is, every point on its world line lies in the future lightcone of the process' starting point. An object is anything found in the ontology of science (such as particles, waves or fields), or common sense (such as chairs, buildings, or people). This will include non-causal objects such as spots and shadows. It is important to appreciate the difference between an object and a process. Loosely speaking, a process is the development over time of an object. Processes are usually extended in time" (Dowe, 2008).

63 According to Riggs (2008), The quantum field is commonly called the 'wave field' for historical reasons.

64 On the causal view, the wave field is not a law but a physical entity in the 3-D space. Here, 'governing' happens when the field literally pushes around and guides the particles in the Bohmian universe. In addition, one might hold that a governing conception of laws and the conserved quantum theory of causation are also compatible.

conservation in isolated quantum systems (Riggs, 2008, p. 21).[65] The story about energy exchange between the wave field and the particle is as such: "The particle's kinetic energy will then increase (decrease) with decreases (increases) in the amount of energy stored in the wave field. Any change in the particle's kinetic energy is explained by an energy conversion process, ... The quantum potential is the physical interface between particle and wave field and its role is to channel energy from wave field to particle and back again" (Riggs, 2008, p. 33). The transference stories told in both the classical (e.g., Newtonian gravitation does not give a mechanism for energy transfers between a massive particle and a gravitational field) and the quantum contexts lack a specific description of how the energy transfer process is carried out (Riggs, 2008, p. 31). Although there is an energy exchange between the wave field and the particle, it is not transparent to us how such exchange actually happens. We do not know the underlying physical process, except that it is a causal interaction, as I will show next using the conserved quantity theory of causation.

Using Dowe's terminology, a causal process of the wave as a deformed spacetime (which is represented by a field as shown earlier) is the world line of the wave field which possesses energy. A casual process of a particle is the world line of the particle which possesses energy, such as kinetic energy. According to Riggs, energy exchange happens between the wave field and the particle (for instance, in a one-particle system), so a causal interaction is an interaction of the wave field world line

[65] There is a more familiar example of energy exchange in electromagnetism. "Consider an electrically charged particle placed in an external electric field. Such an external field may be produced by applying an electrical potential difference to two (usually parallel) metal plates. If the charged particle is released at rest between the plates before they become charged, the particle remains at rest. However, if the particle is released at rest between the plates when they are charged, the particle will immediately accelerate. The electric field between the charged plates imparts energy to the particle as it had no kinetic energy initially. This energy is gained at the expense of some (but not all) of the potential energy stored in the field between the charged plates, i.e., by a small fraction of the potential energy contained within the external electric field" (Riggs, 2008, p. 28). This provides an analogous case to Bohmian mechanics because the electric field is not produced by particles, just like the wave field, and shows that the potential energy is stored in the field. Similarly, the quantum potential does not represent the total energy but "represents an amount of energy in the wave field that is available to the particle at its specific position in the field" (Riggs, 2008, p. 31).

and particle world line involving an exchange of energy. On this conserved quantity theory, we can make causal claims about the entities which partake in the causal processes and causal interactions.

The upshot is that the conserved quantity theory account of Bohmian mechanics requires that the wave function possesses energy. The existence of the wave is inferred through the IBE in the box experiment, and it is stipulated by generalizing from classical fields in Hubert and Romano's account. An attractive Bohmian account requires a way to make sense of the interaction between the wave and the particles, and this further implies that the wave has to be a physical entity in the 3-D space. So this means that even if one might worry that the box experiment cannot be reproduced or its empirical results will be possibly refuted, we have got a theoretical reason from explanatory considerations to believe in the existence of the pilot wave, and Hubert and Romano have presented a theoretical formulation of it.

Conclusion

The debate between wave function ontology and primitive ontology is central to realism about Bohmian mechanics. I argued that although some forms of wave function ontology fail, there are no conceptual difficulties to interpreting the wave function as a real physical entity in the 3-D space. I argued that the wave function has to be taken as a real entity for Bohmian mechanics to be explanatorily adequate, both in the double-slit experiment and the box experiment. But to supply the wave function with more substantive descriptions, we not only need theoretical descriptions of it from the Bohmian theory but also descriptions of it from the causal level. In particular, the box experiment provides descriptions of the wave function as a deformed spacetime that possesses energy. The box experiment supports a wave function ontology because this experiment sheds light on the nature of the wave function by connecting it to the violation of LLI. The experimenters use the epistemic tool of IBE to infer the existence of the wave function that is described in the Bohmian model. By setting up the experiment in a way that it conforms to the result of the threshold behavior of the breakdown of LLI, they argue that the pilot wave is a deformed spacetime which possesses energy. I connect their conclusion with a more natural interpretation of the wave as a field. In particular, Hubert and Romano's multi-field account fits nicely with Cardone et al.'s interpretation of the pilot wave. The fact that the pilot wave carries energy rather than being a hollow wave or a nonphysical entity can accommodate the law of energy conservation, which is a constraint on empirical theories. And the version of Bohmian mechanics that the box experiment supports is one in which makes a nice case for a conserved quantity theory of causation. The box experiment shows that Bohmian mechanics is defensible in both empirical and theoretical grounds.

CHAPTER 4

Bohmian Mechanics: Realism and the "Box" Experiment

1. Introduction

Bohmian mechanics, which is claimed to be a defensible realist quantum theory, seems to be an instance of selective realism. That is to say, the Bohmian does not want to commit to every theoretical claim the theory makes or can make. For instance, the causal version of Bohmian mechanics introduces a quantum potential term and makes a claim that there is a force that 'pushes' particles around in the Bohmian world.[66] But Bohmians who accept a non-causal version do not accept this claim.[67] In general, there are different versions of Bohmian mechanics which come with different theoretical commitments even though they all fall under the framework of Bohmian mechanics with the same formalism (i.e. Schrodinger's equation and the guiding equation), and subscribe to some central characteristics of this theory, such as that the dynamics of Bohmian particles is deterministic. So Bohmians face a challenge of making clear what part of this theory they are realist about, under what conditions they can be realist towards it and what assumptions they have to hold.

In this chapter, I shift attention from more familiar experiments, such as Bell-type experiments and double-slit experiments, to the box experiments which I introduced in Chapter 2 (Cardone et al., 2004, 2006). The box experiment has important philosophical implications for scientific realism. Going beyond its predecessor, the usual double-slit experiment, a box experiment manifests wave-particle duality and provides understanding of the ontological status of the wave function. The box experiment

[66] This is Bohm's version of Bohmian mechanics which he proposes in 1952.

[67] Those who do not endorse a causal version are often called minimalists about Bohmian mechanics. Louis de Broglie's version (1927) does not introduce the quantum potential term (hence force); other minimalists are Allori & Zanghi (2004), Suárez (2015).

supports a version of Bohmian mechanics which takes the wave function to be a real physical entity in the 3-dimensional world in addition to particles as shown in Chapter 3. Here, I use the box experiment as a working example to argue that a causal realist account (in the sense of selective realism, such as entity realism) that is applicable to Bohmian mechanics, has to be supplemented with the use of Inference to the Best Explanation (i.e. IBE).[68] The reason is because causal realism on its own does not form a sufficient basis for Bohmian mechanics. Instead, realism about Bohmian mechanics requires the use of IBE.

The main question to be addressed in this chapter is can a causal realist, as a selective realist, use the box experiment to argue for causal realism about Bohmian mechanics? In particular, the experiment supports a version of Bohmian mechanics which takes the wave function as its ontology in addition to particles, in contrast to other versions of Bohmian mechanics, such as the primitive ontology that Dürr, Goldstein and Zanghi defend. Section 2 gives a brief recap of the box experiment. Sections 3-4 address the main question and the answer is 'no'. Causal realism comes in many forms, and for those applicable to Bohmian mechanics, because each of them (such as entity realism or Egg's causal realism) does not form a sufficient basis for Bohmian mechanics, they have to be supplemented with the use of IBE or considered as a form of IBE. This means that a complete realist account about Bohmian mechanics rests on explanatory considerations. Finally, in section 5, I discuss the implications the box experiment has on some versions of Bohmian mechanics which deny the wave function as part of the Bohmian ontology and show that the box experiment provides empirical evidence for why the pilot wave has to

[68] We should keep the causal version of Bohmian mechanics separate from a causal realist account of Bohmian mechanics. Scientific realism is often formulated in terms of three dimensions, the metaphysical, the semantic and the epistemic. The causal version of Bohmian mechanics refers to the metaphysical dimension of the Bohmian model, such that it introduces a force term which is derivable from the quantum potential when we rewrite the wave function in a polar form. And this force appears when we describe how the wave and particles interact, such that the wave guides and pushes particles around in the universe. On the other hand, a causal realist account purports to offer an epistemic justification on realism about Bohmian mechanics.

exist in order to explain the anomalous effect in the experiment.

2. The box experiment

Before I proceed to discuss the box experiment's philosophical implications for realism about Bohmian mechanics, I will remind the readers what the box experiment of Cardone et al. (2006) is, which I introduced in section 2 of Chapter 2 and also discussed in Chapter 3. The experimental result of the box experiment shows that there is a difference in energy level when the second light source S2 is on and off. And the experiment is designed in a way that no photons from the second light source pass through the second slit, namely F2, so the change in energy level cannot be contributed by photons from the second light source (checked by B and C). The experimenters, Cardone et al., conclude that the non-zero energy gap when the second light source is on and off is a clear signature of an anomalous interference effect. This means that a nonzero ΔA, can be interpreted as an anomalous interference involving the pilot waves associated with photons. And the value of the energy gap they measured (~2. 3 μV) is less than the threshold energy value (~4. 5 μV) for the electromagnetic breakdown of Local Lorentz Invariance (LLI) (Cardone et al., 2004, p. 9). I will explain later what the LLI breakdown means and its implications in section 4.[69] The phenomenon obeyed the threshold behaviour predicted by the analysis of the Cologne experiments (superluminal sub-cutoff propagation in waveguide) and the Florence experiment (superluminal propagation in air), and the other experiments of Cardone and Mignani.[70]

[69] More specifically, ΔA ranged from (2.2 ± 0.4) μ V to (2.3 ± 0.5) μ V, values well below the threshold energy $E_{0,\,em}$ = 4,5 μ V, and the anomalous effect was observed within a distance of at most 4 cm from the sources. See Mignani et al. (2012, p. 3).

[70] See Nimtz et al. (1994); Heitmann and Nimtz (1994); Ranfagni et al. (1993); Cardone and Mignani (2004).

3. Causal accounts and IBE

3.1 Motivating causal realism

What implications does this experiment have for realism about Bohmian mechanics? There is a range of selective realist accounts, but not all of them are applicable to Bohmian mechanics. Causal realism seems to have a better shot for this than other selective realist positions, because causation is often considered to be a more robust account than its alternatives, such as IBE. Some might criticize IBE because we can only at best choose the "best of a bad lot" (van Fraassen 1989, p. 143). This means there is no guarantee that some explanations in the list of possible explanations are true or approximately true because this inference relies on scientists' ability to come up with possible explanations that are close to the truth. It is possible that we might be provided with a list of possible explanations that are nowhere near the truth. Causal realism in the context of scientific realism (e.g. Cartwright 1983, Chakravartty 1998, Egg 2012, Hacking 1983, Suárez 2008) often refers to those realist accounts that employ the notion of causation, although causation can be understood in many ways (e.g. causal regularity, counterfactual, causal process, etc.) or it can refer to different things, such as a causal explanation (e.g. Cartwright 1983) or a causal relation (e.g. Chakravartty 1998). In this chapter, I take *causal realism* to be a realist position about unobservables, such that it offers an epistemic justification of the realist commitments about these unobservables where causation plays an important part in the inferential process. For instance, Hacking's entity realism (as I will discuss later) about electrons makes uses of the well-understood causal properties of electrons to build devices to investigate other phenomena, and this allows him to infer the existence of electrons. However, we face a challenge when trying to make sense of causal realism in the box experiment which supports

Bohmian mechanics. We want to know whether we can infer unobservable entities, such as particles and the pilot wave that the Bohmian commits to, from a causal realist account.[71] It important to keep in mind that we want to see how these causal realist accounts within the context of the box experiment can help us understand realism about Bohmian mechanics. I start with Hacking's entity realism because it is an experimental account and we are dealing with a particular experiment here. Although entity realism is often characterized as a rival to theory realism (that is, committing to the truth of a theory), it might seem like entity realism is a wrong approach because we are looking at the Bohmian *theory*. But we can still use entity realism to test whether we can arrive at the existence of the unobservables that Bohmians believe in, such as the pilot wave. I argue that within the context of the box experiment we can see where and how entity realism fails. Before I get to these causal realist accounts, I will first present what I think the right account of IBE is, which will become important as the argument progresses. Then, I address two selective realist positions, structuralism and semirealism and show their failure to apply to Bohmian mechanics.

3.2 What is IBE?

IBE is an inference that can be understood in many different ways just like the notion of causation. Although I mentioned IBE in Chapter 3, it is important to specify what IBE is, what it can do for us and how it can do it successfully. IBE defenders often think that explanatory considerations are a guide

[71] A notion of causality associated with Bohmian mechanics appears in the discussion of nonlocality. Since nonlocality as action at a distance is an inherent feature of Bohmian theory, one might wonder whether nonlocality is coherent with a causal realist theory. Jean Bricmont (2016) has argued that Bohmian mechanics is nonlocal (p. 111-126; p. 162-169). But it is important that we keep these two aspects of causality separate, as causal realism in this paper is a view that some claims about entities can be satisfied through a causal explanation or inference, while the notion of causality associated with nonlocality is that there can be a causal process between two spatially separated systems. Although there can be a claim about nonlocality that it is causally warranted, one should not confuse these two notions of causality.

to inference (Lipton 2004, p. 6; Psillos 2007, p. 2-3). According to Psillos, this means that "a hypothesis is accepted on the basis of a judgment that it bests explains the available evidence" (2007, p. 442). The best explanation is one that is explanatorily virtuous, for instance it is satisfactory (Musgrave 1988) or good enough (Lipton 1993). The inferential process goes like this: "[scientists] first try to come up with a pool of potential explanations for their empirical findings and then choose the best, or (to speak with Lipton 2004) "loveliest" of them. Inference to the best explanation states that the best explanation is also the most likely to be true or, at any rate, the one that the scientists have the best reasons to believe in" (Wüthrich 2017, p. 462). The key element here is that the best explanation is the one that is most likely to be true. Scientists often rely on IBE to infer the existence of unobservable entities because postulating their existence gives the best explanation for the empirical data. For instance, as was mentioned in Chapter 3, although scientists have not yet detected dark matter and it seems that its existence cannot be established independent of theory, they nonetheless believe in its existence because without it we cannot account for the orbital velocities in galaxies. The dark matter hypothesis, that dark matter exists, is a better explanation for the orbital velocities in galaxies than its alternatives. And it is possible that there can never be any experimental evidence (although there are observational supports) for the existence of dark matter because it does not seem to interact with observable electromagnetic radiation.

A major challenge to IBE is: How do we link the loveliest (provides most understanding) explanation, namely the best explanation (in Lipton's terminology), to the claim that it is likely to be true?[72] IBE does not guarantee that the best explanation is actually true, but only that it is probably true. So there is a chance the best explanation turns out to be false, but this does not undermine the truth claim in IBE, which is that the inferred claim is most likely to be true. IBE takes us to probable truth (likely to be true), and there is no requirement that we actually get to truth. Scientific progress has shown that we can approximate truth, since past theories have been replaced by new theories which are more successful in predicting new phenomena and hence, according to realists, likely to be closer to the truth. For instance, Newtonian mechanics is replaced by a quantum theory which covers the quantum domain predictions the Newtonian theory fails to account for. The pessimistic induction can be easily accounted for because some Bohmians, such as Allori (2018), argue that there is a continuity of ontology, namely particles, in these two theories. Both Lipton (2004) and Psillos (2007) think that background knowledge plays an important role in the generation of potential explanations and selection of the best explanation. So our rich background knowledge can help ensure that we are not too far off from truth, unlike van Fraassen's criticism of choosing 'the best of a bad lot.'

3.3 Some general selective realist accounts that do not apply to Bohmian mechanics

There are some common scientific selective realist positions such as: Psillos' *Divide et Impe* move (making a distinction between idle constituents and essential constituents of a theory), structural realism, entity realism, causal realism, and Chakravartty's semirealism. Some of these selective realist accounts are developed as responses to or in light of the pessimistic induction (which I discussed in Chapter 1), because they identify elements that survive theory change.

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[72] Notice that Psillos (2007) takes a contextual approach rather than Lipton's (2004) logical approach to explain why the loveliest explanation is most likely to be true.

Let us start with Psillos's view. Psillos defends a selective realist account which he calls *Divide et Impera*. This approach is sometimes called explanationsim, because it is concerned with explaining the success of scientific theories (Egg, 2014, p. 19). This account divides a theory into two components: idle constituents of a theory and the essentially contributing constituents. Psillos' distinction between idle constituents and essential constituents often gets treated more or less the same as Kitcher's (1993) distinction between working posits and presuppositional posits. I have introduced these two accounts in Chapter 1, but I will remind the readers of what their differences are. Psillos points out that his distinction is meant to capture how the successes of a theory can differentially support its several theoretical constituents (Psillos, 1996, p. 311). Kitcher's distinction between presuppositional and working posits, however, is meant to capture the difference between referring and non-referring terms. Working posits are said to be "the putative referents of terms that occur in problem-solving schemata," while presuppositional posits are "those entities that apparently have to exist if the instances of the schemata are to be true" (Psillos, 1996, p. 311). Psillos develops this account as a response to the pessimistic induction by arguing that the essentially contributing constituents of a theory deserve realist commitments. Psillos argues that "it is precisely those theoretical constituents that scientists themselves believed to contribute to the successes of their theories (and hence to be supported by the evidence) that tend to get retained in theory-change. Whereas, the constituents that do not 'carry-over' tend to be those that scientists themselves considered too speculative and unsupported to be taken seriously" (Psillos, 1996, p. 312). He thinks his view is plausible because it reflects how scientists treat their theories and the way they differentiate their commitments to their several constituent theoretical claims (Psillos, 1996, p. 312).

However, this view is often criticized for not answering the question: on what grounds can one select those essential constituents to be responsible for the success of a theory? In this sense, it has not gone as far as entity realism, casual realism, structural realism, and semirealism to suggest what those essential constituents might be. Psillos' account at this point is not complete. If the virtue of Psillos' view is that it is a substantive version of scientific realism because it can block the pessimistic induction, its vice is that it does not seem very useful for identifying the realist constituents of any particular theory, including Bohmian mechanics. Psillos' account leaves it open what these essentially contributing constituents might be. Classical mechanics and Bohmian mechanics differ significantly in terms of ontologies since Bohmian mechanics introduces a wave function that is absent in classical mechanics, and Bohmian particles and classical particles behave differently (see Chapter 5). If Psillos takes ontologies to be essentially contributing constituents of a theory, a continuity of ontologies between the two theories seems quite hard to find. His account does very little to answer whether a conceptual change has happened with regard to particles. And even with a single theory, say, classical mechanics, we are not yet settled on what parts of a theory contribute to its empirical success. Alternatively, the fact that the causal version of Bohmian mechanics seems to preserve the mathematical equation (specifically the Hamilton-Jacobi equation) used in classical mechanics might lead some to consider the possibility of structure for realism.

A recent defense of structuralism is ontic structural realism (hereafter OSR) and Michael Esfeld (2013) has applied it to Bohmian mechanics. OSR is the thesis that all there is in the world is structure. Esfeld argues that OSR only seems to capture part of the ontology of Bohmian mechanics, while the basic ontology of Bohmian mechanics, namely Bohmian particles (and for some Bohmians who think the wave function represents a physical entity) is not captured by OSR. However, other structural realist accounts also fail to apply. Here I consider Worrall's (1989) structuralism not just because Worrall has not yet applied his account to Bohmian mechanics, but also because his version of structural realism aims to respond to an anti-realist argument, the pessimistic induction. Worrall's treatment of structuralism in response to the pessimistic induction is to note that there are mathematical equations that are preserved through a theory change, or "[t]here was continuity or accumulation in the shift, but the continuity is one of *form* or *structure*, not of content" (1989, p. 117). He uses the example of Fresnel's light and classical electromagnetism to demonstrate this point (Also see Chapter 1). One can try to run a similar argument for the case of the transition from classical mechanics to Bohmian mechanics. Both classical mechanics and the causal version of Bohmian mechanics are described by second-order Hamilton-Jacobi equations, where Bohmian mechanics adds a quantum potential term and hence a force term. But we need to evaluate whether the two Hamilton-Jacobi equations are in fact identical at the classical limit. Holland (1993) suggests that the condition for the classical limit of Bohmian mechanics is when the quantum potential tends to zero (Brown et al. 1996, p. 313). However, in the simulation of Sengupta et al. (2014), they show that when the quantum potential tends to zero, classical behavior of particles is not observed.[73] This result suggests that the two second-order equations do not constitute a continuity in formalism and classical features are not recovered when we take the classical limit of Bohmian mechanics. So, this undermines Worrall's structuralism.

[73] Sengupta et al. have also shown that both Bohmian trajectories and the Bohmian trajectories as the quantum potential goes to zero exhibit non-crossing behavior, but classical trajectories exhibit crossing behavior (2014, p. 3).

An alternative realist approach is Chakravartty's semirealism. Chakravartty's (1998) semirealism synthesizes entity realism (ER) and structural realism (SR). According to Chakravartty, entities are inferred based on perceptions grounded upon certain *causal regularities* having to do with interactions between objects. He makes a distinction between detection properties and auxiliary properties.[74] *Detection properties* are those upon which the causal regularities of our detections depend, or in virtue of which these regularities are manifested. *Auxiliary properties*, then, are those associated with the object under consideration, but not essential (in the sense that we do not appeal to them) in establishing existence claims (Chakravartty 1998, p. 394-395).[75] They help supplement our descriptions of objects under investigation. But more importantly Charkravartty thinks that ER and SR entail one another. On the one hand, believing in SR forces us to accept ER because "one cannot intelligibly subscribe to the reality of relations unless one is also committed to the fact that some things are related" (Chakravartty 1998, p. 399). And Chakravartty thinks that only those detection properties of entities enter the particular structural relations, namely those that describe causal interactions (1998, p. 400). On the other hand, the causal relations which connect detection properties are retained wherever we recognize the presence of such entities, such as in subsequent theories (Chakravartty 1998, p. 400). If we believe in entities, we will have to believe in relations they stand in. These causal relations "describe interactions between entities which compose the very phenomenal regularities we attempt to map with *mathematical equations* [emphasis mine] in our fundamental physical theories" (Chakravartty 1998,

[74] Chakravartty's (1998) distinction may seem familiar, since it is very much like Psillos's distinction between essential features and idle features, where the latter only plays a role to complete the scientific story without being warranted any realist commitments. But their distinctions differ in that Chakravartty explicitly thinks that the essential features are detection properties that are causally obtained, which goes further than Psillos' criterion to point out where the essential features originate.

[75] Notice that unlike Hacking (1983) and Cartwright's (1983) versions of entity realism which are independent of a particular theory, Chakravartty's entity realism (as part of his semirealism) "explains the fact that we have continuity of reference across theory change by appealing to unchanging attributions of those detection properties which underwrite the causal interactions we exploit by means of detection" (1998, p. 400).

p. 400).

In the box experiment, the experimenters detect a change in energy level when S2 is switched on and off. So this change in energy level, as a kind of relation, is essential to understanding if semirealism could account for the existence of the pilot wave. Chakravartty adopts the Worrall-style of SR, because the mathematical equations in our fundamental physical theories represent the causal relations/regularities that describe interactions between entities (1998, p. 399-400, 402).[76] In particular, "the study of such regularities by means of observation and experiment results in our representing relations between detection properties in terms of mathematical formulae; these mathematical relations, in turn, we take to define the structure of the theory concerned" (Chakravartty 1998, p. 407). In the box experiment, the change in energy level is a relation that represents a difference between two measurements, rather than a mathematical equation that represents a relation that connects detection properties. The two mathematical equations, the Schrodinger equation and the guiding equation in Bohmian mechanics, do not represent the relation of the change in energy level. What this means is that Chakravartty's SR does not capture the relation of change in energy. Because this feature of energy change supports the inference of the existence of the wave function, Chakravartty's account does not help some Bohmians defend a wave function ontology.

3.4 Hacking's entity realism

The first causal realist account I consider in this section is Hacking's (1983) manipulability account (i.e. his entity realism). Hacking's entity realism is the position that we use unobservable

[76] Chakravartty's SR unlike in Worrall's account, "contain substantive information about entities: namely, regarding detection properties" (1998, p. 407). Chakravartty commits only to those "mathematical equations relating detected objects, or more specifically, detection properties, as expressing causal relations between those objects" (1998, p. 401).

entities to investigate other parts of nature by relying on their well-understood causal properties (which we gain by interacting with the entities) to build devices. We know how to get the entities to behave in such and such a way, and when we do this, we should believe in the existence of these entities (Hacking 1983, p. 263).[77] In his example of electrons, Hacking argues that we only cease to take electrons as hypothetical and commit to their existence when we can use them to manipulate other parts of nature. Hacking shows experimenters can use electrons by relying on "a family of causal properties" to build an electron gun to study other unobservables, such as weak neutral currents and neutral bosons (1983, p. 266-272).

Although Hacking can run a similar argument for photons in the box experiment, the existence of the pilot wave is the focus of the box experiment.[78] In this chapter, to argue for the insufficiency of causal realism, it suffices to show that within the context of the box experiment, Hacking's criterion does not provide an adequate basis for realism about the pilot wave. In both the usual double slit experiment and the box experiment, interference patterns are observed. This interference pattern forces scientists to think that particles by themselves cannot produce such an effect. According to Bohmians, the natural explanation is that there is something that experimenters do not know in detail how to

[77] One should keep in mind that not all unobservable entities can fit Hacking's criterion. This limitation of not being able to manipulate some entities is in fact quite general. As Egg points out, there might be some real entities which we will never be able to manipulate, such as events that evolutionary biology reconstructs (2014, p. 23).

[78] Although it is tempting, it is not by default to assume that classical particles and Bohmain particles are the same. A causal account is also inadequate for telling us whether the electrons or photons in the box experiment are in fact Bohmian particles and what their nature is. For instance, Hacking's entity realism, if it works, gets us from the fact that we can use electrons or photons to investigate other parts of nature to the claim that they exist, but this sheds no light on telling us whether classical particles and Bohmian particles are the same sort of particles, or whether electrons or photons are Bohmian particles. This is a serious defect of causal accounts, because some Bohmians, such as Goldstein et al. (2005), think Bohmian particles are conceptually different from classical particles. For instance, Goldstein et al. (2005) defend the view that Bohmian particles are just *points*, that is we do not distinguish electrons from muons, or electrons from photons, for instance. On the other hand, Bohmian mechanics, if one believes in the truth of this theory, offers some insight on the nature of these entities. According to Bohmian mechanics, for instance, a particle is piloted by the wave and does not follow a straight-line trajectory when there is no classical force acting on it (unlike classical particles will move in a straight-line under the same condition). Sometimes, that a particle follows such a trajectory suggests that it is a Bohmian particle. The Bohmian says more than just that particles exist; they exist as Bohmian particles.

manipulate but is jointly responsible for the occurrence of such phenomena.[79] The pilot wave or guiding wave is associated with the particles. If there are only particles but no wave, all particles will simply fall behind the slits.

To infer the existence of the pilot wave, Hacking can say the wave exists but we do not arrive at this conclusion through some explanatory considerations, rather it exists simply because we can use it to manipulate the photons. In particular, just like how electrons are inferred to exist, the wave is inferred to exist by Hacking's criterion because the experimenters can rely on prior knowledge of the wave to build the box experiment to investigate the photons, which are also unobservable entities. For instance, they know how the wave behaves and propagates. The fact that the wave propagates and can affect other entities provides a reason why the box experiment is set up in the style of a double slit experiment. And this is not surprising because it is argued that wave mechanics represents naturally the double-slit experiments and matrix mechanics represents more nicely the entanglement experiments (Lewis 2016, p. 9). Also, the wave produces interference effects with particles in the usual double slit experiment, or produces diffraction patterns in single slit experiments, and these ideas are used to build the box experiment to investigate the photons from S1. It is through our prior interactions and/or experimenting on the wave that we form beliefs about how to use the wave to investigate the photons. It is not that our experimenting on the wave forces us to accept that the wave exists, but because we can use it to study something else that warrants this belief.[80]

Now, we need a more detailed story of how the pilot wave is used to manipulate photons by

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[79] It is often believed (according to the standard interpretation of quantum mechanics) that there are neither particles nor waves before measurement is made at the detector.

[80] If we can manipulate the wave function in the same way we manipulate the particles, which are three-dimensional objects, then we have a reason to think that the wave function is a three-dimensional object. For this possibility of the wave function as a three-dimensional entity, see Hubert. M & Romano. D (2018). But this will imply that configuration space realism is false because configuration space realism says that the wave function is in a configuration space, rather than a three-dimensional physical space.

stressing the geometry of the experiment. The box experiment has a particular geometrical set-up guided by prior LLI breakdown experiments, which reveals the anomalous interference effects. And this setup involves a physical elimination of photons from S2, such that the geometry of the box forbids photons from S2 to travel through F2, so what travels through F2 can only be the pilot wave. We know that no photons from S2 went through the aperture F2 because the detector B was always below the maximum dark threshold (Cardone et al. 2006, p. 1113). When the waves (associated with both S1 and S2) pass though F1 and F2, they form crests and troughs just like in the usual double slit experiments and carry photons from S1 to where the waves reinforce, but not where they cancel out.[81] The presence of the pilot wave associated with S2 affects the trajectories and number of photons from S1 received at the detector A, so this interaction results in an anomalous interference effect, which is reflected in a nonzero Δ A. The anomalous effect, that is a change in energy, can be regarded as an anomalous interference effect. Cardone et al. (2004) do not say whether Δ A is positive, that is when both S1 and S2 are turned on have a lower signal, or negative, when both S1 and S2 are turned on have a higher signal. But in a later paper, Cardone and Mignani state explicitly that a positive value of Δ A, (A (S1 on, S2 off) > A (S1 on, S2 on)), is when the signal at the detector A is lower when both S1 and S2 are on, and this means a "destructive interference of pilot waves of photons from the two sources occurs for detector A (dark fringe)" (2007, p. 4461). On the other hand, a negative value of Δ A, (A (S1 on, S2 off) <A (S1 on, S2 on)), is when the signal at the detector A is higher when both S1 and S2 are on, and this corresponds to a constructive interference of pilot waves of photons from the two sources detected at A (Cardone and Mignani 2007, p. 4460). This interpretation of the results implies that the

[81] Cardone and Mignani (2007) point out that the two lighting sources S1 and S2 emit wavepackets with very similar frequency spectra, so that photons from S1 can be carried by waves emitted by S2 (p. 4442).

pilot wave associated with S2 interacts with the wave associated with S1 photons to 'pilot' these photons. This is a case of Hacking's manipulability, because the pilot wave is used to manipulate the photons, so to affect their paths and the number of them detected at A. We can now say, according to Hacking's criterion, that the pilot wave exists because we can experiment on it to investigate other unobservable entities, just like Hacking (1983) infers the existences of electrons because they are used to manipulate weak neutral currents.

So far, it seems that Hacking's account applies nicely to the box experiment. But what I just showed is not the whole story of the box experiment. Instead, entity realism needs to be supplemented with the use of IBE in order to form a sufficient basis for the realism about Bohmian mechanics. In Hacking's electron example, he denies using explanatory considerations in inferring electrons, but argues that experimenters in fact use electrons in virtue of their causal properties to investigate something else. He thinks that there is no unified description/theory or understanding of electrons that experimenters believe in (Hacking 1983, p. 264). For Hacking, "engineering, not theorizing, is the best proof of scientific realism about entities" (1983, p. 274). Hacking therefore thinks that entity realism does not rely on explanatory considerations (hence some forms of IBE) that other forms of scientific realism use. Hacking stresses that "I have said that ability to explain carries little warrant of truth…. we no longer have to pretend to infer from explanatory success (i.e. from what makes our minds feel good). Prescott *et al.* [i.e. experimenters who build an electron gun to study weak neutral current] don't explain phenomena with electrons. They know how to use them" (1983, p. 271-272).

However, Hacking has not yet successfully dismissed the charge of the requirement of IBE for his entity realism. As Egg suggests, "it is unclear how successful manipulation should warrant belief in electrons (and the corresponding home truths) if not by means of some kind of IBE. At any rate, Hacking does not explain how this is supposed to work" (2014, p. 30). This questions how Hacking arrives at the existence of entities independent of any explanatory considerations. That is, if it is not to explain the produced phenomena, what warrants such beliefs in the existence of the unobservable entities? In the box experiment, if it is not to explain the production of the anomalous interference effect, why believe in the existence of the pilot wave? And if to explain the phenomena by inferring the existence of the unobservables, how can they be understood independently of any theories that describe them? It seems that one can argue that believing in the existence of entities entails believing in the existential claims about them, so entity realism is after all a kind of restricted statement realism.[82] But it is clear that Hacking is defending a sort of entity realism that is experiment-based rather than a semantic kind. The virtue of Hacking's entity realism resides in that we can believe in the existence of unobservable entities without sliding into believing in theory about them or relying on explanatory considerations. However, this is not to say that Hacking has successfully done that. In fact, he cannot escape from theoretical commitments about unobservable entities but has to invoke explanatory considerations in his inferential processes to the existence of these entities. He does not explain how he can arrive at the existence of unobservable entities independent of any explanatory considerations except by stressing that our "ability to explain carries little warrant of truth" (Hacking 1983, p. 271). To infer the existence of the pilot wave, it seems that one has to say how and why the pilot wave interacts with some other entities, particles or waves, in the box experiment to produce the anomalous

[82] According to Lipton, although there is a distinction between truth-values of the statements that make up a scientific theory (for statement realists) and the existence of entities (for entity realists), the comparison is not straightforward (1994, p. 102). He states that, "to say that a particular kind of entity exists is, after all, to make a statement, and one that is true just in case the entity does indeed exist" (Lipton 1994, p. 102).

effect and this requires some appeal to theories. Without the wave, we will not see a change in energy level at detector A and it is not plausible to claim that one can design the box experiment without the use of at least an elementary theory of how the wave behaves. For Hacking, it is because of using the pilot wave (and particles) to manipulate the photons that we are secure in believing in the existence of the wave. But this process also informs us how these unobservable entities can explain the produced effect. If Hacking does not rely on any explanatory considerations, it is hard to believe that manipulation of these unobservable entities can give rise to beliefs in their existence. Nonetheless, Hacking can deny that the box experiment counts as a case of manipulability, so it does not provide a case of why entity realism needs to be supplemented with IBE. But this puts the burden of proof on Hacking to show why the box experiment does not constitute a case of manipulability.

An implication of applying Hacking's criterion to the box experiment is therefore that believing in the existence of the entities implies believing in some descriptions of the entities. For instance, it would be absurd to believe in the existence of electrons but not that they are negatively charged, for otherwise, how can they be distinguished from other particles? Likewise, believing in the existence of the pilot wave implies believing in some claims or theoretical descriptions about them. For instance, the pilot wave contains a potential that pushes particles around. This claim is not a consequence of the set-up of the experiment, but a theoretical commitment. Bohmians can argue that this claim is required to *explain* why we observe interference patterns in the usual double-slit experiment and an anomalous interference effect in the box experiment. Without making such claims, we cannot explain how and why particles and the pilot wave interact to produce interference patterns. This implies that realism about Bohmian mechanics requires explanatory considerations for making commitments to entities and claims about them. It is not enough to believe that something exists, but also requires belief about what they are, namely their physical properties. Therefore, Hacking's manipulability account needs to be supplemented with the use of IBE, as the box experiment demands.

Furthermore, some claims about these entities are required for one to make sense of the manipulation of these entities, and this might already require that we accept some theories that describe them. And this is clearly the case in the box experiment. Cardone et al. believe that the wave is associated with photons and this relation between the wave and photons is nothing but the Bohmian description of the wave-particle duality which we have seen from the usual double slit experiments. Such theoretical beliefs are required in order to know what to predict and what effects we will be looking for in the experiment, that is a change in energy level. This is to say some claims about these unobservable entities are dependent on theories. And I will argue this last point after I discuss Cartwright's entity realism.

3.5 Cartwright's entity realism

Entity realism as a causal realist account, which does not (at best) give more than existential claims, comes in other forms. Another one is Cartwright's version. Cartwright's (1983) entity realism moves from manipulations of entities to causal explanations. "According to Cartwright, theory realism and entity realism both rely on IBE, but there is a crucial difference in the kinds of explanations that are invoked. In the case of theoretical explanations, the explanatory power resides in certain laws. In this case, Cartwright agrees with Hacking that IBE fails, because a law can be explanatory without being true …. But causal explanations work by postulating certain entities which are assumed to bring about the explanandum. These entities can only perform their explanatory role if they actually exist, hence

IBE is valid in this case" (Egg 2014, p. 30).[83] For the first half of Cartwright's view, she thinks that there is a tradeoff between truth and explanatory power. But, an IBE advocate will think that a fundamental law is explanatory in part because it is (approximately) true, and it is the best explanation that is most likely to be true. Nonetheless, there is some room for claiming that a theory is explanatory but need not be true. This relates to the idea of effective theories in physics. Effective theories purport to have explanatory power for phenomena at certain scales or at the limit, but do not need to be true, because they do not claim to provide a true or approximately true description of the world. For instance, effective quantum field theories (EFTs) are quantum field theories that become inapplicable beyond some short distance scale (Williams 2019, p. 210). With respect to the second half of Cartwright's view, IBE in the causal sense is the view that something can only do the explanatory work if it really exists. It is this sort of IBE that Cartwright has to accept according to Egg (2014), even if she denies that a theory is explanatory because it is (approximately) true (i.e., theoretical explanations that theory realists advocate). For instance, although aether was initially posited to exist because it was once thought that aether was necessary for the transmission of electromagnetic waves, scientists later proved that it does not exist because it failed to explain the Michelson-Morley experiment. This example shows that if aether does exist, it can do the explanatory work. Its non-existence is the reason why it does not explain the Michelson-Morley experiment.

To see how Cartwright's entity realism as an instance of IBE applies to the box experiment, consider the causal inference in her entity realism. Cartwright employs an inferential process "inference to the most likely cause" (IMLC). According to Psillos, "Cartwright thinks that it's most

[83] Psillos (2009) has a more detailed discussion on why Cartwright's entity realism is an instance of IBE by connecting it with Inference to the Best Cause.

likely to get things right if you are looking for causes than if you are looking for something else (e.g., general theoretical explanations)" (2009, p. 8). So this seems to suggest that causes can only give us probable truth. For Cartwright, entity realism is more secure than theory realism. Psillos argues that if we were to accept IMLC, there needs to be some intrinsic features of the 'cause' which makes it the most likely cause, rather than some extrinsic features (viz. there are independent reasons to think it is likely), such that one carefully picks a cause to be the best cause (2009, p. 9). And he argues that the most likely cause is the correct one if the intrinsic feature is that it is the best cause. In fact, Cartwright has occasionally described IMLC as "inference to the best cause" (IBC), which connects IBC to IBE (Psillos 2009, p. 9). The reason that IBC is an instance of IBE is that "the 'best cause' is *not just a likely cause*; it is a putative cause that causally explains the effect in the sense that it offers genuine understanding of *how and why* the effect was brought about" (Psillos 2009, p.9). This is to say the best cause has the intrinsic feature that it strives to explain how and why the effect was produced by the cause. In Cartwright's IBC, explanatory considerations are a guide to inference, in the same way that IBE is (Psillos 2009, p. 10).[84] In IBC, the explanation is causal. In our box experiment, to infer the pilot wave is the cause requires that it explains how it interacts with photons from S1 to produce an anomalous interference effect.

3.6 More on causal realism?

A general issue with entity realism is this. If entity realists have to accept some claims about unobservable entities as true, how is this compatible with their not being committed to the truth of the

[84] According to Psillos, "if we think of causal inference as Inference to the Best Cause, then we are committed to the view that the inferential weight is carried by the *explanatory quality* of the causal explanation offered, on its own and in relation to competing alternatives" (2009, p. 8).

theories that best describe these entities? Or the issue boils down to *whether it is possible to infer the existence of the wave without any theoretical baggage or explanatory considerations.* Hacking and Cartwright do not seem to have good answers to this question. Although Hacking proposes 'home truth' and Cartwright proposes phenomenological laws, in what sense those claims are independent of theory is not obvious (Hacking 1983, p. 265; Cartwright 1983, p.8). One suggestion is that the phenomenological laws are effective theories, so they need not be true. But Cartwright describes the phenomenological laws as low-level laws rather than higher level laws which are captured by abstract equations of fundamental theories. If the success of the effective theories relies on abstract equations in these theories, then it is unlikely that Cartwright will identify her phenomenological laws with effective theories. To account for this problem, Egg (2012) has defended a version of causal realism.[85] Egg accepts Suárez (2008)'s distinction between causal warrant and theoretical warrant. Let's first discuss Suárez's (2008) experimental realism and his account of causal warrant beliefs, which set up the background for Egg's (2012) causal realism.

Suárez (2008) defends epistemic experimental realism (EER) which is the thesis that "manipulation is a necessary and sufficient condition on causal warrant: Our belief that x exists acquires this special kind of warrant if and only if we believe that we manipulate x" (p. 141). EER is an epistemic thesis rather than a metaphysical one, such that "according to EER, the belief that we manipulate p does not entail that p is real," but it gives us the ground for warranting such belief (Suárez, 2008, p. 159). What this implies is that although EER does not preclude the claim that we infer the

[85] Nonetheless, Cartwright, Suarez and Egg face a general problem that renders their causal realist accounts dubious. According to Wüthrich, these accounts presuppose rather than infer the existence of the involved entities, "otherwise we could not have observed occurrences of the factors, we could not know to have manipulated them, or we could not have gathered statistical data about them" (2017, p. 463).

existence of x from some other sources, it is claiming that we are secure in this belief through causal warrant, which is stronger than any other ways of warranting. It does not matter how one acquires beliefs about the existence of unobservable entities such as electrons, either through home truths or some theoretical descriptions, but what matters is that only through causal warrant by believing that we have manipulated these entities can we be confident in our belief about these entities. Suárez's account does not rule out home truths and theoretical descriptions of the entities. He thinks "on this epistemic version of experimental realism the "home truths" about an entity x, which we need to believe in for our inference that x is real to be causally warranted, need not in any way exhaust our concept of x" (2008, p. 148). And Suárez gives an example to show causally warranted beliefs are compatible with having these beliefs from theoretical descriptions. "I may have learnt about the facilities at Hotel Barbarossa from a theoretical description, but my corresponding beliefs acquire causal warrant only to the extent that I have manipulated those facilities" (2008, 149). EER is not about how we form our belief about electrons, for example, in the first place, but "makes the distinct and additional claim that our belief in electrons possesses a special sort of warrant, causal warrant, we can be particularly confident in our belief in electrons because we are confident that we routinely manipulate electrons, or their causal properties, in experimental conditions" (2008, p. 149). So unlike Hacking's entity realism, Suárez is not concerned with what is real but what grounds warrant these beliefs about unobservable entities, such as the belief that electrons exist (Suárez, 2008, p. 149). Suárez's EER is compatible with that in some cases, such as the pilot wave, we first acquire our belief about the existence of the pilot wave through Bohmian descriptions, but this belief can only be warranted in a stronger sense, a causal sense, if we believe that we have manipulated the pilot wave.

Based on the distinction between causal warrant and theoretical warrant, Egg argues that theories ascribe different kinds of properties to entities, some of them formal, some of them material. Both theoretical warrants and causal warrants are generated by instances of IBE (Egg 2012, p. 261). This implies that Egg's causal realism inherently has IBE as a constituent. "Statements concerning the former are based on IBTE (i.e. inference to the best theoretical explanation), so the causal realist is not (or at most tentatively) committed to them.[86] By contrast, statements concerning material properties can be warranted by IMLC (i.e. inference to the most likely cause), and if that is the case, belief in these statements does not imply belief in the rest of the theory, for which there is only a weaker kind of warrant" (Egg 2012, p. 270).[87] For example, the claim that electrons are negatively charged is causally warranted and arrived at as a material inference where the material property is the property of being negatively charged. We can modify this property to produce some effects. So, claims that are causally warranted form the hard core of the realist's commitment, and deserve stronger realist commitments than claims warranted theoretically. Egg allows realist commitments to claims that are theoretically warranted, except that he thinks that those are significantly less secure than causally warranted claims. So "they should be seen as forming a more peripheral part of the realist's commitment" (Egg 2012, p. 279). In the box experiment, we can safely accept the claim that, on Egg's ground, the pilot wave pushes particles around in the Bohmian universe and particles have trajectories. In short, both Cartwright's version of entity realism and Egg's causal realism need to be supplemented with the use of IBE, at least when applied to the box experiment, but for different reasons from that of Hacking's account.

[86] Egg's IBTE here is what we usually call IBE.

[87] The way that Egg defines material inference is that "what is to count as material inference needs to be defined in terms of the kinds of properties that can be ascribed to entities as a result of such inference (let us call them material properties)" (2012, p. 265).

These various causal realist accounts, although they are applicable to the box experiment, on their own cannot recover Bohmian explanations. They need to be supplemented with the use of IBE. IBE is inescapable commitments to these causal realist accounts. And if we were to use them to argue for realism about Bohmian mechanics, it can only capture part of the Bohmain story. That is to say, a purely causal realist account of Bohmian mechanics is untenable.

3.7 What about particles?

The discussion on causal realism has focused on the pilot wave, but one might argue that if particles are the only ontological commitments for a Bohmian, as in primitive ontology, causal realism can adequately account for the realism about Bohmian particles, without appealing to explanatory considerations. In fact, the supplementation of IBE has a more general application, given that causal realism in the selective sense I consider here is inadequate even if we don't look at it through the lens of the box experiment. If particles are the only entities that are real as primitive ontologists suggest, then just as we have suggested that Hacking's entity realism will require theoretical descriptions of the pilot wave, we need theoretical descriptions of Bohmian particles to pick them out in the world. To anchor Bohmian particles in the world will require theoretical descriptions of them according to Bohmian mechanics, such that these particles are described and determined by the wave function if regarded as a law. Just like in the argument for the pilot wave discussed above, if it is not to explain the quantum effects, why posit the existence of particles? When we posit the existence of particles, we need theoretical descriptions of these particles, so how can we have these theoretical descriptions without appealing to some theories? In the case of particles, the application of entity realism is inescapable from IBE. Even if one is a primitive ontologist, causal realism has to be supplemented by IBE or is some sort of IBE. This holds regardless of whether one is a primitive ontologist or a wave function ontologist.

4. A positive case of IBE: breakdown of LLI and the pilot wave

One important conclusion the experimenters of the box experiment draw is to identify the pilot wave with a deformed spacetime. Here is some background on deformed spacetime. In special relativity, physical phenomena are often formulated in Minkowskian (local flat) spacetime (three spatial dimensions and one time dimension). "The local flatness of spacetime means that the laws of physics can be locally written in the language of Special Relativity (SR) and hence physical phenomena are locally invariant under Lorentz transformations. The controversial point at issue (from both the theoretical and the experimental side) is whether the validity of local Lorentz invariance (LLI) is preserved at any length or energy scale" (Mignani et al. 2012, p. 1). The analysis by the Deformed Special Relativity (DSR) formalism produced a threshold value of energy and space for the breakdown of LLI for the electromagnetic interaction. DSR is a modified theory of special relativity which includes observer-independent scales, such as maximum velocities, maximum energy scale and minimum length scales (Cardone et al. 2006, p. 1108). Specifically, DSR is "a generalization of Special Relativity based on a "deformation" of the Minkowski space, namely a space-time endowed with a metric whose coefficients depend on the energy of the investigated processes" (Cardone, et al. 2006, p. 1108).[88] In our context, "LLI is broken when the energy exchanged during the process is less than

[88] Although Bohmian mechanics is a non-relativistic theory, it nonetheless possesses features that are relevant to relativity, such as nonlocality which is understood as action at a distance. So it is possible for one to argue that there is an inconsistency between

4.5 μ eV and the maximum distance, over which its non Lorentzian effects can be still detected is about 9 cm" (Mignani et al. 2012, p. 2). In short, DSR formalism provides the framework for LLI breakdown.

First of all, the wave is inferred to exist not in a purely causal way but with the aid of IBE. This has been shown in section 4. Cardone et al. argue that the change in energy level when the second light source is on and off "finds a natural explanation, in the Einstein-de Broglie-Bohm interpretation of quantum wave", in terms of the interaction of photons from S1 with the pilot wave (associated with photons from S2) passed through the second slit F2 in Fig. 1 (2006, p. 1115). The *reality of the pilot wave* is inferred from a theoretical explanation that lies in the Einstein-de Broglie-Bohm interpretation of the quantum wave, such that without the existence of the wave, we will not observe such a change in energy level.

On the other hand, the connection of the wave with the LLI breakdown is provided by the marked threshold behavior the phenomenon exhibited. That is, the values of the energy gap are consistent with the threshold behavior for the electromagnetic breakdown of LLI, obtained in the framework of DSR. Hence, Cardone et al. draw a connection between these two conclusions: the pilot wave is a deformation of space-time. The hypothesis that the pilot wave is a deformed space-time is *not a causal criterion* for understanding the pilot wave. Putting this in IBE terminology, that the wave is a deformation of spacetime is the best explanation for how interactions between the wave and particles happen and how the anomalous effect is produced. The wave as a deformed spacetime explains the anomalous effect in this way: the deformed spacetime stores energy which is used to deform spacetime

Bohmian mechanics and the maximum limit of velocity (i.e. the speed of light). But one can also argue that there is no such inconsistency because there is no transmission of message due to this nonlocality.

around the particles and pilots the particles (Mignani et al. 2012, p. 7). So the change in energy level detected at A is interpreted as the energy possessed by the space-time deformation itself. In comparison to Hacking's criterion, Hacking gets us as far as saying that there is a wave given that we can use it to manipulate the anomalous effect, but it does not tell us what sort of wave it is.

5. What about primitive ontology?

The debate about whether we should treat the wave function in Bohmian mechanics ontologically or nomologically rests on whether the wave function can be regarded as a real physical entity in any sense. One way to divide the various versions of Bohmian mechanics is between primitive ontology and wave function ontology as I showed in Chapter 3.[89] A primitive ontology account of Bohmian mechanics has been defended by Dürr, Goldstein and Zanghi (2013, p. 29) (and is often termed the DGZ interpretation of Bohmian mechanics) and more recently by Allori (2018).[90] In this view, the primitive ontology of Bohmain mechanics is particles, which are "the basic kinds of entities that are to be the building blocks of everything else" and are "described by their positions in space, changing with time—some of which, owing to the dynamical laws governing their evolution, perhaps combine to form the familiar macroscopic objects of daily experience (Dürr, Goldstein and Zanghi, 2013, p. 29). Wave function ontology often refers to the position that the wave function represents a physical

[89] In the literature a three-dimensionalist view sometimes refers to the position of Bohmian mechanics that denies a physical realist attitude towards the wave function. This can include Belousek's (2003) account which takes particles and the quantum forces to be ontology in the 3-D space, or primitive ontology which takes only particles as ontology. But some Bohmians such as Hubert and Romano (2018) argue for a version of Bohmian mechanics which takes the wave function as a multi-field in the 3-D space. So the contrast between primitive ontology and wave function ontology might better capture the ontological difference we need in this chapter, although it might leave out Belousek's (2003) account, compared to a division between a three-dimensionalist view and wave function ontology.

[90] There are other ways to divide different versions of Bohmian mechanics, such as between the guidance approach and the quantum potential approach which focuses on the discussion of the quantum potential. This division places emphasis on the dynamical equations and asks whether the guiding equation (first-order) or the classical-like Hamilton-Jacob equation (second-order) is fundamental. Primitive ontology is considered as a guidance approach.

entity, such as Albert's (1996) configuration space realism and Hubert and Romano's (2018) multi-field account.[91] The primitive ontologists, Dürr, Goldstein and Zanghi (1997), propose that "the wave function is a component of a physical law rather than of the reality described by the law" (Dürr et al. 1997, p. 33). A primitive ontologist's take on the status of the wave function is to regard the wave function as nomological and there are two ways to understand this nomological status.[92] One is the Humean understanding of laws. On the Humean view, the wave function supervenes on the motion of particles, and the best system approach to laws provides a way to understand how the supervening relation is established (Miller 2014; Esfeld 2014; Callender 2015; Bhogal & Perry 2017). Alternatively, one can take the law to be grounded in dispositions (Esfeld et al. 2014). Both nomological views of the wave function do not take the wave function to be primitive. My point here is to show, even if the primitive ontologist claims to make the same predictions as wave function ontology, a wave function ontology is preferred. Hence we can avoid an underdetermination between the primitive ontology account and the wave function ontology account.

For the Humean, the universal wave function is "part of the best system, that is, the system that achieves the best balance between being simple and being informative in capturing what there is in the physical world" (Esfeld, 2014, p. 459). The best system theory of laws in general can be understood in this way, "a proposition is a law iff an ideal observer, someone who is rational and has full information about what is being systematized and embraces our sciences' standards (which include simplicity and comprehensiveness), declares the proposition a law" (Callender, 2015, p. 3160). The

[91] See Belousek (2003, p. 141-143) for Belousek's criticism of Albert's account.
[92] In both nomological interpretations of the wave function, their advocates argue that only the *universal* wave function has the nomological status, rather than effective wave functions, because the universal wave function when considered as a law encompasses all particles in the universe rather than particles in a subsystem.

wave function on the best system approach can be understood as part of the summary of how particles move. "If an ideal observer could survey all the Bohm particles scattered across spacetime and she cared about our scientists' standards for evaluating theories, then she would devise the laws of Bohmian mechanics" (Callender, 2015, p. 3160). So basically, the wave function is part of the laws which summarize how particles move, and to include it in one's summary of the fundamental makes it the best such summary (Callender, 2015, p. 3163).

The second approach to laws of nature is the dispositionalist view which is that "the laws supervene on the disposition [such that properties are considered as dispositions to bring about certain effects] in the sense that they express what objects can do in virtue of having certain properties" (Esfeld et al. 2014, p. 784). Unlike Humean laws, laws on the dispositionalist account "are anchored in the essence of the properties of the objects that there are in the physical world, instead of being mere means of economical description" (Esfeld et al. 2014, p. 784). One way to apply this dispositionalist view of laws to Bohmian mechanics is to think of the wave function as representing a disposition that determines the velocity of the particles as an additional, holistic property of the system of particles under consideration (Esfeld et al. 2014, p. 784). "This disposition is a holistic property of all particles in the universe together – that is, a relational property that takes all the particles as relata. It induces a certain temporal development of the particle configuration, that development being its manifestation" (Esfeld et al. 2014, p. 785).

According to Esfeld et al. (2014), "in the [usual] double-slit experiment with one particle at a time, the particle goes through exactly one of the two slits and that is all there is in the physical world. There is no field or wave that guides the motion of the particle, propagates through both slits, and undergoes interference" (p. 779). In this case, whether or not one posits the wave function as a real entity or takes it to supervene on the motion of particles does not make a difference in the prediction. This seems to favor the position of primitive ontology which denies that the wave function is a part of Bohmian ontology and is an irreducible nonsupervening entity. The primitive ontologist can make a parallel argument about the box experiment, such that the formulation of primitive ontology and its interpretation of the wave function as nomological can make the same predictions as wave function ontology. This is to say if primitive ontology can account for all the empirical predictions as its alternative wave function ontology does, positing the existence of the pilot wave is superfluous.

Wave function ontologists can acknowledge the fact that primitive ontology is empirically equivalent with it because they both make the same predictions in the box experiment and other experimental results, but resist regarding the wave function as nomological and supervening on the motion of particles. Although Belousek (2003) defends a formulation of Bohmian mechanics which takes particles and the quantum forces as Bohmian ontology, his challenges against the explanatory adequacy of primitive ontology can be applied here to address the concern primitive ontologists might raise about the box experiment. Belousek points out that "while correct numerical prediction via mathematical deduction is constitutive of a good physical explanation, it is not by itself exhaustive thereof, for equations are themselves 'causes' (in some sense) of only their mathematical-logical consequences and not of the phenomena they predict" (2003, p. 136). In the context of Bohmian mechanics, this is saying that the guiding equation which primitive ontologists take to be a fundamental equation gives the prediction of particle trajectories. But Belousek goes further to say that "while the *existence* of quantum trajectories in Bohmian mechanics is itself to be left unexplained – the existence of such trajectories is, after all, *postulated* rather than derived from first principles – the mere existence of those trajectories is by itself insufficient for explanation" (2003, p. 136). This is to challenge the explanatory adequacy of primitive ontology even if it makes the right predictions. From a more general perspective, explanatory virtue is appealing in the sense that it favors Bohmian mechanics over standard quantum mechanics which is often accused for not being able to explain quantum phenomena but merely makes correct predictions. In fact, one of Belousek's examples to show the empirical inadequacy of primitive ontology is the double-slit experiment. Belousek's reason is as follows:

> Certainly, assigning an ensemble of particles all with a certain initial quantum state and initial positions distributed according to the amplitude-squared of that state will yield via the guidance equation a set of trajectories that correctly reproduces (as guaranteed by the continuity equation) the expected quantum interference pattern appearing at the screen or photographic plate. To do so, though, is *not* yet to *explain* the interference pattern, but rather to *redescribe* this state of affairs in terms of mathematically precise space-time trajectories. For the question arises regarding *how* it is that those trajectories should produce a pattern at the screen *in that way*; or, in other words, *how* it is that particles having those initial positions and initial quantum state should follow trajectories that produce *just this pattern* at the screen rather than a different one. The 'how' here has *physical*, *not* merely *mathematical*, significance. Thus, appeal to the guidance and continuity equations will simply not do, for they can answer the question 'how?' in at most a formal sense. And to deny this distinction is threaten a collapse of physics into mathematics and the nullification of the very meaning of *physical* theory (Belousek, 2003, p. 137).

Similarly, a wave function ontologist can argue that primitive ontologists and their interpretation of the wave function as nomological face a problem of explanatory inadequacy in the box experiment. When the wave function is regarded as nomological, what are left for primitive ontologists in their toolbox to explain anomalous interference effects in the box experiment are particle trajectories. Can primitive ontologists explain why in both lighting settings (i.e. S1-on-S2-off and S1-on-S2-on) when no photons from S2 pass through slit F2, the detector A detects a change of energy level, by appealing to particle trajectories? Do particles trajectories merely re-describe the different patterns in both lighting settings? If, as Belousek suggests that particles' trajectories cannot by themselves explain the patterns we observe, do we need to introduce some entities which are irreducible to the particles trajectories for the sake of explanation? Despite the fact that primitive ontology and wave function ontology are empirically equivalent, the appealing to explanatory consideration is one of the common criteria to lean towards one position over the other.

6. Conclusion

Bohmians have a strong inclination for believing in some unobservable entities, Bohmian particles and the pilot wave, because these ontological commitments are what allow them to claim that this theory can provide explanations for some peculiar quantum phenomena, such as the interference pattern in a double-slit experiment. Given the basis of the box experiment, it seems that some version of Bohmian mechanics provides a case where the pilot wave and particles exist in 3-D space and avoids the communication problem. And it is empirically adequate because it provides an explanation for the anomalous interference pattern, which primitive ontologists who regard the wave function as nomological fail to. For the Bohmian to be a realist about those unobservables, including unobservable entities and claims about them, the Bohmian will have to provide an epistemological criterion as to how she arrives at her realist conclusion. As I have shown, Bohmian mechanics shows that causal realist positions considered in this chapter cannot fully account for the realism about Bohmian mechanics in the context of the box experiment. Instead, these causal realist accounts will only form a sufficient basis for Bohmian mechanics, that is to recover Bohmian explanations, if each of them is supplemented with the use of IBE or considered as some form of IBE. So a purely causal realist account is not a tenable position. Realism about Bohmian mechanics is inescapable from IBE. Our application of causal realism to the box experiment shows that IBE is the primary tool to argue realism about Bohmian mechanics. It is normal that we start with IBE and abandon it later if we ever detect the wave in experiments. With respect to Bohmian mechanics, we are at an empirical disadvantage compared to neutrinos and Higgs Bosons that were posited before they were detected (for example Higgs bosons were predicted in the Standard Model of particle physics). However, unobservables such as the pilot wave are just like dark matter which we have a strong theoretical reason to believe in, but still lack of empirical evidence of it. If the aim of scientific enterprise is to explain the observable phenomena and unpack the reality, we certainly have a reason to believe in the realist commitments of a theory.

CHAPTER 5

Bohmian Particles, Interpretation and Ontology

Introduction

This chapter purports to answer the question "on what grounds can we take a realist attitude towards a scientific theory?" Not all scientific theories straightforwardly tell us what the world is like, so it is up to us to interpret these theories. Scientific realism about a theory is taken as the thesis that a theory successfully refers to some entities in the world and it provides descriptions of the nature of these entities. Attention about realism in Bohmian mechanics has focused on how to interpret the wave function. Here I switch gear to understand Bohmian particles. In particular, I investigate the implications the Bohmian interpretation of particles has on realism about Bohmian mechanics. The interpretation question under consideration is how a Bohmian interpretation of particles, unlike other theories of particles such as classical mechanics, provide a new description of particles. To be more specific, the central question is whether different descriptions of particles differ merely at the level of descriptions (i.e. different interpretations differ merely in how they describe particles) or if there is a deeper ontological question about whether they refer to the same particles. I use the Bohmian interpretation of particles to show that Bohmian particles are conceptually different from what we have traditionally known about particles. This is to say Bohmian particles are essentially different from particles under the description of classical mechanics. Even though particles under both descriptions have positions, their dynamics and behavior are essentially different. The Bohmian description of particles thus picks up a new referent that is different from that of classical mechanics.

In this chapter, I first provide some preliminaries on what I take scientific realism and interpretation to be. I show that the formalism of a theory endowed with particular interpretations provides descriptions of the nature of entities which the theoretical terms of the theory refer to in the world. I then argue that Bohmian descriptions provide a new understanding of particles and this is to be distinguished from descriptions of particles under the framework of classical mechanics.

1. Preliminary

1.1 Scientific realism and ontology

Scientific realism is defined in terms of beliefs about the ontology of theories. It is about how a theory is interpreted and what ontology it entails. "The first step in the construction of a physical theory is to establish what are the mathematical entities (particles, fields, strings, . . .) with which one intends to describe physical reality. These mathematical entities are what the theory is about and they are often called the ontology of the theory— a rather complicated way of expressing a simple, even though deep, physical notion" (Allori & Zanghi, 2004, p. 1744). In a more precise sense, these mathematical entities refer to some physical entities in the world, and these physical entities are what the theory is about, given that an ontology is established through some referential scheme. Our interpretations of the theory provide descriptions of these entities. The referential account is descriptivist.[93] "The descriptivist picture is highly intuitive with regard to our understanding of expressions referring to theoretical entities on the realist view. According to this picture, an electron is a spatiotemporal entity with such and such a mass and such and such a charge. We detect and

[93] I am using a descriptive account of reference here instead of a direct reference account because this chapter aims to investigate how theories and experiments provide descriptions of entities which some theoretical terms refer to. In particular, I want to say how a theory's formalism and the interpretation of the formalism is connected to entities in the world.

recognize electrons when identifying entities having these properties" (Andreas, 2017). On this account, we can identify entities that satisfy the descriptions that a theory or an interpretation of theory provides. In the case of Bohmian particles, Bohmian mechanics provides descriptions of particles where such descriptions are generated by our interpretation of Bohmian formalism, for instance the guiding equation suggests that particles follow determinate trajectories. In general, one realist theory (or realist interpretation of a theory) might carry more realist commitments than alternative realist theories (or alternative realist interpretations of a theory) in committing to more entities and more substantial descriptions of the entities. For instance, Bohmian mechanics commits to the existence of the pilot wave but standard quantum mechanics does not. Bohm's version of Bohmian mechanics commits to the existence of the quantum potential, but the version of Goldstein and Zanghi does not. Furthermore, Chakravartty points out that the existence of both thinner and more substantial descriptions of the nature of particles does not prevent us from being realists about them. He argues that "realism is a commitment that can be shared, defensibly, by those who subscribe to different and even conflicting conceptions of the natures of particles" (2019, p. 5).

1.2 Interpretations

The fact that Bohmian mechanics commits to particles and provides descriptions of these particles should be unpacked. This involves talking about how the formalism of Bohmian mechanics is interpreted so that it is connected with entities in the world. To do this, we need to examine how formalism, interpretation and ontology in a theory work together to provide descriptions of its ontology. Let's start with interpretations.

Interpretations of a theory's formalism pick out some entities via a referential scheme and provide descriptions of these entities. The notion of 'interpretation' is vague in science, and within different contexts, it can mean something very specific that is different in those different contexts. *In general*, an interpretation of a theory "should take a position about how reality is as described by the theory" (Losada & Lombardi, 2018, p. 389). In the context of quantum mechanics, an interpretation has a more specific goal of solving interpretative questions in quantum mechanics, such as explaining the quantum phenomena, solving the measurement problem, answering what the wave function represents in quantum mechanics, etc. In the context of this chapter, an interpretation of a theory tells us what exists according to the theory and how to describe such entities, and in particular how an interpretation of Bohmian formalism tells us about particles.

I adopt Losada and Lombardi (2018)'s definition of a physical theory which "is constituted by a formal structure and a semantic interpretation that endows the formalism with physical content" (p. 379). It is generally believed that the formalism of a theory and its interpretation are separated. Losada and Lombardi (2018) defend an extended formalism of standard quantum mechanics, Formalism of Contextual Histories (FCH), and they claim that "the FCH is a formalism and does not intend to supply an interpretation of quantum mechanics" but "the FCH may turn out to be interpretively relevant if supplemented with an adequate interpretation" (p. 369). One distinction that can capture the difference between formalism and interpretation is the distinction between syntax and semantics, where the formalism of a theory is syntactic and an interpretation endows the theory with semantic content.

It is appropriate here to point out that the ontological approach to scientific realism about theories is not Quinean, such that if a theory is true it makes certain ontological commitments, but based on interpretation rather than quantification. For Quine, “a theory is committed to those and only those entities to which the bound variables of the theory must be capable of referring in order that the affirmations made in the theory be true” (Quine, 1948). According to Bricker (2016), this means that “if a theory contains a quantified sentence ‘ $\exists x$ Electron(x)’, then the bound variable ‘x’ must range over electrons in order for the theory to be true; and so the theory is ontologically committed to electrons” (Bricker, 2016). Instead of relying on quantification, an interpretation of a theory says what exists, and the theory is true in so far as an interpretation of that theory tells us what exists. An interpretation tells us what exists if the theoretical terms refer to some entities in the world and the interpretation provides descriptions of the nature of these entities. Our belief in a theory requires that we adopt a particular interpretation and this interpretation confers an ontology. Oftentimes, theories are tested, verified or confirmed by empirical evidence, but different interpretations of a theory can make the same predictions even if they have different ontological commitments which may not be subject to empirical testing.[94] In short, our interpretations of a theory inform us what our realist commitments are about the theory.

1.3 Formalism and ontology

It is important we distinguish *formulations* of theories from *interpretations* of theories to avoid confusion. Here formulations refer to mathematical formulations of a theory. In standard quantum mechanics, we have matrix mechanics and wave mechanics. In classical mechanics, we have the Newtonian formulation, the Lagrangian formulation and the Hamiltonian formulation. The

[94] Different interpretations of a theory, although they might lead to different ontological commitments, can nonetheless make the same predictions regarding the phenomena.

mathematical formalism of a theory does not directly inform us about the ontology of the theory; instead a theory's ontological commitments depend on the specific formulation or interpretation of the formalism adopted. This statement should not be understood merely in a superficial way that mathematical formalism and ontology are separated but connected, but more importantly, despite the fact that there might be a mathematical equivalence in the multi-formulations and/or multi-interpretations, the ontology in each formulation or interpretation can differ. Formulations and/or interpretations of the formalism will provide descriptions of the ontology. This view of ontology is not captured by structural realism because the different formulations are mathematically equivalent but not ontologically equivalent. This need not be a drawback because structural realism is a controversial position.

In the context of quantum mechanics, understanding quantum mechanics is basically about answering the question of what the wave function is. Although there are no particle trajectories according to standard quantum mechanics, I discuss the interpretation question of the wave function in standard quantum mechanics to show how mathematical formalism and ontology are separated but connected. Let us first see why standard quantum mechanics (hereafter standard QM) lacks an uncontroversial interpretation of the formalism.[95] Lewis (2016) has provided two examples with regard to standard QM. In the case of entanglement, standard QM does not have a physical interpretation of the entangled state in terms of the properties of the electrons, individually or collectively (Lewis, 2016, p. 22). In standard QM, when two electrons are entangled, it is not possible to describe the entanglement in terms of the properties of individual electrons, because each electron

[95] Standard quantum mechanics can include the Copenhagen interpretation and also some realist interpretations of quantum mechanics that do not take an extreme instrumentalist attitude towards all theoretical entities in quantum mechanics.

is not in its eigen-state and the entangled state is a holistic state. The holistic state cannot be interpreted by the individual states of the electrons. A second example is the case of interference in a double-slit experiment. In standard QM, there is no physical interpretation of the quantum state offered to explain the interference (Lewis, 2016, p. 22). Lewis argues, "without a physical interpretation of the quantum state that is supposedly doing the explaining, it is not clear that we have given an explanation in any sense worthy of the term. You might reasonably suspect that we have simply given a general mathematical re-description of the observed phenomena" (2016, p.23). There are two formulations of quantum mechanics, Heisenberg's matrix mechanics (1925) and Schrodinger's wave mechanics (1926), but neither of them answers the question of "What does a quantum state represent"?, only "What can I expect when I measure it?" (Lewis, 2016, p. 20). And the answer to the latter question is given by the Born rule. The Born rule "becomes the accepted interpretation of the wave function: it determines the probability of finding the system in the configuration q when its wave function is $\psi(q, t)$" (Durr & Teufel, 2009, p. 142). This interpretation seemingly endows the wave function with some physical meaning, such that it allows us to calculate the probability of where a system locates after measurements. And standard QM is *prima facie* connected to the world through the measurement postulate, which says that, for instance, "if the spin of an electron in state (a, b) is measured in the z-direction, one obtains result "up" with probability $|a|^2$ and "down" with probability$|a|^2$" (Lewis, 2016, p. 13). The collapse of the wave function finds the system in a definite state. This procedure is instrumental, as it tells us how to use the wave function, but does not inform us what the wave function is, and how physical things interact with each other. Standard QM, so understood, merely presents itself with the predictive ability of quantum mechanics, and hence is often taken as an instrumentalist position and does not entail any realist commitments. But this is not all there is to standard QM, because we can interpret it even further.

The two formulations of Standard QM, matrix mechanics and wave mechanics are mathematically equivalent. But according to Lewis, it is not clear which we should take as metaphysically privileged, and second it is far from clear how to take either of these theories as descriptive of the world (Lewis, 2016, p. 1). This first point is obvious because the two formulations are mathematically equivalent, but defenders of mathematical formulations of standard QM, such as John von Neumann (2018), avoid giving a metaphysical understanding of the theory and attributing any ontological status to the wave function. Although they are mathematically equivalent, they represent the world in prima facie distinct ways (Lewis, 2016 p. 9). According to Lewis, "interference is more naturally represented using wave mechanics, whereas entanglement of spins is more naturally represented using matrix mechanics" (Lewis, 2016, p. 9). And "it is usually easier to apply wave mechanics to continuous quantities [such as positions] and matrix mechanics to discrete ones [such as spins]" (Lewis, 2016, p. 19).[96] For example, since matrix mechanics uses vector space it makes representing spin-up and spin-down of particles easier. "Pictorially, the probability of obtaining spin-up can be obtained by projecting the state vector (a, b) onto the vector (1, 0) corresponding to spin-up, and squaring the result; this is called the Born rule" (Lewis, 2016, p. 13). Similarly, in classical mechanics where the three formulations, Newtonian, Hamiltonian and Lagrangian are mathematically equivalent, it is generally believed that each of them represents one sort of system more naturally than the other.[97] For instance, the

[96] One should note that the discrete and continuous features are features in matrix mechanics and wave mechanics respectively, and they are not general features of quantum mechanics.
[97] Jill North (2019) attempts to deny the mathematical equivalence of the three formulations of classical mechanics.

Hamiltonian fits more naturally with simple harmonic oscillating systems, while Newtonian mechanics represent systems of free fall more naturally.[98] One might wonder how representations based on mathematical formulations are related to explanatory power of the theory. In fact, it is more appropriate to say that representation power can make calculations more effectively tractable, but explanatory power seems to rest on what unobservable entities a theory posits, because these entities are responsible for the phenomena. If a Newtonian commits to the existence of force, her Newtonian account might differ from the Hamiltonian formulation in explanatory power in terms of explaining a projectile motion. But this difference in explanatory power has to do with a Newtonian's commitment to force, rather than its mathematical representation of the physical system.

An implication of the fact of mathematical equivalence in different formulations of classical mechanics and that of standard QM is that mathematical formalism on its own cannot be an indication of the ontology of the theory (Also see Chapters 1 and 3.). This point suggests that formalism by itself is inapt to elicit the ontology of the theory, but the physical content of the theory appears when we adopt a specific formulation or interpretation of it. In classical mechanics, it is generally believed that the three formulations are translatable, but different formulations make it possible for there to be a divergence of ontological commitments. At the level of a specific formulation, the ontological question can be asked. Here, I discuss the comparison between Newtonian mechanics and the other two energy-based formulations Lagrangian and Hamiltonian. "Newtonian mechanics describes the world in terms of forces and accelerations (as related by the second law), and "Lagrangian and Hamiltonian mechanics

[98] One formulation can have more advantages over the other. "The advantage of the Hamiltonian form is that it directly expresses the [Newtonian] law as a differential equation. And it has the further advantage that it allows one to talk simultaneously about all possible trajectories of a system" (Durr & Teufel, 2009, p. 17).

describe systems in terms of energy, with force being "a secondary quantity" derivable from the energy … Although energy and force functions are inter-derivable in ways that physics books will show, these are nonetheless prima facie different pictures of the world, built up out of different fundamental quantities, with correspondingly different explanations of the phenomena" (North, 2019, p. 14). Although the Newtonian formulation and Lagrangian (and Hamiltonian) formulation are mathematically equivalent, they can differ in their realist commitments with respect to force, such that a Newtonian can be a realist about this term. For the Lagrangian and the Hamiltonian, force is not part of the ontology because the force term does not appear in their formulations. However, if an adherent of the Lagrangian or Hamiltonian formulations wants to regard this derived quantity, namely force, as part of the ontology, then they will have to provide a justification for why force, which is derived from energy, has to be regarded as real because within the Hamiltonian formulation, force is not necessary to provide explanations. The Newtonian may make this realist commitment because force can explain why objects fall to the ground, for instance and because force is part of the basic ontology of the Newtonian formulation. For the Newtonian, force is required to provide adequate explanations for phenomena. And this is a consequence of our interpretations of the Newtonian formalism. The principle of least action that is used to derive the equations of motion in Lagrangian motion can likewise give an explanation of the object's motion without invoking a force. The principle of least action is a variational principle that says an object will always take the path of least action. A similar issue arises in the causal version of Bohmian mechanics, where some advocates, such as Bohm, take the quantum potential to be real, but it is also a derived quantity. Belousek (2003) argues that the quantum potential which gives rise to the quantum force is necessary for an explanatory reason because without a commitment to the quantum force Bohmians who only rely on particle trajectories cannot adequately explain quantum phenomena.[99] As we can see, our interpretation of the theory goes further than the formalism itself to tell us what the world is like. Interpretations connect the formalism to the world. The fact that different formulations are mathematically equivalent does not entail an equivalent ontological commitment, and the reason is that when each formulation is evaluated on its own right to provide descriptions of the world, it can lead to different commitments of ontology compared to other formulations.

In quantum mechanics, formalism also does not directly provide an answer to the ontological question, but it requires that we invoke certain interpretations of the formalism. According to North (2019), "the Schrödinger and Heisenberg formulations of quantum mechanics are generally considered inter-derivable, yet you might not want to regard them as wholly metaphysically equivalent even so; many philosophers take only the former to directly or perspicuously represent what is going on physically, for instance" (p. 14). It seems that the Schrödinger formulation of wave mechanics is tied to the ontological question of what the wave function represents. This is analogous to the classical counterpart, where the question of whether force exists is a question asked in the Newtonian formulation of classical mechanics but not in its alternative formulations. However, to go from quantum formalism to the ontological question, it seems that quantum physicists cannot simply follow what classical physicists do. In fact, they have to make an extra step to access the formalism, that is they need to interpret whether a formalism is adequate for representing the physical structure. Some alternatives to the formalism of standard QM, which are often called interpretations of quantum

[99] The quantum force is obtained by taking the gradient of the quantum potential, and the version of Bohmian mechanics which Belousek proposes commits to the particles and the quantum force is a causal version of Bohmian mechanics. In Chapter 3, I had a more explicit discussion on a causal version of Bohmian mechanics.

mechanics, are proposed. Notice that 'interpretations' here is used in a broader sense to refer to theories of quantum mechanics that can make predictions for quantum phenomena but they can differ in their formalism in various ways from the formalism of standard QM. These include the Theory of Quantum Histories (Griffiths, 2013; Gell-Mann & Hartle, 1993) and the Formalism of Contextual Histories (Losada & Lombardi, 2018) which extend the standard formalism, and also Bohmian mechanics which introduces a guiding equation in addition to Schrodinger's equation. Strictly speaking, a new formalism although it is extended from the formalism of standard QM ought to be regarded as a distinct theory in its own right.

Different interpretations of a theory give rise to different ontological commitments and descriptions of the ontology. It is possible that a structural realist may argue that given this fact about mathematical variants of theories leading to different ontologies, such that a Newtonian might commit to force but a mathematically equivalent formulation Lagrangian does not, we should only commit to the reality of these mathematical structures. My point is instead that mathematical formalism in different formulations or interpretations of a theory can entail different ontological commitments and provide different descriptions of the ontology. We should not think that we should only stop at the abstract level of description provided by the mathematical formalism because the formalism is disconnected from the world without being interpreted. One reason is that the same mathematical structure might be applied to different sorts of systems. In Chapter 1, I discussed that the Lotka-Volterra model involves two differential equations of prey-predator populations and can be applied to different systems, such as biological, chemical or social systems (Knuuttila & Loettgers, 2013). This suggests that mathematical formalism has to be interpreted to correctly capture the physical content it tries to represent.

2. Bohmian descriptions of particles

Our interpretation of the mathematical formalism of a theory furnishes the theory with certain ontological commitments where the theoretical terms of the theory pick out some entities in the world that satisfy the mathematical descriptions the theory provides**.** Let us first see how Bohmians in general interpret the formalism of Bohmian mechanics to include particles as part of its ontology and describe these particles. The Bohmian thinks the wave function does not completely describe the state of a system which is governed by the Schrodinger equation, so they introduce the hidden variables, namely positions of particles. “In nonrelativistic Bohmian mechanics the world is described by point-like particles which follow trajectories determined by a law of motion. The evolution of the positions of these particles is guided by the wave function which itself evolves according to Schrodinger’ s equation” (Allori & Zanghi, 2004, p. 1744-1745). Allori and Zanghi (2004) show how the mathematics in Bohmian mechanics describes particles with the property of positions and determinate trajectories. “In Bohmian mechanics the velocities are not independent of positions, as they are classically, but are constrained by the guiding equation. The correct way of regarding the Bohmian mechanics is as a first-order theory, in which the fundamental quantity is the position of particles, whose dynamics is specified directly and simply by the velocity field (Allori & Zanghi, 2004, p. 1750-1751). Put succinctly, “the particles move on trajectories given by their positions and velocities as determined by the guiding equation” (2015, p. 3205).[100] This is an interpretation of Bohmian formalism that regards

[100] The lack of this guiding equation in the formalism of standard QM and the constraint of Heisenberg’s principle prevent

particles as part of its ontology where the trajectories of particles are in principle measurable, which implies that particles exist. In a word, particles under the description of Bohmian mechanics have definite positions and follow determinate trajectories which are prescribed by the mathematical equations of Bohmian mechanics. "Bohmian mechanics is quantum mechanics with particle trajectories. It describes the motion of point particles in physical space R^3" (Goldstein et al. 2004, p. 2).

The point that our interpretation of a theory can provide descriptions of the entities that the theoretical terms of the theory identify in the world is connected with Chakravartty's (2019) discussion that theories offer top-down descriptions of particles. According to him, a theory provides descriptions of particles such that "the (explicit or implicit) operating principle that insight regarding the natures of particles should be intimately and exclusively connected to interpreting the mathematical formalism" (Chakravartty, 2019, p. 10). To give a more concrete example of how the mathematics of Bohmian mechanics provides descriptions of particles, consider indistinguishable quantum particles and the fact that they obey Bose-Fermi statistics. This description of indistinguishable particles is not offered by some kind of experiments but by the interpretation of Bohmian mechanics.

The definition of indistinguishability in classical mechanics is that indistinguishable particles are particles that have the same intrinsic properties (French, 2019). Let us consider two point-particles.[101] Under the description of classical mechanics, when we swap these two particles' locations in a

the advocates of standard QM from advocating the existence of particles.

[101] When I refer to particles in classical mechanics and quantum mechanics, I don't imply that classical mechanics and quantum mechanics describe these particles in the same way. Instead, this is what I am investigating. I mean these particles that have the same intrinsic properties, such as charge.

coordinate, it gives rise to a new arrangement, because we can discern them by their different spatio-temporal properties. We can label these two particles as particle 1 and particle 2, and initially particle 1 is at location L1 and particle 2 is at location L2. Specifying the locations of classical particles can be a way of labelling. But one should not simply generalize this to Bohmian mechanics. After swapping the two particles, particle 1 is now at L2 and particle 2 at L1. Our labelling of particles has physical meaning because it tells us which particle is where at a given time. In terms of particle statistics, these particles obey Maxwell-Boltzmann statistics. In contrast, for quantum particles, such as electrons, labelling does not make a difference, we cannot tell whether particle 1 is at location 1 or location 2, and the same for particle 2. Switching the two particles does not generate a new arrangement. As a result, some argue that there is no way to individuate the two particles in standard QM, so quantum particles are non-individuals. In general, quantum particles obey Bose-Fermi statistics, where bosons such as photons obey Bose-Einstein statistics and fermions such as electrons obey Fermi-Dirac statistics. Bohmian mechanics reproduces Bose-Fermi statistics as well as does standard QM and they can do that in a more natural way. Let us see why this is the case.

It has been widely argued that Bohmian particles are indistinguishable point particles (Goldstein et al., 2005; Durr & Teufel, 2009, p. 166), such that labelling positions of particles with Q_i=1, …, N does not play a physical role, so Bohmian particles cannot be physically distinguished. According to standard QM, the lack of precise trajectories (positions) is the reason for the Bose-Fermi statistics. Because if particles had trajectories, they would automatically be distinguishable (Goldstein, Tumulka, Zanghi, 2009). This is to say if particles have positions, one could say a particle is over here and the other one is over there (Durr and Teufel). But Goldstein et al. (2009) and Durr and Teufel (2009), argue that *Bohmian trajectories are not in contradiction with Bose-Fermi statistics*, instead they actually enhance our understanding of the Bose-Fermi statistics. According to Durr and Teufel, the Bose-Fermi statistics are a straightforward prediction of Bohmian mechanics. The fact that particles have positions allows us to find a configuration space where the symmetry condition is satisfied, where the symmetry condition is whether a two-particle wave function of indistinguishable particles is either symmetric (bosonic) or anti-symmetric (fermionic) (Durr & Teufel, 2009, p. 167). The symmetric (anti-symmetric) condition is fulfilled defending on the framework used to describe the wave function and particles. For instance, "in many particle quantum mechanics, the indistinguishability of particles is encoded in the symmetry (boson) or antisymmetry (fermion) of the wave function *under exchange of particle coordinates*. For example, a two-particle wave function of indistinguishable particles $\psi(x1,x2)$ is either symmetric (bosonic) $\psi(x1,x2) = \psi(x2,x1)$, or antisymmetric (fermionic) $\psi(x1,x2) = -\psi(x2,x1)$" (Durr & Teufel, 2009, p. 166). Alternatively, "take a wave function defined on this space [a configuration space]. Then it is a function depending on sets. Since the set has elements, it is a function also of elements, but as such it is symmetric, since *exchanging the order of elements* in a set does not change the set" (Durr & Teufel, 2009, p. 167). This is to say (anti-) symmetric conditions are understood in terms of exchanges of the order of elements in a set. So the very fact that particles have positions, according to Bohmian mechanics, is what allows Bohmain mechanics to reproduce the Bose-Fermi statistics. The mathematical proof is omitted here, because it involves giving a topological interpretation of indistinguishable particles which is beyond the scope of this chapter.[102] For our purpose here, it suffices to say that the indistinguishability of quantum particles and the Bose-Fermi

[102] For a detailed explication of the topological interpretation, see Durr and Teufel (2009, p. 166-171).

statistics can be reproduced precisely given the interpretation of Bohmian formalism. This also implies that the idea that particles have positions and that they obey the Bose-Fermi statistics are compatible. It does not require the nonexistence of particle trajectories (as in standard quantum mechanics) to accommodate the Bose-Fermi statistics according to Bohmians.

3. What are particles?

Bohmian mechanics describes particles in such a way that they follow determinate trajectories, and this property of particles seems to receive a general consensus within different scientific theories that this feature provides descriptions of particles (and also descriptions provided by experimentations, such as causal properties about how the particles interact with other particles). However, philosophers of science have always been bothered by a deeper ontological question on whether different theories are referring to the same sort of particles. In the case of electrons, one might ask "Were Rutherford and Bohr talking about the same type of entities when using the expression 'electron'?" (Andreas, 2017). So the issue is that when our descriptions of particles change over time, are we are still referring to the same sort of particles? In the present context, there are different descriptions associated with particles and particle trajectories within the different theories, and one might wonder whether classical particles and Bohmian particles are the same sort of theoretical entities. Realism requires successful referents, and different realist accounts are compatible with there being such entities, which are the referents, but these accounts may differ in their descriptions about the entities. Chakravartty points out that how to describe the natures of particles is not an issue about realism with respect to particles, because once we successfully pick out the referent, different realist positions (such as structural realism, entity realism) might give thinner or more substantive descriptions of the nature of particles, but they do not disagree on whether particles exist (2019, p. 21). He says, "from a realist perspective, successful reference is, in fact, all that is required to anchor realism, and it is a shared judgment that such anchoring has been achieved that unifies different sorts of realists about any given x" (2019, p. 21). However, it is not uncontroversial that particles under the descriptions of Bohmian mechanics are the same particles described by other theories, such as classical mechanics and standard quantum mechanics. Perhaps, it is less controversial that particles are of different sorts described under the Standard Model and classical mechanics, where it is generally agreed that "the particles of the Standard Model are radically unlike what could be imagined in classical physics – thus providing an example of how descriptions of the physical and metaphysical natures of something conceived in connection with earlier theorizing would have to be relinquished in light of subsequent theorizing" (Chakravartty, 2019, p. 5). But this is not the case when we compare the descriptions of particles under the Bohmian framework and the classical framework. Part of the reason is because these two theories seem to provide similar descriptions of particles, which makes it difficult to distinguish Bohmian particles from classical particles.

First of all, there is a temptation to think that Bohmian descriptions and classical descriptions of particles pick out the same referents. Bohmian particles are reminiscent of classical ontology. Prima facie, some might argue that particles and their properties (such as charge and mass) are carried over from classical mechanics to Bohmian mechanics, hence we can describe the world in the way that we already learned from classical mechanics. In particular, if we can make sense of those particles being the same kind as classical particles, then we can say that we have retained an ontological continuity between Bohmian particles and classical particles. Putting the idea in terms of reference is to say a change of theories through the development of science picks out the same referents even if the descriptions of these particles have changed throughout this theory transition. This trend of thought is quite well-motivated at least from a practical point of view.[103] In addition, some Bohmians, such as Goldstein, Tumulka and Zanghi (2011), claim that particles and particle positions are central to Bohmian mechanics. This nostalgia for the classical framework inclines some realists to adopt Bohmian mechanics because it seems to reclaim a classical picture of the world in terms of what we are familiar with from classical mechanics in terms of particles' positions. Classical mechanics has been empirically successful in accounting for physical phenomena in the limit of ordinary perceptions. And if we can have a theory at the quantum level that does not make radically different ontological commitments and understanding of entities, then it seems that we will not face a radical conceptual change when we abandon classical mechanics to accept Bohmian mechanics. This move is intuitive because in some quantum experiments, we measure positions which are observational variables. For instance, in a double slit experiment, an interference pattern is manifested in terms of the spread of points on the screen. So positions seem to be properties that unveil much more about the quantum world than one might think. Positions of particles are properties that some Bohmians take to be fundamental quantities (Allori & Zanghi, 2004, p. 1750-1751). Our examination of particles can shed light on whether classical ontology can be recovered in the quantum domain.

[103] The development of Bohmian mechanics might be motivated for different reasons, such as being able to solve the measurement problem a collapse theory faces, or because it is a nonlocal theory that meets the condition of violating Bell's inequality in order to reproduce the same statistical predictions as standard QM.

3.1 Classical descriptions and Bohmian descriptions: particle positions and individuality

Both classical and Bohmian descriptions of particles assign positions to particles, despite the fact that Bohmian particles and classical particles can be taken to obey different statistical laws. The earlier discussion on indistinguishable particles seems to suggest that the fact that Bohmian particles obey the Bose-Fermi statistics entails that something in nature differs from classical particles that obey the Maxwell-Boltzmann statistics. It is worthwhile to emphasize that “the `quantum statistics’ today seen as an integral part of quantum mechanics, Bose and Fermi statistics, was mostly an independent development” (James & Joas, 2015, p. 672). For instance, “Schrodinger in December 1925 showed that a gas of particles obeying the curious new Bose-Einstein statistics could also be understood as a system of quantized wave modes obeying the “natural” Boltzmann statistics” (James & Joas, 2015, p. 671). The Bose-Fermi statistics is not a consequence of quantum mechanics, but has been incorporated into it by Heisenberg. So it seems that the fact that Bohmian particles can reproduce the Bose-Fermi statistics does not prevent us from thinking that they may be the same sort of particles as classical particles.

The fact that particles have positions suggests that they are individuals because we can individuate a particle based on its location, and this is the case despite the fact that Bohmian particles and classical particles obey different statistical laws. Particles, according to classical descriptions are individuals, as are particles under the description of Bohmian mechanics.[104] According to French, “classical

[104] Even if attempts (such as French & Krause, 2006) to retain the individuality of standard quantum particles have been proposed, this leads to a problem of metaphysical underdetermination in standard QM (French, 2011). On standard QM, particles as individuals are defended in various ways. For instance, one can give a field-theoretic account. On this account, particles are represented as dichotomic ‘Yes/No’ fields: with such a field, the field amplitude is simply ‘Yes’ at location *x* if the ‘particle’ is present at *x* and ‘No’ if it is not (Redhead, 1983). The feature of the individuality of Bohmian mechanics is a virtue because it avoids the metaphysical

statistical mechanics typically assume that such particles are impenetrable, in precisely the sense that their spatio-temporal trajectories cannot overlap. Hence they can be individuated via their spatio-temporal properties" (French, 2015). Likewise, Bohmian particles can be individuated if we assume non-coincidence [two or more particles cannot occupy the same location at the same time] of particle positions and trajectories, just like in individuating classical particles (French, 2015). In Bohmian mechanics, indistinguishability, which is the feature that the equation of motion does not change under the exchange of particle labels, and this (anti-)symmetric feature of the wave function is related to the dimension of space rather than the fact that particles have positions. In the Bohmian description, particle positions do not conflict with the idea of indistinguishibility of particles. This is because in Bohmian mechanics, indistinguishability has to do with the true configuration space in which the wave function resides, in fact, it is a reduced configuration space rather than the full configuration space which is 3N-dimensional. Particles under the Bohmian description can still be individuated based on particle positions, just like particles under the classical description. The particles under both classical and Bohmian descriptions so far might seem to indicate that they are the same sort of particles if positions are all that matter for describing particles. Our next question is whether particle positions are all we need to understand particles or there is more to say about particles.

So far, it is still not decisive whether Bohmian particles and classical particles are the same except that they all have positions and follow determinate trajectories. It would be too quick to conclude that they are the same sort of entities based on the fact that they have positions. Are there other relevant features other than particle positions to distinguish Bohmian particles and classical particles?

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underdetermination of particles-as-individuals and particle-as-nonindividuals that standard QM has to deal with.

According to Goldstein et al. (2005), we have two possibilities about the nature of Bohmian particles: particles belonging to different species may be metaphysically different, i.e., electron points may be different from quark points or photon points, or, alternatively, they may all be just points (p.7). If it is the case that there are different kinds of particles, to know what kind of particle we have, for instance whether it is an electron or a quark, requires us to identify them based on their trajectories, when for example subject to external fields. Goldstein et al. argue "if, say, electrons and muons were different kinds of points then this difference in the nature of these points would be in no way directly accessible to us, such that we can only know something about the particles through their behavior but cannot have direct access to their intrinsic properties. Our decision as to whether a given particle is an electron or a muon would be based on its behavior under the conditions (such as external fields) we impose, i.e., based on its trajectory" (2005, p. 7-8). But they argue further the "impossibility of deciding experimentally between these possibilities is a fundamental limitation of science. A choice can only be based on theoretical considerations" (Goldstein et al., 2005, p. 7). The conclusion of Goldstein et al. is that Bohmian particles are just points, because the other possibility "would be in no way directly accessible to us" and "sometimes progress in theoretical physics forces us to regard what was previously considered two species as two quantum states of the same species" (Goldstein et al., 2005, p. 8). On the one hand, one might question how the limitation of science affects our understanding of the nature of Bohmian particles. On the other hand, if what Bohmians need to specify about the physical states of a system is through particles' positions and trajectories, then whether a particle is an electron or a muon does not affect how Bohmians describe the world, and they have a reason not to pursue further the question about particle kinds. Although Bohmians might disagree on whether

Bohmian particles are of different kinds, these disagreements make no difference in empirical predictions, because the relevant properties are positions, rather than charge, mass or energy.

3.2 Particle trajectories and dynamics

So far, Bohmian particles, as point particles that have positions, might seem to be the same kind of particles as classical point particles. *Prima facie*, if we stop here, it seems that Bohmian mechanics and classical mechanics are picking out the same referential entities (particles) in the world. "While the law of motion of Bohmian mechanics is highly non-Newtonian, Bohmian mechanics has in common with Newtonian mechanics that there are real particles—with actual positions—in contrast to most other versions of quantum mechanics" (Goldstein et al. 2005, p.2). And this belief of similarity is supported by the fact that it follows a deterministic trajectory. In order to access whether classical mechanics and Bohmian mechanics describe particle trajectories and particle dynamics differently, we should go back to the discussion on mathematical formalism that provides a description of particles. Mathematically, some versions of Bohmian mechanics are analogous with classical mechanics, such as Bohm's causal version of Bohmian mechanics where the *law of motion* is governed by a second-order Jacobi-Hamiltonian (classical-like) equation (with a new term, the quantum potential) that Bohm introduces. Our interpretations of their mathematical formalism may provide some insight on the question of Bohmian descriptions of particle trajectories and classical descriptions of particle trajectories. The reason why the nature of particle trajectories plays a role in determining whether Bohmian particles are the same sort of particles as classical particles is that if Bohmian particles are just point particles as Goldstein et al. (2005) argue, then particle trajectories are essential to what Bohmian particles are. To determine whether classical particles and Bohmian particles are the same sort of particles will depend on understanding particle trajectories under the descriptions of both theories.

Peter Holland (1993) thinks that the condition for the classical limit of Bohmian mechanics is when the quantum potential in the Jacobi-Hamiltonian equation tends to zero (Brown et al., 1996, p. 313). What this means is that, in principle, whether classical behavior of particles can be observed depends on the results of taking a zero quantum potential on a Bohmian system. Brown et al. (1996) deny “the necessity of recovering all the familiar classical ontology when taking the classical limit of quantum mechanics” (p. 313). They argue that it is possible to recover this classical ontology in the case of a single particle without the ψ-field becoming spatially localized, and without the mass of the system becoming large (p. 313). And they also point out that it is questionable whether this is consistent with true classical behavior. Now it seems that we run into a difficulty of whether a mathematical formalism can tell a difference between particles’ trajectories under the classical framework and under the Bohmian framework. The Bohmian theory by itself cannot tell us what trajectories are like, except that there are such trajectories. Chakravartty thinks “establishing successful reference requires more than the examination of a formalism” (2019, p. 11). In fact, successful reference of the theoretical terms in the theory requires supplementations of detections and/or measurements which have to do with the causal interactions, relations and processes (Chakravartty, 2019, p. 11). In other words, to successfully anchor the referents in the world requires causal descriptions of these referents. In the case of Bohmian particles, in addition to mathematical structures (via the guiding equation), understanding the causal properties and relations can help identify Bohmian particles and to distinguish them from classical particles.

In fact, examining how particles behave under the Bohmian description at the causal level can distinguish Bohmian particles from classical particles. As I noted in Chapter 3, the simulation of Sengupta et al. (2014) has shown that "it has been observed that the zero quantum potential limit of a Bohmian system [an ensemble of particles] does not necessarily exhibit the corresponding classical characteristics" (p. 1). So the classical limit as the quantum potential goes to zero does not recover the classical behavior of particles. In particular, both Bohmian trajectories and the Bohmian trajectories as the quantum potential goes to zero exhibit non-crossing behavior, that is there is no crossing of quantum trajectories, but classical trajectories exhibit crossing behavior (Sengupta et al., p. 2014, p. 3). Moreover, it is often demonstrated in a double-slit experiment that Bohmian particles guided by the wave function do not follow a straight-line in the absence of external force. In contrast, classical particles move in a straight-line when there is no external force acting on them. So this feature of Bohmian trajectories described in a less formal way indicates that it is inherent in Bohmian mechanics that it cannot reproduce classical ontology. In fact, there is no obvious reason why classical ontology should be reproduced at some limit of Bohmian mechanics. There seems to be a fundamental difference between Bohmian particles and classical particles which is responsible for the failure to reproduce classical predictions. So we can conclude from the above discussion that not only that the law of motion of Bohmian mechanics is highly non-Newtonian as described in Goldstein et al. (2005), but also that even if Bohmian particles are real particles with positions they differ ontologically from classical particles. Even if we take a classical limit, we cannot observe classical behavior of Bohmian particles. As a result of this, there might be an ontological discontinuity between classical mechanics and Bohmian mechanics. Moving from classical mechanics to Bohmian mechanics involves a conceptual change about particles. The feature that trajectories of Bohmian particles differ essentially from that of classical particles is a reason to think that two theories anchor in different referents.

Conclusion

A scientific theory is often not explicit about what its ontological commitments are, so it is up to us to interpret its formalism and to identify the entities in the world, such that these entities satisfy the descriptions provided by the theory. To believe in a scientific theory is to believe in what the theory says about the world. An interpretation of the Bohmian mathematical formalism bestows Bohmian mechanics with a commitment to particles, and under the description of the Bohmian framework, these Bohmian particles have positions and follow determinate trajectories. Although Bohmian descriptions and classical descriptions of particles share a set of descriptions such as following trajectories, they differ in some fundamental aspects of particle trajectories, which suggests that the two theories are referring to different kinds of particles. This is different from saying that during theory transitions, the descriptions of particles have simply been redescribed. More importantly, the sort of particles which are identified and described are different in classical mechanics and Bohmian mechanics. Some formulations of Bohmian mechanics, such as the one adopts a Hamilton-Jacobi equation, might hold a continuity of formalism (expect Bohmians have introduced a quantum potential term) with classical mechanics. But the fact that Bohmian mechanics and classical mechanics posit different kinds of particles (supported by different dynamical laws and natures of particle trajectories) suggests that continuity of formalism is not sufficient for realism about classical mechanics and Bohmian mechanics. This confirms Chakravartty's view that structural realism is not a sufficient thesis for scientific realism. Furthermore, primitive ontology of Bohmian mechanics, which denies the Hamilton-Jacobi equation is a fundamental equation of Bohmian dynamics, will further deemphasize the importance of the continuity of theoretical formalism. In fact, for primitive ontologists, the continuity of theoretical formalism is not a necessary condition for realist commitments. At last, a further implication for scientific realism about theories is that the level of theoretical formalism is not the appropriate level of description for realism, instead, realists should be looking at the level of specific formulations or versions of a scientific theory.

REFERENCES

Acuña, P., & Dieks, D. (2014). Another look at empirical equivalence and underdetermination of theory choice. *European Journal for Philosophy of Science*, *4*(2), 153-180.

Albert, David Z. 1996. Elementary Quantum Metaphysics. In Cushing, James, Fine, Arthur, and Goldstein, Sheldon (eds.). *Bohmian Mechanics and Quantum Theory: An Appraisal*. Dordrecht: Kluwer. 277-284.

Allori, V. (2013). Primitive ontology and the structure of fundamental physical theories. *The wave function: Essays on the metaphysics of quantum mechanics*, 58-75.

Allori, V. (2018). Scientific realism and primitive ontology or: The pessimistic induction and the nature of the wave function. *Lato Sensu, revue de la Société de philosophie des sciences*, *5*(1), 69-76.

Allori, V., & Zanghì, N. (2004). What is Bohmian mechanics. *International Journal of Theoretical Physics*, *43*(7-8), 1743-1755.

Andersen, A., Madsen, J., Reichelt, C., Ahl, S. R., Lautrup, B., Ellegaard, C., ... & Bohr, T. (2015). Double-slit experiment with single wave-driven particles and its relation to quantum mechanics. *Physical Review E*, *92*(1), 013006.

Andreas, Holger, "Theoretical Terms in Science", *The Stanford Encyclopedia of Philosophy* (Fall 2017 Edition), Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/fall2017/entries/theoretical-terms-science/>.

Arageorgis, A., & Earman, J. (2017). Bohmian Mechanics: A Panacea for What Ails Quantum Mechanics, or a Different and Problematic Theory?.

Barrett, T. W. (2014). On the structure of classical mechanics. *The British Journal for the Philosophy of Science*, *66*(4), 801-828.

Beebee, H. (2000). The non-governing conception of laws of nature. *Philosophy and Phenomenological Research*, *61*(3), 571-594.

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

Belousek, D. W. (2003). Formalism, ontology and methodology in Bohmian mechanics. *Foundations of Science*, *8*(2), 109-172.

Belousek, D. W. (2005). Underdetermination, realism, and theory appraisal: An epistemological reflection on quantum mechanics. *Foundations of Physics*, *35*(4), 669-695.

Bhogal, Harjit and Perry, Zee R. (2017): "What the Humean should say about entanglement". Noûs 51, pp. 74-94.

Boström, K. J. (2015). Is Bohmian Mechanics an empirically adequate theory?. *arXiv preprint arXiv:1503.00201*.

Bricker, Phillip, "Ontological Commitment", *The Stanford Encyclopedia of Philosophy* (Winter 2016 Edition), Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/win2016/entries/ontological-commitment/>.

Bricmont, J. (2016). *Making sense of quantum mechanics*. Cham: Springer International Publishing.

Brown, H. R., Elby, A., & Weingard, R. (1996). Cause and effect in the pilot-wave interpretation of quantum mechanics. In*Bohmian mechanics and quantum theory: an appraisal*(pp. 309-319). Springer, Dordrecht.

Callender, Craig (2015): "One world, one beable". Synthese 192, pp. 3153-3177.

Cardone, F., & Mignani, R. (2004). *Energy and geometry: an introduction to deformed special relativity* (Vol. 22). World Scientific.

Cardone, F., & Mignani, R. (2007). The shadow of light: challenging classical and quantum electrodynamics. *International Journal of Modern Physics B*, *21*(26), 4437-4471.

Cardone, F., Mignani, R., Perconti, W., & Scrimaglio, R. (2004). The shadow of light: non-Lorentzian behavior of photon systems. *Physics Letters A*, *326*(1-2), 1-13.

Cardone, F., Mignani, R., Perconti, W., Petrucci, A., & Scrimaglio, R. (2006). The shadow of light: Lorentz invariance and complementarity principle in anomalous photon behavior. *International Journal of Modern Physics B*, *20*(09), 1107-1121.

Cartwright, N. (1983) *How the Laws of Physics Lie*, Oxford: Clarendon Press.

Chakravartty, Anjan. "Semirealism." (1998). *Stud. Hist. Phil. Sci.*, Vol. 29, No. 3, pp. 391–408.

Chakravartty, A. (2008). What you don't know can't hurt you: realism and the unconceived. *Philosophical Studies*, *137*(1), 149-158.
Chakravartty, A. (2019) Realist Representations of Particles: The Standard Model, Top-Down and Bottom-Up. *Contemporary Scientific Realism and the Challenge from the History of Science*.

Colin, S. (2011). Relaxation to quantum equilibrium for Dirac fermions in the de Broglie–Bohm pilot-wave theory. *Proc. R. Soc. A*, rspa20110549.

Colin, S., & Valentini, A. (2014, November). Instability of quantum equilibrium in Bohm's dynamics. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* (Vol. 470, No. 2171, p. 20140288). The Royal Society.

Cushing, J. T. (1994). *Quantum mechanics: historical contingency and the Copenhagen hegemony*. University of Chicago Press.

Dowe, P. (1992). Wesley Salmon's process theory of causality and the conserved quantity theory. *Philosophy of science*, *59*(2), 195-216.

Dowe, P. (2008). Causal processes. *Stanford encyclopedia of philosophy*.

Dürr, D., Goldstein, S., and Zanghi, N. 1992: Quantum Equilibrium and the Origin of Absolute Uncertainty. Journal of Statistical Physics, 67, 843-907.

Dürr, D., Goldstein, S., & Zanghi, N. (1997). Bohmian Mechanics and the Meaning of the Wave Function. Experimental Metaphysics–Quantum Mechanical Studies in Honor of Abner Shimony, ed. RS Cohen, M. Horne. *J. Stachel. Boston Studies in the Philosophy of Science, Kluwer*.

Dürr, D., Goldstein, S., & Zanghì, N. (2013). *Quantum physics without quantum philosophy*. Springer Science & Business Media.

Dürr, D., Goldstein, S., Norsen, T., Struyve, W., & Zanghì, N. (2014). Can Bohmian mechanics be made relativistic?. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *470*(2162), 20130699.

Egg, M. (2012). Causal warrant for realism about particle physics. *Journal for General Philosophy of Science*, *43*(2), 259-280.

Egg, M. (2014). *Scientific realism in particle physics: a causal approach* (Vol. 29). Walter de Gruyter GmbH & Co KG.

Esfeld, M. (2013). Ontic structural realism and the interpretation of quantum mechanics. *European Journal for Philosophy of Science*, *3*(1), 19-32.

Esfeld, Michael (2014): "Quantum Humeanism, or: physicalism without properties". Philosophical Quarterly 64, pp. 453-470.

Esfeld, M., Hubert, M., Lazarovici, D., & Dürr, D. (2014). The ontology of Bohmian mechanics. *The British Journal for the Philosophy of Science*, *65*(4), 773-796.

Fahrbach, Ludwig (2011). “How the Growth of Science Ends Theory Change”, Synthese 180 (2): 139–155.

Feyerabend, P. K.: 1981, 'Explanation, Reduction and Empiricism', in P. K. Feye rabend (ed.), Realism, Rationalism and Scientific Method, Philosophical Papers, Vol. 1, Cambridge University Press.

Feynman, Richard P., 1967, *The Character of Physical Law*, Cambridge, MA: MIT Press.

Feynman, Richard P., Robert B. Leighton, and Matthew Sands, 1963, *The Feynman Lectures on Physics, I*, New York: Addison-Wesley.

French, S. (2011). Metaphysical underdetermination: why worry?. *Synthese*, *180*(2), 205-221.

French, Steven, "Identity and Individuality in Quantum Theory", *The Stanford Encyclopedia of Philosophy* (Fall 2015 Edition), Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/fall2015/entries/qt-idind/>.

French, S., & Krause, D. (2006). Identity in physics: A historical, philosophical and formal account. Oxford: Oxford University Press.

French, S., & Ladyman, J. (2003). Remodelling structural realism: Quantum physics and the metaphysics of structure. *Synthese*, *136*(1), 31-56.

Gell-Mann, M., & Hartle, J. B. (1993). Classical equations for quantum systems. Physical Review D, 47, 3345–3382. https://doi.org/10.1103/PhysRevD.47.3345.

Gisin, N. (2018). Why Bohmian mechanics? One-and two-time position measurements, Bell inequalities, philosophy, and physics. *Entropy*, *20*(2), 105.

Goldstein, S. (2010). Bohmian mechanics and quantum information. *Foundations of Physics*, *40*(4), 335-355.

Goldstein, Sheldon, "Bohmian Mechanics", *The Stanford Encyclopedia of Philosophy* (Summer 2017 Edition), Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/sum2017/entries/qm-bohm/>.

Goldstein, S., & Tumulka, R. (2003). Opposite arrows of time can reconcile relativity and nonlocality. *Classical and Quantum Gravity*, *20*(3), 557.

Goldstein, S., Taylor, J., Tumulka, R., & Zanghı, N. (2005). Are all particles real?. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *36*(1), 103-112.

Goldstein, S., Tumulka, R., & Zanghi, N. (2011). Bohmian trajectories as the foundation of quantum mechanics. *Quantum trajectories*, 1-15.

Goldstein, S., & Zanghi, N. (2013). Reality and the role of the wave function in quantum theory. *The wave function: Essays on the metaphysics of quantum mechanics*, 91-109.

Goldstein, S. and N. Zanghì, N.,. Reality and the role of the wave function in quantum theory. In A. Ney and D. Z. Albert, editors, *The Wave Function: Essays On The Metaphysics of Quantum Mechanics*, chapter 4, pages 91–109. New York: Oxford University Press, 2013.

Griffiths, R. (2013). A consistent quantum ontology. Studies in History and Philosophy of Modern Physics,
44, 93–114. https://doi.org/10.1016/j.shpsb.2012.12.002.

Hacking, I. (1983). *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science.* Cambridge: Cambridge UP.

Healey, R. A. (1991). Holism and nonseparability. *The Journal of Philosophy*, *88*(8), 393-421.

Healey, R. (1997). Nonlocality and the Aharonov-Bohm effect. *Philosophy of Science*, *64*(1), 18-41.

Heitmann, W., & Nimtz, G. (1994). On causality proofs of superluminal barrier traversal of frequency band limited wave packets. *Physics Letters A*, *196*(3-4), 154-158.
Holland, P. R. (1993), *The Quantum Theory of Motion.* Cambridge, Cambridge University Press.

Holland, P. (1993), The Quantum Theory of Motion: An Account of the de
Broglie-Bohm Causal Interpretation of quantum mechanics, Cambridge University
Press, Cambridge.

Hubert, M., & Romano, D. (2018). The wave-function as a multi-field. *European Journal for Philosophy of Science*, *8*(3), 521-537.
James, J., & Joas, C. (2015). Subsequent and subsidiary? Rethinking the role of applications in establishing quantum mechanics. *HIST STUD NAT SCI*, *45*(5), 641-702.

Karakostas, V. (2012). Realism and objectivism in quantum mechanics. *Journal for general philosophy of science*, *43*(1), 45-65.

Kitcher, P. (1993), The Advancement of Science. Oxford University.

Knuuttila, T., & Loettgers, A. (2013). The productive tension: Mechanisms vs. templates in modeling the phenomena. In *Models, simulations, and representations* (pp. 21-42). Routledge.

Kitcher, P. (1993), The Advancement of Science. Oxford University.

Lakatos, I. (1976). Falsification and the methodology of scientific research programmes. In *Can theories be refuted?* (pp. 205-259). Springer, Dordrecht.

Laudan, L. (1981). A confutation of convergent realism. *Philosophy of science*, *48*(1), 19-49.

Laudan, L., & Leplin, J. (1991). Empirical equivalence and underdetermination. *The journal of philosophy*, *88*(9), 449-472.

Lewis, P. J. (2001). Why the pessimistic induction is a fallacy. *Synthese*, *129*(3), 371-380.

Lewis, P. J. (2004). Life in configuration space. *The British journal for the philosophy of science*, *55*(4), 713-729.

Lewis, P. J. (2016). *Quantum ontology: A guide to the metaphysics of quantum mechanics*. Oxford University Press.

Lipton, P., (1993). “Is the Best Good Enough?” *Proceedings of the Aristotelian Society*, 93: 89–104.

Lipton, P. (1994). Truth, existence, and the best explanation.

Lipton, P. (2000, July). Tracking Track Records: John Worrall. In *Aristotelian Society Supplementary Volume* (Vol. 74, No. 1, pp. 179-205). The Aristotelian Society.

Lipton, P. (2004). *Inference to the best explanation*. Routledge.

Losada, M., & Lombardi, O. (2018). Histories in quantum mechanics: distinguishing between formalism and interpretation. *European Journal for Philosophy of Science*, *8*(3), 367-394.

Maudlin, Tim (2002). *Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics*. Blackwell.

Maudlin T. (2013), “The Nature of the Quantum State”, in A. Ney, D. Albert (eds.), The Wave Function, Oxford University Press, pp. 126-154.

Maxwell, James Clerk (1872). *Theory of Heat*.

Mignani, R., Petrucci, A., & Cardone, F. (2012, May). Possible Experimental Evidence for Violation of Standard Electrodynamics de Broglie Pilot Wave and Spacetime Deformation. In *2012 Symposium on Photonics and Optoelectronics* (pp. 1-8). IEEE.

Miller, Elizabeth (2014): "Quantum entanglement, Bohmian mechanics, and Humean supervenience".

Australasian Journal of Philosophy 92, pp. 567-583.

Mizrahi, M. (2013). The pessimistic induction: a bad argument gone too far. *Synthese*, *190*(15), 3209-3226.

Müller, F. (2015). The Pessimistic Meta-induction: Obsolete Through Scientific Progress?. *International Studies in the Philosophy of Science*, *29*(4), 393-412.

Musgrave, A., (1988). "The Ultimate Argument for Scientific Realism," in R. Nola (ed.), *Relativism and Realism in Science*, Dordrecht: Kluwer, pp. 229–252.

Nikolić, H. (2005). Relativistic quantum mechanics and the Bohmian interpretation. *Foundations of physics letters*, *18*(6), 549-561.

Nimtz, G., Enders, A., & Spieker, H. (1994). Photonic tunneling times. *Journal de Physique I*, *4*(4), 565-570.

Norsen. T. (2010) The theory of (exclusively) local beables. Foundations of Physics, 40(12): 1858–84.

North, J. (2019). Formulations of Classical Mechanics. Reference?

Park, S. (2019). Optimistic realism over selectivism.

Petrucci, A. (2019, June). Lorentz violation and quantum mechanics. In *Journal of Physics: Conference Series* (Vol. 1251, No. 1, p. 012040). IOP Publishing.

Psillos, S. (1996). Scientific realism and the'pessimistic induction'. *Philosophy of Science*, *63*, S306-S314.

Psillos, S. (2005). *Scientific realism: How science tracks truth*. Routledge.

Psillos, S. (2006). Thinking about the ultimate argument for realism. In *Rationality and Reality* (pp. 133-156). Springer, Dordrecht.

Psillos, S. (2007). The fine structure of inference to the best explanation. *Philosophy and Phenomenological Research*, *74*(2), 441-448.

Psillos, S. (2009). Cartwright's realist toil: From entities to capacities. In *Knowing the Structure of Nature* (pp. 99-122). Palgrave Macmillan, London.

Quine, W. V., 1948, “On What There Is”, *The Review of Metaphysics*, 2(1): 21–38. Reprinted in Quine 1953: 1–19.

Ranfagni, A., Fabeni, P., Pazzi, G. P., & Mugnai, D. (1993). Anomalous pulse delay in microwave propagation: A plausible connection to the tunneling time. *Physical Review E*, *48*(2), 1453.

Redhead, M., 1983, “Quantum Field Theory for Philosophers”, in Asquith, P.D. and Nickles, T. (eds), *Proceedings of the 1982 Biennial Meeting of the Philosophy of Science Association* (PSA 1982, Volume 2), East Lansing: Philosophy of Science Association (1983): 57–99.

Riggs, P. J. (2008). Reflections on the deBroglie–Bohm Quantum Potential. *Erkenntnis*, *68*(1), 21-39.

Riggs, P. J. (2009). *Quantum causality: conceptual issues in the causal theory of quantum mechanics* (Vol. 23). Springer Science & Business Media.

Rivadulla, A. (2004). The Newtonian limit of relativity theory and the rationality of theory change. *Synthese*, *141*(3), 417-429.

Saatsi, J. (2005). Reconsidering the Fresnel–Maxwell theory shift: How the realist can have her cake and EAT it too. *Studies in History and Philosophy of Science Part A*, *36*(3), 509-538.

Saatsi, J. (2019). Scientific realism meets metaphysics of quantum mechanics. In *Philosophers Look at Quantum Mechanics* (pp. 141-162). Springer, Cham.

Santos, E. (2015). Towards a realistic interpretation of quantum mechanics providing a model of the physical world. *Foundations of Science*, *20*(4), 357-386.

Sengupta, S., Khatua, M., & Chattaraj, P. K. (2014). Bohmian trajectory from the “classical” Schrödinger equation. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *24*(4), 043123.

Solé, A. (2013). Bohmian mechanics without wave function ontology. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *44*(4), 365-378.

Suárez, M. (2008). Experimental realism reconsidered: How inference to the most likely cause might be sound. In *Nancy Cartwright's Philosophy of Science* (pp. 149-175). Routledge.

Suárez, M. (2015). Bohmian dispositions. *Synthese*, *192*(10).

Tadrist, L., Shim, J. B., Gilet, T., & Schlagheck, P. (2018). Faraday instability and subthreshold Faraday waves: surface waves emitted by walkers. *Journal of Fluid Mechanics*, *848*, 906-945.

Teufel, S., & Dürr, D. (2009). *Bohmian Mechanics: The Physics and Mathematics of Quantum Theory*. Springer.

Thomson, William. (1851). "On the Dynamical Theory of Heat, with numerical results deduced from Mr Joule's equivalent of a Thermal Unit, and M. Regnault's Observations on Steam." Excerpts. [§§1-14 & §§99-100], Transactions of the Royal Society of Edinburgh, March, 1851; and Philosophical Magazine IV. 1852, [from Mathematical and Physical Papers, vol. i, art. XLVIII, p. 174]

Valentini, A. (2002). Subquantum information and computation. *Pramana*, *59*(2), 269-277.

van Fraassen, B. C. (1989). *Laws and symmetry*. Oxford: Clarendon.

Von Neumann, J. (2018). *Mathematical Foundations of Quantum Mechanics: New Edition*. Princeton university press.

Williams, P. (2019). Scientific realism made effective. *The British Journal for the Philosophy of Science*, *70*(1), 209-237.

Worrall, J. (1989) 'Structural Realism: the Best of Both Worlds?', *Dialectica* **43,** 99–124.

Worrall, J. (2011). Underdetermination, realism and empirical equivalence. *Synthese*, *180*(2), 157-172.

Wüthrich, A. (2017). The Higgs discovery as a diagnostic causal inference. *Synthese*, *194*(2), 461-476.