Bohm’s Theory of Quantum Mechanics and the Notion of Classicality

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Abstract
When David Bohm published his alternative theory of quantum mechanics in 1952, it was not received well; a recurring criticism was that it formed a reactionary attempt to return to classical physics. In response, Bohm emphasized the progressiveness of his approach, and even turned the accusation of classicality around by arguing that he wanted to move beyond classical elements still inherent in orthodox quantum mechanics. In later years, he moved more and more towards speculative and mystical directions.
This paper aims to explain this discrepancy between the ways in which Bohm’s work on quantum mechanics has been received and the way in which Bohm himself presented it. I reject the idea that Bohm’s early work can be described as mechanist, determinist, and realist, in contrast to his later writings, and argue that there is in fact a strong continuity between his work on quantum mechanics from the early 1950s and his later, more speculative writings. In particular, I argue that Bohm was never strongly committed to determinism and was a realist in some ways but not in others. A closer look at Bohm’s philosophical commitments highlights the ways in which his theory of quantum mechanics is non-classical and does not offer a way to avoid all ‘quantum weirdness’.

Keywords:
David Bohm, Foundations of Quantum Mechanics, Classicality, Realism

1. Introduction

Bohm’s theory of quantum mechanics, which he first introduced in 1952, offers an account of quantum mechanical processes which is fully deterministic and according to which each particle has a well-defined position at all times. With this theory, Bohm went against the prevailing orthodoxy in quantum physics; but it has often been regarded as an attempt to return to classical ideals of realism, objectivity and determinism, and in that sense as conservative or even reactionary.

In recent literature, proponents of Bohm’s theory of quantum mechanics argue that it offers a possibility to give an ontological account of quantum phenomena, thereby basing quantum physics on solid foundations and restoring realism in quantum mechanics. They take

Bohm's interpretation of quantum mechanics to show that you can do quantum mechanics without the puzzling features commonly associated with it, such as complementarity or the observer-dependence of reality – the title of a recent book on Bohmian Mechanics is *Quantum Physics without Quantum Philosophy* (Dürr, Goldstein and Zanghi 2013). In this vein, Bohm's theory of quantum mechanics has also been invoked in critiques of quantum mysticism and of antirealist and 'postmodernist' tendencies in contemporary thought, with the idea that it shows that one can interpret quantum mechanics in a way which does not have any implications which are detrimental to objectivity or realism (Norris 2000, Bricmont 2016, 2017). All of this fits with the idea that Bohm's interpretation makes a return to classical conceptions and ideals possible, that it means a turn away from the weirdness of orthodox quantum mechanics and back to a more common-sense way of thinking about physical phenomena.

At the same time, it is well known that in his later years, Bohm developed a strong interest in spiritualism and eastern mysticism, and in this context drew very broad, speculative and strongly non-classical implications from quantum mechanics. For example, Bohm connected quantum non-locality (a feature of quantum mechanics which Bell has shown to be inherent in all interpretations of quantum mechanics, but which comes out explicitly in Bohm's interpretation) with holistic theories of the mind as well as of human society. From this, it seems that Bohm was not at all opposed to 'quantum weirdness' and that his way of thinking was in many ways nonclassical (Seager 2018). There are thus two distinct images of Bohm: on the one hand, there is the image of Bohm as a conservative physicists who aimed to restore the classical ideals of determinism, objectivity and realism, on the other hand there is the image of Bohm as a type of new age mystic.

This paper aims to explain how these two images can correspond to the same person. It is tempting to distinguish between an 'early Bohm' and a 'late Bohm', where the early Bohm is a realist, mechanist and determinist and the late Bohm an antirealist and mystic (and those who like his interpretation of quantum mechanics but are not fond of his later, speculative writings may think that Bohm lost his way when he got older, so his late writings can safely be ignored). I argue, however, that there is a lot of continuity in Bohm's writings. To understand the different images of David Bohm requires an understanding of the nature of debates on the foundations of quantum mechanics in the 1950s and 1960s, and the rhetoric used on both side of the debate. I argue that during this period, there were widespread revolutionary ideals in physics, and there was a broad consensus that a return to classical ideals would be a betrayal of the quantum revolution of the 1920s. In this context, labelling Bohm's theory as 'classical' was an effective way of criticizing it. Bohm resisted the idea that his research program was reactionary, and insisted that rather than returning to the past, he wanted to go *beyond* current quantum physics, towards something more radically new. In (1957a), Bohm even argued that it were in fact his opponents who were dogmatically attached to classical ideals in physics. Bohm's interest in alternative theories and revolutions led him to engage in philosophy of science, especially with the ideas of Feyerabend and Kuhn.

I argue that Bohm indeed never was a classical thinker, and that his core philosophical commitment in fact remained remarkably consistent throughout his life – although the fact that his theory was criticized as reactionary probably pushed him further into unorthodox directions. A closer look at Bohm's philosophical commitments reveals the ways in which his theory is non-classical. In particular, Bohm was never very committed to determinism, and was a scientific realist in some ways but not in others; most remarkably, in his later writings he uses his theory of quantum mechanics to argue that science does not describe an independently existing reality.

A note on terminology: an approach similar to Bohm's was proposed by De Broglie in the 1920s, however, he soon abandoned it and only returned to it after being convinced by Bohm of its viability. The account of quantum mechanics that emerged from the work of Bohm and De Broglie has been known variously as Bohm's interpretation of quantum mechanics, the causal or ontological interpretation of quantum mechanics, pilot-wave theory, De Broglie-Bohm theory, or Bohmian mechanics. It is thus variously referred to as a *theory* or as an *interpretation* of quantum mechanics. In (1952a), Bohm presented his proposal as a demonstration that an alternative theory of quantum mechanics was possible and as a starting point for reworking the foundations of quantum mechanics, rather than as a finished theory; in the following years, he worked on developing it into a more independent theory (and for some time, he abandoned it altogether, while looking for completely new foundations of quantum physics). Pinch (1977) therefore writes that in his 1952 paper, Bohm offered an interpretation of quantum mechanics plus an outline of a broader research program going beyond mere interpretation. In this paper, I will not go into this issue, and make no strict distinction between 'theory' and 'interpretation'. Finally, the term 'Bohmian Mechanics' was introduced by Dürr, Goldstein and Zanghi in (1992); their account deviates at some points from Bohm's original ideas, and Bohm in fact thought that it should rather be called "Bell mechanics", because of its reliance on the ideas of John Stewart Bell (Hiley 1999, 119).

2. Bohm's alternative theory of quantum mechanics

In the period after the second world war, many quantum physicists thought that the foundational issues in quantum mechanics had essentially been settled. Kaiser (2011) argues that the aftermath of the second world war and the onset of the cold war created an environment in physics which was most of all pragmatic: there was a focus on practical (including military) applications of physics, and large numbers of students had to be taught. In this environment, there was generally little interest in foundational and philosophical issues connected to quantum mechanics.

However, despite these general trends within the community of physicists, in the 1950s there were a number of physicists who developed alternative approaches to quantum physics, thereby challenging the consensus (see Camilleri 2009, Freire 2015). Most notable among these critics was David Bohm. Bohm had done his PhD with Robert Oppenheimer in the 1940s, and was generally regarded as a very promising young physicist (Freire 2015, 26). In 1951, he published a successful textbook in which he presented what seemed to be a conventional account of quantum physics. However, after finishing the book, Bohm felt dissatisfied with the current theory of quantum physics. Within a short time, he worked out an alternative account, which is fully deterministic and based on particles which have a well-defined position at all times and which are guided in their motion by a quantum potential (Bohm, 1952a).

While working on the paper, Bohm found out that a similar approach had been proposed by De Broglie in the 1920s (Bacciagaluppi and Valentini, 2009, and see Freire 2015, 30), but that De Broglie had abandoned the approach after receiving criticism. However, Bohm found a way to deal with the criticism which had been directed at De Broglie, and argued that the idea was worth pursuing further. Bohm's theory did find support from a small number of physicists; and notably it motivated De Broglie to take up his old approach again (Freire 2015). But otherwise it did not receive the reception Bohm had hoped for. Einstein, Pauli and Heisenberg expressed criticism on the level of physics, and objected especially to the fact that Bohm took the quantum mechanical wave function to be physically real and to the fact that in Bohm's interpretation, position and momentum are not treated symmetrically: positions can be measured directly, but a measurement of momentum always disturbs the system and does not reveal the momentum a particle had before measurement (Myrvold 2003).

Besides physical objections, also ideological and political factors played a role in the reception of Bohm's theory (see Cushing 1994; Freire 2005, 2015, 2019; Camilleri 2009). For a while, Bohm had been a member of the Communist Party, which caused him to become politically suspect. Completing his PhD research involved some trouble, as his research was classified due to possible relevance for the research on atomic weapons, and Bohm did not receive clearance to access it (Freire, 2015, 25). In 1949 he was called to testify for the House Committee on Un-American Activities, and in 1951 he was suspended from his position at Princeton University. Realizing he did not have a future in US academics, Bohm obtained a position at the University of São Paulo (Freire, 2015, 49), where he remained for about three years.[1] It has been argued that the lack of positive reception of Bohm's theory was connected to the marginalization of those with affiliations to communism during the cold war and to Bohm's isolation in Brazil (Olwell 1999). However, ideological dividing lines were not always obvious: two of Bohm's harshest critics, Fock and Rosenfeld, were committed Marxists, and argued that Bohm's interpretation went against dialectical materialism when properly understood (Fock 1957, Rosenfeld 1953; see also Jacobsen 2007, Camilleri 2009). Furthermore, Freire (2005) has argued that Bohm's stay in Brazil must not be understood as a period of isolation: there was a lively physics community and regular visits from well-known physicists from abroad (most significantly for Bohm, the French physicist Jean-Pierre Vigier came to visit Bohm for a few months, starting a long-term collaboration). Nevertheless, there is significance in the fact that around the time when Bohm's alternative theory of quantum mechanics was published, he relocated from Princeton to São Paulo: he became separated from the physics community in the US he had been part of, which subsequently reacted negatively to the theory he proposed. When asked for his opinion about Bohm's interpretation, his former PhD advisor Oppenheimer replied: "We consider it juvenile deviationism" (cited in Peat, 1997, 133).

3. The reception of Bohm's theory as an attempt to return to classical physics

A recurring theme in the reception of Bohm's account of quantum mechanics is that it was often seen as a return to classical ideals in physics and therefore as essentially conservative and even reactionary (see also Cushing 1994). For example, Heisenberg notes that although

[1] After Bohm's arrival in São Paulo, his passport was confiscated by US authorities, preventing him from traveling anywhere except back to the US. Rather than taking the risk of returning, Bohm remained in Brazil until he obtained a Brazilian citizenship in 1954, which enabled him to leave the country and move to Israel (Freire, 2015).

there are differences between the approach of Bohm and those of a number of other critics of quantum mechanics, they all "agree on one point. It would, in their view, be desirable to return to the reality concept of classical physics, or, more generally expressed, to the ontology of materialism" (Heisenberg, 1955, 17). According to Heisenberg, all these proposed alternative approaches are ultimately unsuccessful:

> ...we see (...) how difficult it is when we try to push new ideas into an old system of concepts belonging to an earlier philosophy, or, to use an old metaphor, when we attempt to put new wine into old bottles. Such attempts are always distressing, for they mislead us into continually occupying ourselves with the inevitable cracks in the old bottles, instead of rejoicing over the new wine. (Heisenberg, 1955, 23).

This paper by Heisenberg has been pinpointed as the text in which the term 'Copenhagen interpretation of quantum mechanics' first appeared (Howard, 2004). Howard argues that Heisenberg introduced this term to establish the idea that there was a broad consensus among physicists on how to interpret quantum mechanics – the Copenhagen interpretation was supposed to be the standard interpretation, on which a large majority of physicists agreed.[2] Heisenberg presented the Copenhagen interpretation of quantum mechanics as a final break with the past, which meant that any criticism of it could be seen as regressive. This attitude is also apparent in an interview Heisenberg gave to Kuhn in 1963, in which he describes his reaction to Schrödinger's attempt to develop an alternative account of quantum mechanics:

> I felt, "Now Schrodinger puts us back into a state of mind which we have already overcome, and which has certainly to be forgotten." (Heisenberg 1963)

Also Pauli felt that alternative approaches to quantum mechanics, including the one of Bohm, were essentially attempts to turn back the quantum revolution and go back to the world view of classical physics:

> Contrary to all reactionary efforts (Bohm, Schrödinger etc. and in a certain sense also Einstein), I am certain that the statistical character of the ψ-function and thereby of the laws of nature (...) will determine the style of the laws for at least a few centuries. It could be that later on, something completely new will be found, for example in connection with the processes of life; but to dream of a way back, back to the classical style of Newton-Maxwell (and they are merely dreams, to which these gentlemen dedicate themselves) seems to me without hope, devious, of bad taste. And, we may add, it is not even a good dream. (Pauli to Born, December 1954, in Von Meyenn (ed.) 1999, 887).[3]

The Russian physicist Vladimir Fock also argued that Bohm and De Broglie were first of all concerned with reconciling quantum mechanics with classical preconceptions, and took particular offence from the fact that Bohm's interpretation restored determinism in physics

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[2] Howard (2004) and Camilleri (2009) have argued that Heisenberg downplayed the fact that there were significant differences between how individual physicists understood quantum mechanics (a fact of which Bohm was very conscious).

[3] "Entgegen allen rückschrittlichen Bemühungen (Bohm, Schrödinger usw. und im gewissen Sinne auch Einstein) bin ich gewiß, daß der statistische Charakter der ψ-Funktion und damit der Naturgesetze (...) den Stil der Gesetze wenigstens für einige Jahrhunderte bestimmen wird. Es mag sein, daß man später, z. B. im Zusammenhang mit den Lebensvorgängen, etwas ganz Neues finden wird, aber von einem Weg zurück zu träumen, zurück zum klassischen Stil von Newton-Maxwell (und es sind nur Träume, denen sich diese Herren hingeben) scheint mir hoffnungslos, abwegig, schlechter Geschmack. Und, könnten wir hinzufügen, est is nicht einmal ein schöner Traum."

(Fock, 1957). He argued that the current quantum theory should not be regarded as final and will be developed further, "but it is already clear today that this development will further depart from classical conceptions and in no case return to them" (Fock, 1957, 656). A solution to the problems still inherent in quantum mechanics "cannot be attained by choosing quotations from the classics, but must be approached in a creative way" (Fock, 1957, 656). Similarly, Rosenfeld (1957, 45) argues in a criticism of Bohm that "the new conceptions which we need will be obtained not by a return to a mode of description already found too narrow, but by a rational extension of quantum theory".

Along with other alternative approaches to quantum mechanics, Bohm's approach was regarded as reactionary and unimaginative in its attempt to turn back the quantum revolution. Although Heisenberg, Pauli and Fock also offered objections to the interpretations proposed by De Broglie and Bohm on the level of physics, they shared the idea that these were attempts to restore the classical ideals of determinism, realism and objectivity, and as such were fundamentally misguided or simply 'bad taste'. This view of Bohm's interpretation of quantum mechanics is one which has persisted, as illustrated by a remark made by Christopher Fuchs in correspondence: "Bohmism is an example of such a dull point of view: If we can just return to the womb of classical physics, everything will be oh so much more warm and comfortable. Yuck!" (Fuchs, 2010, 417).

4. Bohm's philosophical commitments

The characterization of Bohm's account of quantum mechanics as conservative could not have been further from how Bohm himself presented his approach. In the years following the publication of his interpretation, he argued empathically that his aims were *progressive*, that he wanted to move beyond the standard account of quantum mechanics and towards something more radically new.

Bohm emphasized that the interpretation he proposed in 1952 was only a starting point for a more thorough rethinking of the foundations of quantum physics. It showed the possibility of alternative accounts, but was not entirely satisfactory yet and needed to be developed further (Bohm 1957a, 110). Because it did not lead to new predictions, many working physicists found Bohm's interpretation irrelevant, and it came to be labeled as philosophy. However, Bohm intended for his theory to be physics, rather than philosophy. From the very beginning, Bohm was concerned that his interpretation would be dismissed as being merely philosophical: in 1952, he wrote from Brazil to a friend in the US:

> What I am afraid of is that the big-shots will treat my article with a conspiracy of silence; perhaps implying privately to the smaller shots that while there is nothing demonstrably illogical about the article, it really is just a philosophical point, of no practical interest (Bohm, in Talbot ed., 2017, 224).

In the following years, Bohm continued to argue that a further development of his ideas may lead to contradictions with the standard theory of quantum mechanics and thereby to new predictions (Bohm, 1957b). The idea that his interpretation could lead to progress in physics formed a major part of the motivation behind it. In (1957a, 121), Bohm argues that physics is in a state of crisis, and that this legitimizes the search for a radically new approach.[4] The

[4] Talk of a crisis in fundamental physics was common at the time; see e.g. De Broglie (1958), Bunge (1956).

reasons he mentions for why physics is in a state of crisis are not of a foundational or philosophical nature, but are concrete physical problems: physicists have not succeeded in making quantum mechanics compatible with relativity theory, and the so-called elementary particles have turned out not to be elementary after all but can decay and transform into each other and ever more particles are being discovered, which puts the whole notion of 'elementary particles' into question (Bohm 1957a, 121-23). Bohm's aim was thus not to make mere philosophical points about the interpretation of quantum mechanics but to contribute to progress within physics.

Although Bohm's interpretation of quantum mechanics has often been represented as being first and foremost an attempt to restore determinism within the quantum domain, I argue that for Bohm himself, determinism was never the main issue. In his (1951) textbook on quantum mechanics, written before he started working on alternative approaches, Bohm presented what seemed to be a standard account of quantum mechanics, and provided arguments for why determinism has to be given up. Here, he argues not merely that quantum mechanics has forced us to come to terms with indeterminism, but argues moreover that there is no reason to expect a physical theory to be deterministic: the modern idea of determinism is historically contingent and the indeterminism of quantum mechanics is in fact closer to everyday experience (Bohm, 1951, 150-53). It is thus determinism which should be seen as surprising, not indeterminism.

The alternative theory of quantum mechanics which Bohm proposed in (1952a) was indeed deterministic. However, in (1954) Bohm and his coauthor Vigier argued that the quantum potential which plays a central role in this interpretation is not fundamental, but may arise statistically from random fluctuations at a lower level, in analogy with the laws of thermodynamics. Thus, already in this paper, Bohm distanced himself from a strictly determinist view. In (1957a), Bohm expanded on this idea by arguing that the assumption of strict determinism and the assumption of fundamental chance in the laws of nature are equally unsupported: whenever one has deterministic laws of nature, one cannot exclude the possibility that they arise as statistical regularities from underlying chance, and similarly, whenever one has statistical laws of nature, which ascribe probabilities to future events but do not determine them, one cannot exclude the possibility that a more detailed knowledge would reveal exactly how these events are determined. Thus, Bohm objected to the standard interpretation of quantum mechanics insofar as it took chance to be fundamental and excluded the possibility of ever being able to describe the exact trajectories of particles. However, he also argued against a strictly determinist picture. He argued that we can never ascertain that we have arrived at a fundamental level and at a set of laws of nature which hold absolutely; rather, we should suppose that no laws hold absolutely and that it is always possible to probe deeper and arrive at deeper levels of reality in our descriptions of nature.

Thus, if Bohm was ever committed to determinism, it must have been only for a short period of time, between writing the (1951) textbook in which he argued against determinism and his (1954) paper with Vigier in which he modified his theory of quantum mechanics to include random fluctuations. It seems more likely that determinism never was a core commitment for Bohm. A different question is whether Bohm was committed to *causality,* in a broader sense. After all, as Freire (2015, 21) has pointed out, Bohm did choose the term 'causal interpretation' for his interpretation of quantum mechanics (Bohm 1952b, Bohm and

Vigier 1954), which he later abandoned in favor of 'ontological interpretation'. The term 'causality' can have various meanings: it is sometimes used synonymously with determinism, but can also stand for the idea that weaker causal connections are present (e.g., there can be 'statistical causality'). Bohm's correspondences from the period 1950-1954 make clear that he drew a distinction between determinism and causality, and that he distanced himself from the former but not from the latter (Talbot ed., 2017, 164, 255). For Bohm, determinism is connected to a mechanistic point of view, according to which the world is composed of fundamental elements, which are "fixed in nature" and only undergo quantitative change according to fixed laws (Talbot ed., 2017, 172). According to this view, everything that happens is determined through the interactions of these fundamental elements and all change is ultimately quantitative, meaning that nothing really new can ever arise. Bohm argues against this view, and argues for the view that qualitatively new things can emerge at different scale levels, and that we should assume that the number of levels is unlimited. Not only do the lower levels causally affect higher levels, but moreover "there can be a reciprocal influence from a higher to a lower level, which by itself would make impossible a complete analysis of all properties of the higher level in terms of the lower" (Talbot ed., 2017, 171).

The main contrast which Bohm draws between determinism and causality is that causality is a broader concept, which can allow for qualitative as well as quantitative change:

> ...causal laws not only determine the future in a mechanical sense; i.e., in the sense of determining quantitative changes in the arrangements of entities whose intrinsic character is fixed. The causal laws also tell when qualitative changes will occur and may define the characteristics of the new entities that can come into being. Thus, causality is a broader concept than that of mechanical determinism. It contains limited mechanical determinism as a special case (Bohm to Melba Phillips, 1953, in Talbot ed., 2017, 164).[5]

He argues in a letter in 1952 that with the concept of a limitless number of levels of nature "the nightmare of complete determinism is avoided" (Talbot ed., 2017, 254). Bohm thus thought that both the idea that there is fundamental chance and the idea that there are laws of nature which hold absolutely are inacceptable, and that a middle way is possible between absolute determinism and fundamental chance.

Freire (2015, 52) has argued that during the 1950s, Bohm abandoned determinism, and that it is plausible that this development is connected to his break with Marxism which took place during the same period. I think this claim is problematic, for a few reasons. It is true that in this period, Marxism played a major role in Bohm's thought, and that this was not restricted to his political views: he directly connected Marxist philosophy to his work on

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[5] See also the following fragment: "One other point, a distinction between 'determinism' and 'causality'. Although both words have roughly the same meaning, their implications are different. For causality implies (a) that if you know the causes, you can predict the effects. (b) That if you change the causes, you can change the effects in a predictable way. But determinism implies only predictability. In fact, with complete determinism, it would be impossible for us ever to change anything. Now, if there are a finite number of levels, then complete causality obviously implies complete determinism. But if there are an infinite number, then the two concepts part company. For we can have complete causality at every level, in the sense that we can use this causality to change the world in a predictable way, with the error in the predictions dependent only on our level of knowledge; whereas we can in no sense conceive of the world as completely determined. In this connection, note that the statement that new things can come into existence is consistent with causality, only if what is already in existence has an infinite number of levels. For if we have a finite number of causal levels, then the future is already contained logically in the present, but not if we have an infinite number." (Bohm to Miriam Yevick, 1952, in Talbot ed., 2017, 255)

quantum mechanics. It is also true that during the 1950s, Bohm became disillusioned with Marxism, at least on a political level (see Talbot ed, 2017, 67). However, to me it seems that there is no evidence for the claim that Marxism had motivated a commitment to determinism. Bohm was influenced in particular by Engels and Lenin (see Talbot ed., 2017, 23) and was familiar with dialectical materialism, which departs from mechanical reductionism and crude determinism. Bohm's conception of infinite levels of nature can be connected with Lenin's views on the infinity of nature (Talbot ed., 2017, 25-26). Forstner (2008) has argued that after writing his (1952a) paper and moving to Brazil, where he became isolated from his former community, Marxist philosophy became more central to Bohm's thought and helped him develop a dialectical materialist account of causality. Bohm conceived of a dialectic relation between determinism and indeterminism, necessity and chance; these dialectic elements of his view of causality are also expressed in his correspondence with Biederman in the early 1960s (Pylkkänen ed., 1999, 16). This would mean that rather than motivating a determinist view, Bohm's engagement with Marxism helped him develop an account of causality which was not deterministic. That a commitment to Marxist thought can go together with a criticism of determinism is also shown by the fact that both Rosenfeld (1953) and Fock (1957) argue explicitly against determinism from a Marxist or dialectical materialist point of view (see also Cross, 1991).

Thus, it seems that Bohm was never strongly committed to determinism. There is a development in his thought on causality during the 1950s, as he developed his dialectical materialist account of causality, but it is not clear that this development should be understood as a break with earlier philosophical commitments; rather, it seems plausible that Bohm could only gradually develop an account of causality that he was satisfied with, and that the (1952a) paper, in which Bohm proposed a deterministic model, represented an intermediary stage in this development. There is evidence for this account of the development of Bohm's thought in a letter to Miriam Yervick, in which Bohm describes the motivations behind his (1951) textbook on quantum mechanics and how his views had changed since writing it:

> When I started the book, I was in no position to see through the matter, because I still hadn't made complete sense of it. All I knew was that there was one school, which utterly repelled me, in which one was supposed to introduce abstract mathematical postulates, and be satisfied if the calculations agreed with experiment. Against this, Bohr's school seemed to be a big improvement, because at least he tried to explain the physical meaning of the theory. Moreover, there was an element of dialectics in Bohr's point of view which attracted me. It seemed progressive because it broke the old mechanist materialist determinism, which left no room for growth and development of something new. After I had written the book, I finally began to grasp the full meaning of the theory, and could see that it leads inevitably to a form of (dialectical) idealism.
> (...) Now with my new point of view, I can see an infinitely better way to get out of the trap of mechanistic determinism; namely through the concept of an unlimited number of causal levels. (Bohm to Miriam Yervick, 1952, in Talbot ed., 2017, 235).

It is true that by the early 1960s, Bohm abandoned his (1952a) interpretation of quantum mechanics in search of a more radically new account, but there seems to be little evidence that this should be understood as a break with causality; rather, he seems to have been disillusioned by the lack of positive reception of his theory and by the lack of concrete results. In later years, dialectical materialism becomes less apparent in Bohm's writings. By the

1990s, Bohm preferred the term 'ontological interpretation', over 'causal interpretation', to refer to his interpretation of quantum mechanics (Bohm and Hiley, 1993, 2). However, I think it is also not clear that this indicates a break with his earlier philosophical commitments and is merely a difference of emphasis.[6] Bohm never abandoned causality in a broader sense: he never came to accept pure chance, and always sought to develop an understanding of how things came about.

Bohm often emphasized the need to be able to imagine quantum processes: already in his (1951) textbook on quantum mechanics, he criticizes the tendency of physicists to think that "the quantum properties of matter imply a renunciation of the possibility of their being understood in the customary imaginative sense" (Bohm, 1951, iii). He writes that his aim is to develop such an imaginative understanding of quantum physics, and that this is possible in particular through a development of the ideas of Niels Bohr (Bohm, 1951, iii). The alternative interpretation which he developed soon after seems to have been motivated by the feeling that he had not succeeded after all in this aim, and that, to actually understand what happens at the quantum level, a new interpretation is needed:

> The usual interpretation of the quantum theory can be criticized on many grounds. In this paper, however, we shall stress only the fact that it requires us to give up the possibility of even conceiving precisely what might determine the behavior of an individual system at the quantum level, without providing adequate proof that such a renunciation is necessary. (Bohm, 1952a, 168).

He writes furthermore that "our suggested new interpretation provides a consistent alternative to the usual assumption that no objective and precisely definable description of reality is possible at the quantum level of accuracy" (Bohm 1952a, 188). Bohm objects especially to the fact that in the conventional interpretation of quantum mechanics, there is a strict limit to the extent to which nature can be understood and analyzed. Bohm argues that these limitations are not justified and that it would be desirable to have a more detailed understanding of quantum processes; moreover, to deal with current problems in quantum physics it may be needed to speculate about a sub-quantum level, at which the laws of quantum mechanics breaks down and there are qualitatively different types of laws.

Since Bohm was concerned with developing an ontological account of quantum processes, one may conclude that Bohm's actual concern was with realism, rather than with determinism. And one may conclude that therefore, Bohm's case is similar to that of Einstein. Einstein's opposition to quantum mechanics has often been summarized by the sentence "God does not play dice", which suggests that he primarily objected to the indeterminism of quantum mechanics. Like Bohm, Einstein's concerns with quantum mechanics were often regarded as stemming from an attachment to outdated classical ideals, in the first place determinism. It helped that Einstein already belonged to an older generation: the caricature is

[6] In the introduction to *The Undivided Universe*, Bohm and Hiley write that they prefer the term 'ontological interpretation' over 'causal interpretation' and that the theory they propose does not have to be deterministic: "The question of determinism is therefore a secondary one, while the primary question is whether we can have an adequate conception of the reality of a quantum system, be this causal or be it stochastic or be it of any other nature" (Bohm and Hiley, 1993, 2). When they speak about causality in more detail, later in the book, the views expressed are similar to those in (1957a): whenever there is determinism, there can be underlying chance and vice versa, and "ultimately our overall world view is neither absolutely deterministic nor absolutely indeterministic" (Bohm and Hiley, 1993, 324).

that of an old man who has been a revolutionary in his days, but is no longer able to keep up with new developments. However, also for Einstein, it has been argued that this image is not correct, that determinism was only a secondary issue and that his actual concerns with quantum mechanics went deeper (see e.g. Fine 1986, Howard 1993, Paty 1995). The claim that both Bohm and Einstein were primarily concerned with the possibility of giving a realist account of quantum phenomena, rather than with restoring classical determinism, however, requires a closer analysis of what realism exactly means in their cases. And such an analysis reveals significant differences. According to Howard (1993), what Einstein means when he says that he wants to hold on to what is real is the idea that what exists in one part of space is independent of what exists in other parts of space:

> ...that which we conceive as existing ("actual") should somehow be localized in time and space. That is, the real in one part of space, A, should (in theory) somehow "exist" independently of that which is thought of as real in another part of space, B. If a physical system stretches over the parts of space A *and* B, then what is present in B should somehow have an existence independent of what is present in A. (Einstein to Born, 1948, quoted in Howard, 1993, 234).

Howard calls this the "separability principle". This principle was behind the argument presented by Einstein, Podolsky and Rosen (1935), to argue that quantum mechanics is incomplete: the argument essentially shows that this principle of separability is violated in quantum mechanics. According to Howard, this was Einstein's main objection to quantum mechanics, together with the principle of nonlocality which states that there can be no superluminal signals. Einstein was committed to the separability principle because he thought that if we cannot divide nature into parts which exist independently of each other, science becomes impossible (Howard, 1993, 239). Howard gives two reasons why, for Einstein, this separability principle is linked to the idea that physics describes an independent physical reality: first, the separability principle is required to arrive at an ontology and thus to be able to say what there *is*, and secondly, the idea that there is a mind-independent external world requires a separation between mind and external world, and between the observer and the observed. (The account given here of Einstein's views on quantum mechanics is necessarily limited; for more details see Fine 1986, Howard 1993 and Paty 1995).

If Einstein's commitment to separability can be taken to be a form of realism (a question which Howard leaves open), then in this particular sense, Bohm was never a realist. In fact, throughout his entire career, Bohm's primary philosophical commitment was to 'wholeness' and nonseparability. In his (1951) textbook on quantum mechanics, Bohm argues that quantum mechanics goes against the assumption

> ...that the universe can correctly be regarded as made up of distinct and separate parts that work together according to exact causal laws to form the whole. In the quantum theory, we have seen that none of the properties of these "parts" can be defined, except in interaction with other parts and that, moreover, different kinds of interactions bring about the development of different kinds of "intrinsic" properties of the so-called "parts". It seems necessary, therefore, to give up the idea that the world can correctly be analyzed into distinct parts, and to replace it with the assumption that the entire universe is basically a single, indivisible unit. (Bohm, 1951, 139-40).

Bohm furthermore notes that the assumption that nature can be divided into parts is the basic assumption behind the mechanistic world view, and in this way quantum mechanics directly goes against mechanism. He notes in a footnote: “This means that the term ‘quantum mechanics’ is very much of a misnomer. It should, perhaps, be called ‘quantum nonmechanics’.” (Bohm, 1951, 167). The alternative interpretation of quantum mechanics which Bohm proposed soon after went against the standard account he had presented in (1951) in significant ways, but it preserved the nonseparable aspect of quantum mechanics which Bohm saw as its central feature.

The nonlocality of Bohm’s theory of quantum mechanics became more clear and explicit after the development of Bell’s theorem in 1964, but nonlocality was already part of Bohm’s (1952a) theory from the beginning. In Bohm’s interpretation, the movement of particles is guided by a quantum potential, which depends on the system as a whole and does not generally vanish at large distances: therefore, two systems which are far removed from each other can instantly affect each other. Moreover, although each particle has a well-defined position at all times, other properties usually attributed to particles, including momentum, depend on the larger context in which the particle is embedded and cannot be ascribed to individual particles. According to Bohm, any division of nature into parts is therefore always an idealization; at a more accurate level, nature is indivisible. This commitment to wholeness persisted throughout Bohm’s entire career; in Bohm and Hiley (1993) we find:

> The relationship between parts of a system described above implies a new quality of *wholeness* of the entire system going beyond anything that can be specified solely in terms of the actual spatial relationships of all the particles. This is indeed the feature which makes the quantum theory go beyond mechanism of any kind. For it is the essence of mechanism to say that basic reality consists of the parts of a system which are in a preassigned interaction. (...) We emphasize that *this is the most fundamentally new aspect* of the quantum theory. (Bohm and Hiley, 1993, 59)

Thus for Bohm and Einstein, different things were ultimately at stake. Bohm was committed to the possibility of imagining what goes on at the quantum and the sub-quantum level and forming hypotheses about this, and was not content to merely talk about measurement outcomes; in this sense, he can be called a realist. But he did not share to Einstein’s assumption that nature can be divided into separately existing parts. On this basis it could perhaps be argued that Einstein was more ‘classical’ than Bohm, insofar as division into parts can be linked to the classical idea of mechanism. However, it seems that Einstein thought that in other respects, Bohm’s theory was too classical. Having originally encouraged Bohm to work on an alternative version of quantum theory, Einstein was not satisfied with the result presented in Bohm’s (1952a) paper, remarking in a letter to Born that he thought Bohm’s interpretation was “too cheap” (Freire, 2015, 44). Fine (1986) argues that Einstein never showed much interest in the ideas developed by De Broglie and Bohm because they were formulated in terms of classical concepts such as position and momentum, wave and particle; according to Einstein, the way to arrive at a quantum theory based on proper foundations was to develop a new conceptual scheme for the quantum domain.

However, in this regard, Bohm was actually fully in agreement with Einstein, at least from the mid-1950s onwards. Like a commitment to ‘wholeness’ and the need for an imaginative understanding of quantum processes, also the idea that quantum mechanics requires the development of new conceptual insights is a thread that can be found throughout Bohm's career. Already in the preface of his (1951) book on quantum mechanics, Bohm writes: "It is not generally realized (...) that the quantum theory represents a radical change, not only in the content of scientific knowledge, but also in the fundamental conceptual framework in terms of which such knowledge can be expressed" (Bohm, 1951, iii) The main conceptual changes brought by quantum mechanics were, according to Bohm, the replacement of continuous trajectories by discontinuous transitions, the replacement of determinism by statistical trends, and the idea that nature cannot be divided into distinct parts. After finishing the book, he came to think that these changes did not go deep enough, and he devoted much of his further life to developing more radical conceptual changes. In (1957a), Bohm expressed dissatisfaction with the interpretation he had proposed in (1952a), arguing that it was a promising starting point but still needed to be worked out further; in particular, Bohm thought that the central concepts in the theory, especially those of 'wave' and 'particle', were still too classical (Bohm 1957a, 127). Bohm thought it was more plausible that wave and particle were "both aspects of some fundamentally new kind of entity which is likely to be quite different from a single wave or a single particle, but which leads to these two limiting manifestations as approximations that are valid under appropriate conditions" (Bohm 1957a, 117-18). From the early 1960s onwards, Bohm actively worked on developing new concepts for the quantum domain: in particular, he proposed to replace Cartesian coordinates of space and time with topological relations (Bohm 1962). His attempt to develop a more radically new account of quantum physics led him to abandon his original interpretation, to which he only returned in the late 1970s.

To Bohm's philosophical commitments can be added the idea of the unlimited complexity of nature, which already occurs in (Bohm 1952a, 189) and which became a central issue in his later work. In (1957a), Bohm presents a model of science according to which there are different levels of reality, e.g. the classical, the quantum and the sub-quantum level. As science progresses, we can reach deeper levels in our descriptions of nature. There is no reason to suppose that there is a fundamental level; rather, we should suppose that nature is inexhaustibly rich and complex, and that there are always deeper levels. None of the levels can be regarded fully in isolation: no level is fully closed off from effects arising from other levels. This means that we can never assume that a law of nature holds absolutely and universally: any law of nature will only hold approximately and will have a limited domain of application, beyond which it will break down.

Most of all, Bohm was committed to the idea that science is open-ended, that we should always attempt to dive deeper into the complexities of nature and reveal new levels of reality and new relations between them. This is in stark contrast with his portrayal as a conservative and reactionary.

5. The rhetoric of the debate

We have seen that both Bohm's and Einstein's concerns with quantum mechanics were often understood as an unwillingness to accept the indeterminism of quantum mechanics, but that their actual concerns went deeper. Beller (1999) argues that there has been a tendency to see all opposition to the standard interpretation of quantum mechanics as an attachment to determinism in science (another example is Schrödinger – see Ben-Menahem, 1989). Beller argues that because determinism was strongly associated with the past period of classical physics, emphasizing the indeterminism of quantum mechanics as its central feature and interpreting the opposition to quantum mechanics as an opposition to indeterminism made it possible to portray opponents as conservative:

> The ideas of the opposition are projected as most characteristic of the overthrown past. In this way opponents are automatically presented as conservatives; disposing of the old and discrediting opponents go hand in hand. (Beller, 1999, 281).

But the accusations of conservatism went both ways. Bohm's *Causality and Chance in Modern Physic*s (1957a) seems to be written with the purpose of arguing that he was not the conservative person in the debate: not only did he emphasize the progressiveness of his views, but he went as far as arguing that it were actually his opponents who were dogmatically attached to classical ideals. Bohm argues that after having established that quantum mechanics only yields statistical predictions for measurement values, quantum physicists have come to the agreement that "there is nothing in the universe that will not eventually be found to fit into [their] scheme, the general features of which are thus regarded as absolute and final" (Bohm, 1957a, 102). However, according to Bohm, the assumption that the indeterminacy of quantum mechanics is final is just as unjustified as the assumption that classical determinism holds absolutely – in both cases, the possibility that future developments will lead to changes in the theoretical framework is excluded. Bohm argues against this finality on two main grounds: it is not in agreement with the history of science, which shows that scientific theories can thoroughly change over time, and it goes against proper scientific method, since scientists should always be open to the possibility of further development. Bohm sees assumptions of finality as characteristic for the framework of classical physics. He therefore argues that, although quantum physicists have abandoned classical determinism, they still retain the central feature of classical mechanism through their assumptions of finality of their current theory (Bohm, 1957a, 63), and that therefore his opponents (in particular Heisenberg) are the real conservatives.

In contrast to this perceived conservatism in physics, Bohm argues for the need to develop radically new concepts and theories, especially in the light of the present crisis in physics (Bohm, 1957a, 121-22). He writes that like most late-nineteenth century physicists thought that the problems that arose at that time in physics (Kelvin's famous "two clouds on the horizon") could be dealt with by merely changing the details of their (deterministic) theories, unaware of the revolutions in physics that were ahead, so most current physicists "feel that the present crisis in physics will be resolved by revisiting the details of the general kinds of probabilistic theories that are now current" (Bohm 1957a, 103). Bohm, however, thinks that more thoroughgoing change is needed, basically calling for a new revolution and for developing a theory dealing with a sub-quantum level.

To a certain extent, Bohm succeeded in portraying himself as progressive and his opponents as conservative. In 1957, Bohm was invited to give a talk at the Ninth Symposium of the Colston Research Society in Bristol, which brought together physicists and philosophers to talk about foundational issues in quantum physics. Bohm gave a general introduction to his account of quantum mechanics, which was followed by a talk by the Belgian physicist Léon Rosenfeld. Rosenfeld gave a very dismissive criticism of Bohm: rather than going into the details of Bohm's interpretation and pointing out specific problems with it, Rosenfeld argued that all attempts at giving alternative interpretations of quantum mechanics are misguided in principle, and even argued against the very idea that there could be different interpretations of quantum mechanics.[7] Rosenfeld's talk was not received very positively: even relatively conservative physicists, who were generally not in favor of Bohm's approach, thought that Rosenfeld's criticism of it was too dogmatic and that there should be some space for speculation within physics. In the discussion which followed, Bohm successfully profiled himself as a progressive thinker, willing to explore new ideas, in contrast to Rosenfeld who came off as more dogmatic. Koznjak (2018) has argued that the event had an unexpectedly positive outcome for Bohm, and meant a turn in the reception of his interpretation of quantum mechanics – even if many participants were not convinced that Bohm's account of quantum physics was the right one, they at least came to think that looking for alternative interpretations was a legitimate enterprise.

Rosenfeld, however, continued to argue that Bohm's position was dogmatic and conservative. The next year, he published a review of Bohm's *Causality and Chance in Modern Physics* in *Nature*, in which he argues that Bohm's attempt to find a position in between determinism and indeterminism is not convincing and that the program of Bohm and like-minded physicists is motivated by a "metaphysical prejudice" of determinism, despite all the scientific evidence which shows that determinism does not hold in the quantum domain:

> That such irrational dogmatists should hurl the very accusation of irrationality and dogmatism at the defenders of the common sense, uncommitted attitude of other scientists is the crowning paradox which gives a touch of comedy to a controversy so distressingly pointless and untimely. (Rosenfeld, 1958).

The Colston symposium was not the only occasion at which Bohm successfully portrayed himself as progressive: a similar outcome can be observed in a series of discussions on quantum physics broadcast by the BBC in 1961, of which the contributions were published the following year in a small volume titled *Quanta and Reality* (Bohm et al, 1962). It features a discussion between Bohm and Maurice Pryce, Bohm's head of department in Bristol and one of the organizers of the above-mentioned Symposium in 1957. Pryce starts their discussion with the remark "In this discussion, I seem to stand for orthodoxy and you for unorthodoxy – that's fair, isn't it?" (Pryce, in Bohm et al, 1962, 61). In the following discussion, Pryce raises the objection that Bohm's concerns seemed of merely philosophical interest. In reply, Bohm argues: "if we have a situation where people are discouraged (...) from entertaining new ideas because they may be philosophical, this may impede the progress of physics" (Bohm et al, 1962, 70).[8] The publication includes a postscript by the philosopher of science N. R. Hanson, of which the main purpose seems to be to make sure that Bohm's open and anti-dogmatic rhetoric does not mislead the reader into thinking that Bohm's position is more reasonable. According to Hanson, the alternative which Bohm offers to

[7] Rosenfeld in fact objected to the interpretation 'Copenhagen interpretation of quantum mechanics' because it gave the false impression that more than one interpretation was possible (Rosenfeld 1960, 831). Later, in correspondence, he remarked about the Copenhagen interpretation: "there has never been any such thing and I hope there will never be. The only distinction is between physicists who understand quantum mechanics and those who do not." (Rosenfeld to Belinfante, 1972, quoted in Freire, 2015, 82).

[8] Bohm argued furthermore that every physicists works with philosophical preconceptions and that when physicists are not aware of the preconceptions they have, they can be limited by them in the sense of being unaware of other possible ways of thinking (Bohm et al, 1962, 71).

orthodox quantum mechanics is vague, speculative and not very well developed, and it is better to stick with the orthodox theory as long as there is no convincing alternative. He gives the following characterization of the debate between orthodox physicists and 'heretics' such as Bohm and Vigier:

> The standard pattern of this controversy is that the orthodox find the Bohm-Vigier suggestions vague, speculative, shy of numbers and hence an object of scorn. These heretics are stigmatized as 'mere philosophers'. This is the ultimate insult among physicists. The heretics tend to react sharply to what seems like legislation from senior science-dictators... people who, in defiance of history, presume to prescribe what will and will not count as respectable programmes of future physical research. These 'dictators' are themselves the very men who grappled with the conceptual restraints of classical physics and reinstituted a freedom of scientific thought which is reminiscent of the seventeenth century; and how it galls *them*, above all others, to be called 'dogmatic'. (...)
> Very often the heretics appear to come out of these discussions mantled in rationality, glowing with philosophical insight, steeped in historical perspectives and perspicuous for their intellectual boldness. In contrast, the great ranks of orthodoxy seem reactionary and dull – adhering to the last generation's conjectures as if they were laws of thought, despite reason, philosophy and all the lessons of history. (Hanson, in Bohm et al 1962, 89-90)

Thus, after being criticized for being dogmatic, Bohm succeeded to some degree in turning the tables around and establishing himself as a progressive thinker who went against orthodoxy. Meanwhile, he continued to pursue new ideas. By the mid-1960s he had mostly abandoned his (1952a) interpretation of quantum mechanics, and focused on developing a new account of quantum physics based on a discrete space-time structure and topology (see Freire 2019, 151-52); however, he returned to his original approach in the 1970s.

We have seen how central the themes of dogmatism and revolution were in the debates surrounding Bohm's interpretation of quantum mechanics. Both sides of the debate accused each other of being dogmatic and conservative; terms like 'classical', 'deterministic' and 'mechanistic' were polemical terms, almost used as accusations. At both sides of the debate, being open to revolutionary change seems to have been the highest ideal. There seems to be a meaningful contrast here between debates on the foundations of quantum mechanics in the 1950-60s and nowadays: in recent philosophy of quantum physics, it often seems that the ultimate aim is to minimize counter-intuitiveness and maximize the recovery of classical intuitions. But at the time when Bohm developed his theory of quantum mechanics, there seems to have been a widespread conviction, shared by both Bohm and his opponents, that restoring classical intuitions was not the right approach.

6. Bohm's engagement with philosophy of science: Feyerabend and Kuhn

Given the centrality of the themes of dogmatism and revolution in the reception of Bohm's theory as well as in his own rhetoric, it comes as no surprise that Bohm was highly interested in Kuhn's *Structure of Scientific Revolutions*, which appeared in 1962. As I will show in this section, Bohm thought that Kuhn's ideas were very valuable, but was critical of Kuhn's concept of 'normal science', during which there is a consensus about the main theories and practices within a domain and no questions are raised about foundational issues. Bohm's objections to the idea that this is (and should be) the normal state of science are similar to those of Feyerabend, and this is not a coincidence. Bohm and Feyerabend knew each other well: in 1957-58, they were both in Bristol and spent a lot of time discussing physics and philosophy together. Bohm's biography contains the following anecdote:

> Feyerabend was struck by the intensity of Bohm's discussions. On one occasion Bohm called at Feyerabend's home, walked into the living room, and took off his raincoat, all the while enthusiastically discussing philosophy, only to find that Feyerabend was not home! (Peat, 1997, 187-88)

At the time, Feyerabend was a relatively unknown philosopher of science, who specialized in the philosophy of quantum physics. His encounters with Bohm left deep traces: through his interactions with Bohm, Feyerabend became convinced that it would be worthwhile to look for alternative accounts of quantum mechanics, and that the physics community was dogmatically closed to such alternatives. This was an essential step in the development of Feyerabend's pluralist philosophy of science (Van Strien 2019). Moreover, Feyerabend developed his arguments for scientific pluralism in dialogue with Bohm: he specifically acknowledged Bohm's role in developing the argument that developing alternatives to an established theory is essential for testing this theory (Feyerabend 1965, 153; Feyerabend 1993, 262; and see Van Strien 2019). Arguments for pluralism can also be found in Bohm's writings; in (1961), Bohm had argued that also scientific methods can be subjected to change, and that under certain circumstances, it can become unclear how methods should be applied.[9] And in (1966), Bohm and his coauthor Bub argue that "there is a very important methodological justification for the consideration of hidden variable theories, even those which are not necessarily seriously regarded as 'right' ones", namely that the current language of quantum mechanics makes certain types of questions impossible.

> As long as we use this language, no experiment is ever likely to be devised that could conceivably refute the basic postulates of quantum mechanics and thus in principle provide a test of these postulates. We shall always search for energy levels, scattering probabilities, magnetic moments, etc. (Bohm and Bub, 1966, 458)

Through developing hidden variable theories, it may be possible to develop a new language for quantum mechanics, and this may make it possible to ask different types of questions and may open up new experimental possibilities for testing (and possibly falsifying) the basic postulates of quantum mechanics (Bohm and Bub, 1966, 458). If the current theory of quantum mechanics is not challenged through alternative points of view, this "might lead to our being trapped in a given set of concepts, without our even realizing that we are thus trapped" (Bohm and Bub, 1966, 458).

For Feyerabend, his conviction of the importance of developing alternative theories was a reason to object to Kuhn's conception of normal science, which is characterized by consensus and an uncritical adherence to an established framework. In 1961, Feyerabend commented on a proof of the *Structure of Scientific Revolutions*, and harshly criticized Kuhn's account of normal science. He argues that Kuhn's idea that there should only be one paradigm

[9] Bohm (1961) moreover criticized Popper's falsificationism by arguing that as long as one stays within a certain framework, it is possible to determine whether a hypothesis has been falsified or not, but if the framework itself is in question or being transformed, then the question under which circumstances a hypothesis would be falsified can become unanswerable. This objection is related to the evidential holism of Duhem and Quine, which states that a hypothesis cannot be tested in isolation. For Bohm's relations with Popper, see also Del Santo (2019).

at the time is damaging to science, because insisting on a single paradigm eliminates important tests; and this may be what it happening in current quantum mechanics:

> Your insistence upon faithfulness to one and only one paradigm is bound to result in the elimination of otherwise very important tests and it is bound in this way to reduce the empirical content of the paradigm you want to be accepted. It may well be – and Bohm and Vigier are definitely of this opinion – that the situation is the same in the present quantum theory. The 'orthodox' refuse considering alternatives and their argument is that the present point of view has not yet encountered anomalies which would necessitate reconsideration of it in its entirety. Bohm points out that the limitations of the present point of view will become evident only if one has first introduced an alternative and shown that it is preferable. Hence if the absence of limitations is taken as a reason for not considering alternatives, then trouble will never be discovered, simply because it could be discovered only with the help of alternatives. This, then, would make the present quantum theory a wonderful metaphysics. (Feyerabend in Hoyningen-Huene 1995, 365)

Kuhn himself seems not to have commented much on the issue of alternative interpretations of quantum mechanics, at least not publicly. However, he indeed seems to have thought that in this case, it is better to stick with 'normal science', that is, the standard interpretation of quantum physics. In (1970b, 246), Kuhn briefly remarks that he thinks Bohm's pursuit of an alternative theory of quantum mechanics is "almost certain to fail", since scientific progress generally takes place through working on technical problems within a theory, rather than through actively pursuing alternative theories. Moreover, he seems to have shared the image of Bohm as a conservative physicists: in his *Structure of Scientific Revolutions*, he mentions Bohm as an example of someone who is unwilling to accept scientific change and holds on to superseded ideas (Kuhn, 1970a, 163).

Bohm, however, valued Kuhn's ideas on scientific revolutions: in a review of Kuhn's *Structure of Scientific Revolutions*, Bohm called it "without a doubt one of the most interesting and significant contributions that has been made in recent years in the field of the history and philosophy of science" (Bohm 1964, 377). After a brief summary of Kuhn's ideas, he ends his review with: "In addition, it may be worthwhile for scientists to try to become aware of the role that paradigms actually play in the life of scientific research in order that they shall be able more easily to realize the need for a change of Gestalt, when a particular field of study has been characterized by general confusion for some time" (Bohm 1964, 379). For Bohm, a main value of Kuhn's work is that it explains the tendency of scientists to stick to a certain framework; becoming aware of this tendency is helpful in avoiding dogmatism (see also Bohm 1968).

However, in (1974), Bohm argues that, although scientists tend to stick to their basic framework, the idea that there are periods of 'normal science', during which no essential changes take place, is an illusion. Scientists tend to regard their basic framework as permanent and unchangeable, and tend to be unaware of the degree to which it develops over time and of the divergences between the views of different scientists.[10]

[10] In making this argument, Bohm was likely motivated by the fact that many physicists thought that since Bohm's interpretation of quantum mechanics yielded no new predictions, it was not essentially different from the standard interpretation: notably Heisenberg argued that Bohm's interpretation offered mere "ideological superstructure" and brought nothing new to physics (Heisenberg 1958, 117).

In *Science, Order and Creativity,* Bohm and his co-author Peat argue that Kuhn's paradigms are harmful for science: "a paradigm tends to interfere with that free play of the mind that is essential for creativity" (Bohm and Peat 1987, 52). Bohm and Peat argue that in any stage of science, scientists should be prepared to give up their preconceived notions and change their basic conceptions:

> In many cases, however, this sort of response does not actually take place and scientists attempt to press on by putting "new wine in old bottles." But why should this be? The answer to this question involves a psychological factor, the mind's strong tendency to cling to what it finds familiar and to defend itself against what threatens seriously to disturb its overall balance and equilibrium. Unless the perceived rewards are very great, the mind will not willingly explore its unconscious infrastructure of ideas but will prefer to continue in more familiar ways. (Bohm and Peat, 1987, 22)

The phrase "new wine in old bottles" is a clear reference to the criticism which Heisenberg directed at Bohm, three decades earlier (see section 3), showing again how deeply Bohm was affected by the criticisms and lack of positive reception of his theory. Bohm and Peat argue that scientists should be open to change their preconceptions and actively pursue new ideas, and note that if scientist would work in this manner, this would lead to pluralism in science:

> ...at any given moment, there would be a number of alternative points of view and theories available in each particular area of science.
> Traditionally scientists have assumed that when several theories appear to account for the same phenomenon, then only one of them can be correct. (....)
> There is no logical reason, however, why, in the unfolding of scientific ideas, several theories may not offer alternative but equally valid and important accounts of a particular aspect of nature. (Bohm and Peat, 1987, 54).

Bohm and Peat thus come close to the Duhem-Quine thesis of underdetermination of scientific theories, which states that there can be several theories accounting for the same empirical evidence. In the case of quantum mechanics, this pluralism would mean that Bohm's interpretation can be considered as one among several possible interpretations of quantum mechanics, without the need to immediately narrow down the options and choose one interpretation as the 'right' one; Bohm strategically argues for a creative dialogue between diverse interpretations of quantum mechanics (Bohm and Peat 1987, 100).

7. Was Bohm really a realist?

Bohm's arguments for pluralism raise the following question: can we assume that after some period of time, a consensus will be reached? Can scientists, after a period of openness and creative dialogue, come to agree on a single theory, which can then be regarded as an approximately true description of reality, or will there always be a plurality of different views?

This question is relevant because it concerns the question of whether and in what sense Bohm can be regarded as a realist. As we have seen in section 4, Bohm aimed to develop an imaginative, ontological account of what happens at the quantum level. In current philosophy

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This paper by Bohm was presented at a symposium in 1969 on the structure of scientific theories, organized by Frederick Suppe; the discussion, in which also Kuhn participated and reacted to Bohm's paper, is printed in Suppe (1974). See also Freire (2019), 148-50.

of physics, possibly following Bell, Bohm's account of quantum mechanics is often first and foremost presented as a realist one, as it enables a full description of quantum processes and does not involve a restriction to measurement outcomes. It is thus realist in the sense of going beyond observable phenomena. However, scientific realism is often defined in terms of approximate truth of theories: a realist presumes that the current best theories can be regarded as approximately true, and that theories come closer to truth as science progresses[11] – and realism in this sense may be hard to reconcile with Bohm's insistence on always developing radically new ideas and concepts, breaking through paradigms and considering different possible accounts. If there can really be several distinct but equally valid theories which describe a range of phenomena, it seems they can't all be (approximately) true, and there seems to be no basis for singling out just one of them as (approximately) true.[12] Can Bohm's theory be regarded as providing a description of *what actually happens* at the quantum level, when it is merely one among several possible interpretations?

One may think that Bohm's insistence that he did not intend to propose a definitive theory of quantum mechanics but merely a possible one, and that above all, he thought that there should be more room for discussing alternative points of view, was merely rhetorical, and that he was more attached to his own interpretation of quantum mechanics than he admitted. Although I think it is probably true that Bohm was more attached to his own interpretation than he tended to admit, I want to argue that he was not a realist in the sense of taking scientific theories to offer approximately true descriptions of reality – although he did think that scientific theories get *something* right.

According to Bohm, Kuhn's account of paradigms show that scientists always work within a certain framework and with certain habits of thought, and therefore scientific theories and scientific facts depends on the scientist as well as on nature.[13] In (1980, 4), Bohm writes: "it might be said that a theory is primarily a form of insight, i.e. a way of looking at the world, and not a form of knowledge of how the world is." Already in (1957a), Bohm argues that scientific theories hold only approximately and within a restricted domain: as science progresses, its reach extends and it becomes possible to deal with deeper levels of reality, but we should not assume that we will ever reach a fundamental level, and therefore we should not assume that science progresses towards some final theory. Since nature is infinitely complex, we can always probe deeper and find out that our best theories are only approximations emerging from a deeper level, at which different types of laws of nature hold. In this sense, "there is no point in the effort to get closer to ultimate truth" (Bohm 1974), and we should rather expect never-ending change.

However, although scientific theories should not be taken to directly correspond with reality, they do get something right, in the sense that they offer reliable predictions within their proper domain. "The ultimate reality is unlimited and unknown, but its successive appearances serve as an ever more accurate guide to coherent action in relation to this reality"

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[11] See e.g. Van Fraassen (1980, 8), who defines realism in terms of truth of theories.

[12] For an attempt to reconcile pluralism and realism, see Chang (2017).

[13] "It follows from the above that facts are not like things that exist in nature independently of man, so that they can, so to speak, be gathered as if they were stones or flowers. Rather, as the derivation of the word indicates, they are *made* (or manufactured). In this regard, nature may be compared to the raw material, while the fact is a finished product, having a form determined in part by man. Like a pair of shoes, for example, the fact reflects both the material (i.e. nature) and the process by which it was made." (Bohm, 1961, 106).

(Bohm and Hiley 1993, 323). Scientific theories remain approximately valid within their domain, and even though scientists can always develop new theories, these new theories will contain the older ones in some way. And even though there may be different theories which deal with the same domain, they must make more or less the same predictions, despite providing different ontological pictures.[14]

Realism is also often defined as the statement that science deals with an independent reality. For example, Chakravartty (2017) writes that "Metaphysically, realism is committed to the mind-independent existence of the world investigated by the sciences". The issue here is not just whether an external world exists; more often, the debated issue is whether we can have knowledge of the world which is independent of our perceptual apparatus and theoretical assumptions (Chakravartty, 2017). Also in this sense, it is hard to bring Bohm's views in line with a realist conception. In particular, Bohm did not think that there can be a separation between ourselves and the world. It is usually taken to be one of the most appealing features of Bohm's theory that it can deal with the measurement problem. This makes it possible to argue against the idea that the observer plays an active role in creating the reality it observes, which is often taken to follow from quantum mechanics. However, it is remarkable that the measurement problem does not play a big role in Bohm's writings. In most of Bohm's writings from the 1950s, 1960s and 1970s, the issue of measurement is in fact hardly mentioned (an exception is Bohm and Bub, 1966).[15] And in Bohm's writings of the 1980s, Bohm actually seems to argue that his theory of quantum mechanics supports the view that the observer plays an active role in creating the reality it observes. He argues that in his theory of quantum mechanics, measurements do not reveal intrinsic properties of the system under observation, and that "there is mutual and irreducible participation of the measuring instrument and the observed object in each other" (Bohm and Hiley 1993, 97).

In Bohm's account, the process of measurement can be described exactly; moreover, each particle has a well-defined position at all time, so it is not the case that particles only obtain a well-defined position through the act of measurement. However, the same does not hold for momentum, spin, or any variables other than position – in these cases, although the measurement process can be described exactly, the measured value does not reveal a property of the particle which it already had before measurement, but depends on the entire experimental setup. In contemporary accounts of Bohmian mechanics, this is taken to mean that the only intrinsic property of Bohmian particles is their position. All other variables are contextual: they cannot be ascribed to a single particle but depend on the experimental arrangement as a whole. However, Bohm drew much stronger conclusions and argued on this basis that generally, in his account of quantum mechanics, measurements do not reveal intrinsic properties of the observed system:

[14] For this reason, Feyerabend argued that Bohm's philosophical standpoint is "traditional, and perhaps even reactionary" (Feyerabend 1960, 322). Feyerabend objects to the idea that theories will continue to hold within their domain, and argues that in Bohm's view, no statement that anyone ever held can be completely wrong.

[15] In fact, Freire (2015, 142-55) has argued that the measurement problem only started to be established as the central problem in quantum foundations in the 1960s. Bohm objected to Von Neumann's account of measurement, which involved wave collapse; however, he thought that Bohr's account of measurement based on complementarity was on the right track, but objected that it did not provide a full understanding of the measurement process. Bohm's theory of quantum mechanics in (1952a) thus aimed to supplement Bohr's account.

> ...the key new feature here is that of the undivided wholeness of the measuring instrument and the observed object, which is a special case of the wholeness to which we have alluded in connection with quantum processes in general. Because of this, it is no longer appropriate, in measurements to a quantum level of accuracy, to say that we are simply 'measuring' an intrinsic property of the observed system. Rather wat actually happens is that the process of interaction reveals a property involving the whole context in an inseparable way. Indeed it may be said that the measuring apparatus and that which is observed *participate irreducibly* in each other, so that the ordinary classical and common sense idea of measurement is no longer relevant. (Bohm and Hiley 1993, 6)

In Bohm and Hiley (1993), position is treated rather as an exception to the rule that measurements do not reveal intrinsic properties. This fits well with Bohm's deep-seated commitment to 'wholeness' (see section 4), according to which no two things can ever really be separated. He argues that no sharp distinction is possible between measurement apparatus and the system under observation, or between us and the world.

Recall that for Einstein, the idea that physics describes an independent physical reality is directly connected to the idea that nature can be divided into parts which exist independently of each other, and to the idea that there is a separation between the observer and the observed. Bohm argues strongly against these conditions. And it seems that for Bohm, the fact that we cannot really separate observer from observed is related to the fact that science cannot describe reality as it really is. For example, Bohm and Peat (1987) argue that although science deals with an external reality, this reality cannot be regarded as independent of us, and scientific knowledge is therefore neither fully objective, nor fully subjective:

> We suggest that there is indeed a meaning to a reality that lies outside ourselves but that it is necessary that we, too, should be included in an essential way as participators in this reality. Our knowledge of the universe is derived from this act of participation which involves ourselves, our senses, the instruments used in experiments, and the ways we communicate and choose to describe nature. This knowledge is therefore both subjective and objective in nature. (Bohm and Peat 1987, 55).

Bohm and Hiley (1993) ask what the point is of developing an ontological interpretation of quantum mechanics, when scientific theories cannot be conceived of as descriptions of an independently existing reality. Their answer is that there is a weaker sense in which theories do reflect reality within their domain, "a reality that is however always dependent for its existence as well as for its qualities and properties on broader contexts and deeper levels" (Bohm and Hiley 1993, 325). Moreover, Bohm and Hiley argue that also if the ontological interpretation of quantum mechanics they propose cannot be taken to correspond to reality, there is an intrinsic advantage in the fact that it offers an imaginative and intuitive way of understanding quantum phenomena.

The question whether Bohm was a realist thus must be given a nuanced answer. He did think that scientific theories should go beyond observables and measurement outcomes. He did *not* think that scientific theories can be taken to correspond to reality, or that science describes a reality that is independent of us, or that there can only be one valid theory for a given domain, or that science converges towards a final theory. However, he did think that scientific theories get something right, and that although scientific progress can always result in the development of new theories, something of the older theories is preserved in the new ones.

8. Postmodernism: Bohm's double role

Bohm's interpretation of quantum mechanics has become popular with people who want to argue that quantum mechanics poses no threat to objective reality and does not have the weird implications often associated with it, such as the idea that there is a superposition of states which only collapses through the act of measurement, or that reality is only created when you look at it. Bohm's interpretation is often seen as putting quantum mechanics back on solid grounds, by offering a realist account of quantum phenomena. For example, Bricmont (2017) appeals to Bohmian mechanics to argue against various types of 'nonsense' and mystery connected to quantum mechanics, including the idea that the observer plays an active role in bringing about what it observes, the idea that quantum mechanics is linked to consciousness, and connections between quantum mechanics and eastern mysticism.

This use of Bohm's interpretation of quantum mechanics is very much opposed to Bohm's own ideas. The previous section has shown that it is problematic to see Bohm as a defender of the idea that science gives objective descriptions of an independent reality, and he actually did think that the observer plays an active role in some way. But furthermore, Bohm tended to draw very broad and speculative conclusions from quantum mechanics: he developed quantum mechanical, holistic theories of the human mind (arguing that thought is nonlocalized in the way quantum entities are), as well as of society as a whole (Bohm, 1980), and was highly interested in connecting quantum mechanics with eastern mysticism. He had many intense discussions about science and spiritualism with Krishnamurti. Bohm's later writings present the very opposite of a down-to-earth, non-mysterious approach to quantum mechanics.

Even more peculiar is the connection between Bohm's work and postmodernism. The claims that quantum mechanics implies that there is no objective reality independent of whether we observe it, and no separation between the observer and the observed, have found their ways into postmodern accounts of science; a number of authors have appealed to Bohm's theory of quantum mechanics (or to the Bohmian mechanics derived from it) in order to argue against these postmodern uses of quantum mechanics. For example, Norris (2000) argues that quantum mechanics has generally been a motivation behind antirealist tendencies in recent thought and has been taken to support postmodern and cultural relativists approaches to scientific knowledge; he argues that Bohm's interpretation shows that quantum mechanics does not have to have any of these implications. Also Bricmont (2017) argues explicitly against postmodern uses of quantum physics, and appeals to Bohmian mechanics to argue that quantum mechanics does not have the implications postmodernists attribute to it. Beller (1998, 33) argues that if physicists would have declared that Bohmian mechanics is a respectable interpretation of quantum mechanics, this "could have diminished greatly the explosive proliferation of the postmodernist academic nonsense".

Also this use of Bohm's interpretation is hard to reconcile with Bohm's own thought. In fact, Bohm explicitly argued in favor of a postmodern physics. In 'Postmodern Science and a Postmodern World' (1988), Bohm argues: "Whereas modern physics has tried to understand the whole reductively by beginning with the most elementary parts, I am proposing a postmodern physics which begins with the whole" (Bohm, 1988, 66). In the holistic account he proposes, there is no strict separations between us and the world, observer and observed, fact and value:

> A postmodern science should not separate matter and consciousness and should therefore not separate facts, meaning, and value. Science would then be inseparable from a kind of intrinsic morality, and truth and virtue would not be kept apart as they currently are in science. (Bohm, 1988, 60)

Bohm argues that we have to give up on the belief that "our thinking processes and what we are thinking about are fundamentally distinct": "It is a mistake to think that the world has a totally defined existence separate from our own and that there is merely and external 'interaction' between us and the world". Using a concept of 'enfoldment' which he developed especially in *Wholeness and Implicate Order* (1980), Bohm argues that the world is enfolded in our consciousness and we are enfolded in the world. If we would all realize that we are one with the world, we would take better care of our environment and the world would respond better to us:

> I want to emphasize this point. Because we are enfolded inseparably in the world, with no ultimate division between matter and consciousness, *meaning and value are as much integral aspects of the world as they are of us*. If science is carried out with an amoral attitude, the world will ultimately respond to science in a destructive way. Postmodern science must therefore overcome the separation between truth and virtue, value and fact, ethics and practical necessity. To call for this nonseparation, is, of course, to ask for a tremendous revolution in our whole attitude to knowledge. But such a change is now necessary and indeed long overdue. (Bohm, 1988, 68)

Although Bohm explicitly argued in favor of postmodernism, I doubt that he can properly be called a postmodern thinker. However, Carson (1995) mentions Bohm as one of the authors on physics read by postmodern thinkers, and indeed, one can find numerous examples of authors who write within a postmodern context and appeal to Bohm's ideas; some examples are Chia (2003), Oppermann (2008), and Peters (1985). It may also not be a coincidence that Bohm had a large influence on Feyerabend (section 6), who has often been held responsible for contributing to postmodern tendencies in late-twentieth century thought (on Feyerabend and postmodernism see Kidd 2016).

Bohm's relation to postmodernism is thus a peculiar one: I don't think the work of any other physicist has explicitly been used to argue against postmodernism, in the way Bohm's work has; at the same time, he is one of the few physicists who has inspired postmodern thinking and who has even argued in favor of postmodernism.

9. Concluding remarks

Bohm's work has often been interpreted as a reactionary attempt to return to the ideals of classical physics; but he also created the image of being an unorthodox thinker, going against dogmatism. His interpretation of quantum mechanics has been used to argue against drawing antirealist, mystical or postmodern implications of quantum mechanics; but he was prolific in drawing such implications himself. This paper has attempted to explain this remarkable situation. I reject the idea that Bohm's early work can be described as mechanist, determinist, and realist, in contrast to his later writings. On the contrary, his philosophical commitments remained remarkable consistent throughout his life. Bohm was committed to the idea that we should try to develop an intuitive understanding of natural processes, to the idea of 'wholeness' and interconnectedness of everything in the universe as well as to the infinite complexity of nature, and to the methodological value of developing alternative points of views, new ways of understanding and new concepts. As I have argued, these commitments can be found in his (1951) textbook in which he presented a more or less standard account of quantum mechanics, in the interpretation of quantum mechanics he presented in 1952, in his philosophical writings of the 1950s and 1960s as well as in his more speculative later writings.

That Bohm's ideas on quantum mechanics have often been seen as reactionary can at least partly be explained by the general character of debates on the foundations of quantum mechanics in the 1950s: established physicists defended the quantum revolution of the 1920s and tended to see all dissent as a refusal to accept the past revolution. The fact that Bohm's theory of quantum mechanics was again and again criticized for being reactionary may have pushed Bohm further in unorthodox directions and likely stimulated his revolutionary rhetoric. His philosophical thought was further influenced by Kuhn and Feyerabend: Kuhn showed the strength of paradigms in scientific thinking, and Feyerabend the importance of not being restricted by them (although in this regard, Bohm probably had a larger influence on Feyerabend than conversely). But although Bohm's later writings are more speculative and unconventional, they are still based on the basic ideas which can already be found in his earlier work.

If there is a strong continuity between the early and the late Bohm, one may still argue that there is a distinction between the theorist and his theory: Bohm's interpretation of quantum mechanics may lead to a realist, mechanist and determinist view and may have a classical (or 'reactionary') character, even if this does not match Bohm's commitments. For example, Gross and Levitt (1994, 218) note the postmodern uses of Bohm's later writings, and note: "It is thus an irony that a rigorous working-out of Bohm's ideas about physics (...) lead to a strong reaffirmation of the 'mechanistic' and 'atomistic' picture of reality."

I agree that this distinction can be made. After all, Bohm's interpretation on quantum mechanics is similar to the ideas proposed by De Broglie in the 1920s, and has been further developed by other people since Bohm first presented it, notably in the theory known as 'Bohmian mechanics' which builds on the work of John Bell and eliminates the quantum potential introduced by Bohm (Dürr, Goldstein and Zanghi 1992, 2013) – one surely does not have to subscribe to Bohm's larger philosophical picture in order to subscribe to this theory of quantum mechanics, and it may well turn out to have implications which are in tension or in contradiction with Bohm's more general outlook. Bohm may therefore be a dubious hero for those who want to use his ideas to develop a mechanistic, no-nonsense interpretation of quantum mechanics and argue that it has no mysterious implications, but this is not an argument against these views themselves.

However, taking into account Bohm's larger philosophical picture calls attention to a few things. First, Bohm's theory of quantum mechanics has strongly nonclassical aspects, and in this sense one should not be mislead by the claims that it is a conservative account. It makes it possible to give an exact analysis of the measurement process and provides a very straightforward explanation of the double split experiment, which is often at the heart of quantum mystery. However, it is not a classical, mechanistic view and does not remove all weirdness from quantum mechanics: it is nonlocal and does not provide particles with a well-defined momentum, even though their position is well-defined at all times.[16] Secondly, there is more than one way to be a realist. Bohm offers an ontological picture, according to which there is no limit to the extent to which quantum processes can be analyzed and understood. This does not have to correspond with whether scientific theories offer true descriptions of reality, and also does not necessarily have to correspond with whether scientific theories describe an independent reality. This highlights the fact that Bohm's theory of quantum mechanics does not have to be connected to a strongly realist program, in the sense of offering a fundamental ontology which corresponds to nature as it really is – this is also pointed out by Oldofredi (2020, draft), who argues that the demand for an ontology of quantum mechanics can be combined with a pluralist approach, aimed at formulating physically clear theories. Third, Bohm's theory was not motivated by an outdated concern with determinism; his main objection to the standard version of quantum mechanics was that it puts a fundamental limit to understanding. One does not have to go along with all aspects of Bohm's thought to find this appealing.

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[16] Passon (2018) points out that it is often overlooked that in Bohm's theory, particles do not have a well-defined momentum, which has led to misunderstanding. Passon concludes that "it has to be acknowledged that [Bohmian mechanics] is not only a consistent interpretation of quantum mechanics but includes also 'quantum weirdness'—like any other interpretation of quantum theory."

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