Olival Freire Jr.

Statement

and

Readings

Alternative interpretations of quantum mechanics since the 1970s

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Abstract

The definition of alternative interpretations of quantum mechanics is not exempt of controversies among philosophers of science. Thus I roughly understand by them those proposals adding some pictures or models to the terms coming from the mathematical formalism of quantum mechanics. Still, I include in this category rearrangements in the presentation of this formalism and even minor changes of it. With this broader meaning I may include Bohm's 1952 hidden variable model and Everett's 1957 relative state formulation as the first alternative interpretations. As alternative I mean alternative either to Bohr's complementarity view or to von Neumann's presentation. From the 1970s on this scene dramatically changed with the continuous increasing in the number of interpretations, all of them empirically equivalent to quantum mechanics at least in the non-relativistic domain. A short inspection the compendium Greenberger, Hentschel & Weinert (2009) includes the following interpretations: Bohm interpretation, Bohmian mechanics, complementarity principle, Consistent histories, Copenhagen interpretation, GRW theory, Hidden-variables models of quantum mechanics, Ithaca interpretation, Many worlds interpretation, Modal interpretations, Orthodox interpretation, Probabilistic interpretation, and Transactional interpretation. While there is some redundancy in this list, it is not comprehensive; one could still include, for instance, Stochastic interpretation, Ensemble interpretation, and Montevideo interpretation. Indeed, this list has been growing in recent decades. I want to chart this plethora of interpretations and suggest some problems it implies for physics as discipline and its persona.

Chapter 22
Continuity and Change: Charting David Bohm's Evolving Ideas on Quantum Mechanics

Olival Freire Jr.

22.1 Introduction[1]

"It is too bad, very sad indeed, that he did not live to see how his reputation has shot up recently. His interpretation of quantum mechanics is becoming respected not only by philosophers of science but also by 'straight' physicists." The words of the American physicist Melba Phillips, a long-standing friend of David Bohm (1917–1992), demonstrate yet another case of posthumous recognition in science.[2] In fact since the 1990s Bohm's first proposal for an interpretation of quantum mechanics (Bohm, 1952a), now labeled "Bohmian mechanics", has enjoyed a larger audience than his original proposal got in the early 1950s. A sign of the late prestige accorded to Bohm and to the field he mostly worked in is the volume in honor of the centenary edition of *Physical Review,* the most influential American physics journal. It includes commentaries and reprints from the most important papers ever published in this periodical. In the chapter on "Quantum Mechanics", edited by Sheldon Goldstein and Joel Lebowitz, all the papers including Bohm's 1952 paper on the causal interpretation concern foundations of quantum mechanics and a photo of Bohm opens the chapter (Freire, 2005). However, Bohm's current prestige was not totally unexpected. An inspection of the Festschrift honoring his 70th birthday reveals that in life Bohm received tributes from scientist such as Ilya Prigogine, Maurice Wilkins, and Richard Feynman, all Nobel Prizes at the time of this book appeared, Anthony Leggett, who would go on to win the 2003 Physics Nobel Prize, John Bell, Roger Penrose, David Pines, Bernard d'Espagnat, Jean-Pierre Vigier, in addition to a number of Bohm's collaborators (Hiley and Peat, 1987), and the ultimate accolade was to be elected Fellow of the Royal Society in 1990.

David Bohm was a thinker whose influence went well beyond that of the field of "straight" physics. Neurophysiology, biology, and psychology are some of the

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[1] An early version of this paper was read at the 6th meeting of the Associação de História e Filosofia da Ciência do Cone Sul [AFHIC], Montevideo, May 2008.

[2] Melba Phillips to David Peat, 17 Oct 1994, David Bohm Papers, A22, Birkbeck College, London.

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fields where traces of Bohm's influence can be found. His sphere of influence grew from the 1980s on and he became a cultural icon as a consequence of his contact with eastern thinkers, such as Jiddu Krishnamurti and the Dalai Lama, and his search for a dialogue among science and religion and mysticism. All this influence is claimed to be based on David Bohm's work on the foundations of quantum mechanics. However, Bohm's thoughts on this subject changed meaningfully over the course of the four decades he worked on this and it has been hard to identify which part or stage of his thinking is being considered when his ideas are invoked by his readers. An early example of this was Fritjof Capra and his best seller *The Tao of Physics* (Capra, 1991), where Bohm's ideas on order in quantum theory were presented while Bohm's previous ideas on a causal interpretation of the same theory were ignored. Bohm did not help his readers to make sense of the evolution of his thoughts and in the most widely influential of his books, *Wholeness and the implicate order* (Bohm, 1980), he conflated different stages of his interpretation of quantum mechanics. Even in a paper showing the connections between two of his most important approaches to quantum mechanics, when "asked to explain how [his] ideas of hidden variables tie up with those on the implicate order" he emphasized the continuity more than his change of emphasis (Bohm, 1987).

This paper thus intends to chart the evolution of Bohm's ideas on the interpretation of quantum mechanics dealing with both the elements of continuity and change. Continuity in his thoughts is mainly related to his reflections on realism in physics and attempts to depict the kind of world quantum physics is intended to describe. From the search for a "quantum worldview," a chapter of his 1951 *Quantum Theory* textbook, to the presentation of *The Undivided Universe* as "an ontological interpretation of quantum theory," Bohm kept ontology as the philosophical goal of his investigations. The main changes were related to the role of causality, differences in scientific styles, and the creation of new concepts. Bohm indeed abandoned the quest for a causal interpretation of quantum mechanics moving to give both deterministic and probabilistic laws the same philosophical status. Bohm also moved from the construction of physical models able to reproduce quantum mechanical predictions to attempts to mathematize a few foundational concepts such as order and ultimately to build new physical theories with quantum theory as their limits. It is beyond the scope of this paper to discuss the historical contexts which led him from one stage to another in detail. Instead, I will only review the growing relevant literature. This paper is organized as follows: Section 22.2 is devoted to his early reflections on quantum theory as expressed in his 1951 *Quantum Theory* textbook, but it also deals with Bohm's causal interpretation, including its reception among physicists and its developments. Section 22.3 covers a period beginning in the late 1950s when he abandoned his causal interpretation to the early 1980s, when research to mathematize the insight of implicate and explicate orders matured. Section 22.4 deals with Bohm's thoughts at a later stage, when parts of the causal interpretation were revived, wearing different philosophical clothes, and overlapped with research on the mathematization of the idea of order, eventually leading to the concept of "active information." The fifth and final section is devoted to the legacy of Bohm's ideas, which includes both the research program called "Bohmian mechanics" and the continuing quest for the mathematization of order by Basil Hiley, a longstanding collaborator of Bohm.

22.2 Shifting to a Causal Quantum Mechanics

From the philosophical point of view, Bohm's (1951) *Quantum Theory* is remarkable for its attempt to combine Niels Bohr's complementarity with Bohm's own kind of realism. The former denied quantum theory the ambition of describing a world independent of measurements, while the latter included an ontological description of the quantum world, referred to by Bohm as "an attempt to build a physical picture of the quantum nature of matter." Commitment to an ontology for the quantum phenomena was to be a lasting philosophical feature of Bohm's approach to quantum mechanics. The book is also noteworthy for his conceptual clarity and a few innovations such as the reformulation of the EPR thought experiment using spin instead of position and momentum, which later became the standard formulation for theory and experiments about Bell's theorem due to its mathematical simplicity. Bohm also included a treatment of the measurement process using random phases.

No sooner was the book completed, Bohm was already dissatisfied with it. In a process yet to be well charted by historians, Bohm moved to a causal interpretation of quantum mechanics. Unlike Planck, Lorentz, Einstein, or the early critics to quantum mechanics, he did not express just a hope of going back to a causal description for atomic phenomena. In fact, he built a model for his approach assuming that an object like an electron is a particle with a well defined path, which means it has a simultaneously well defined position and momentum. In this model it suffers the physical influence both from potentials such as electromagnetic potential and a new potential resulting from the mathematical manipulations of Schrödinger equation, which Bohm labeled "quantum potential." These ideas were encapsulated in his 1952 paper titled "A suggested interpretation of the quantum theory in terms of 'hidden' variables." This model was very close to the pilot wave that Louis de Broglie had suggested in 1927 though did not pursue. Bohm was unaware of this but quickly learnt of Pauli's early criticisms to such a model. Bohm further developed his approach, the second part of the paper being a consequence of this. Thus, even a harsh critic like Pauli conceded that the approach was logically consistent while he did not accept it for epistemological reasons (Freire, 2005).

Bohm's 1952 paper had philosophical implications as a consequence of its own physical assumptions. According to Bohm (1952a: p. 166), his interpretation "provides a broader conceptual framework than the usual interpretation, because it makes possible a precise and continuous description of all processes, even at the atomic level." More explicitly, he stated that

> This alternative interpretation permits us to conceive of each individual system as being in a precisely definable state, whose changes with time are determined by definite laws, analogous to (but not identical with) the classical equations of motion. Quantum-mechanical probabilities are regarded (like their counterparts in classical statistical mechanics) as only a practical necessity and not as a manifestation of an inherent lack of complete determination in the properties of matter at the quantum level.

Bohm was so fully aware of the philosophical implications of his proposal that he concluded (pp. 188–9) by associating and criticizing the usual interpretation of quantum mechanics, that of complementarity, as following from the nineteenth century positivism and empiricism preached by Ernst Mach. Such philosophical implications concerned the adoption of a realist point of view toward physical theories and the recovery of determinism as a mode of description of physical phenomena, both discarded by the complementarity view. Later in his career, Bohm (1987: p. 33) emphasized that recovering determinism was not his main motivation and that his major dissatisfaction was that "the theory could not go beyond the phenomena or appearances." The building of an ontology to overcome appearances became a permanent goal in Bohm's research. Later, the priority he gave to determinism was relaxed but in the 1950s the debate triggered by Bohm's proposal did indeed privilege the recovery of determinism. Bohm and his collaborators had supported the emphasis on determinism by choosing "causal interpretation" as the label for their approach. Bohm did not use this term in the title of his initial 1952 papers but he used it in his subsequent paper, while reacting to the first criticisms (Bohm, 1952b). Since then both critics and supporters have emphasized the philosophically minded *causal interpretation* over the philosophically neutral while technically accurate *hidden variable interpretation*. To illustrate how attached to the philosophical priority for causality Bohm and collaborators were we can make reference to the work he and Jean-Pierre Vigier did in 1954 slightly changing Bohm's original model. In this work, they embedded the electron in a fluid undergoing "very irregular and effectively random fluctuation" in its motion (Bohm and Vigier, 1954). While these fluctuations could be explained by either a deterministic or a stochastic description, Bohm and Vigier framed them into the causal interpretation approach, titling their paper "Model of the causal interpretation of quantum theory in terms of a fluid with irregular fluctuations."

Bohm's proposal stirred up a debate and gathered adherents, yet it got a poor reception among physicists (Freire, 2005). In the late 1950s, however, Bohm's research split from that of his collaborators like Vigier and de Broglie. While the latter persevered in their research into the causal interpretation, Bohm gave it up. A number of factors may have played a role in his decision, including discouragement by the limited response to these ideas and "because [he] did not see clearly, at the time, how to proceed further," (Bohm, 1987: p. 40). Another influential factor, not acknowledged by Bohm himself, was his ideological rupture with Marxism in 1956–1957, which may have led him to play down the role he attributed to determinism in science and society (Freire, 2009). As a matter of fact, from 1960 on Bohm gradually began to search for a new approach to the interpretation of quantum mechanics.

22.3 Implicate and Explicate Order

The new approach took 10 years to mature. Indeed, only around 1970 the first papers suggesting "a new mode of description in physics" (Bohm et al., 1970) and taking "quantum theory as an indication of a new order in physics" (Bohm, 1971, 1973) appeared. Bohm drew heavily on analogies and images to convey the content of his new ideas on order, the most well known being the image of a drop of ink falling into a rotating cylinder full of glycerin. When the cylinder rotates in one direction the ink disappears in the glycerin, which Bohm referred to as the implicate order. When it rotates in the opposite direction, the drop reappears, namely the explicate order. Bohm would associate the explicate order with classical or macroscopic phenomena and implicate order with quantum phenomena. As for Bohm the usual interpretation of quantum mechanics was not the final word in quantum physics, he went on to associate the implicate order to a physical theory yet to be worked out that has standard quantum mechanics as a limiting case (Freire, 1999).

Implicate and explicate order would have remained just as philosophical or scientific insights if it had not been the mathematical elaboration it later received. To accomplish this Bohm did not work alone. He counted on the collaboration of Basil Hiley, his assistant at the Birkbeck College since the early 1960s. Their strategy was to analyze the algebraic structures behind quantum mechanics mathematical formalism and subsequently look for more general algebras which could be reduced to the quantum algebras as special cases. This strategy was informed by the fact that they did not want to take any kind of space-time geometry from the beginning of their reasoning. Instead they tried to develop algebraic structures from which space-time could emerge. Here the algebraic primary structure would be the implicate order and the emerging space-time geometry would be the explicate order. With the benefit of hindsight, we can identify Hiley's unique contribution in this sense. A number of different factors also contributed to the development of this mathematical approach, such as new and mathematically talented students including Fabio Frescura, interactions with the mathematician Roger Penrose at Birkbeck Collehe, and inspiration from the Brazilian physicist Mario Schönberg's early works on algebras and geometry. Highly sophisticated from the mathematical point of view, such an approach has however suffered from little contact with experimental results, which could help to inform the mathematical choices to be done.

Before going on to the next stage of Bohm's ideas on quantum mechanics, let us summarize the influences which had led to the ideas of implicate and explicate order. As recalled by Bohm, there was his search for new ideas, his enduring reflection about what was common to his previous approach and standard quantum mechanics (a task that was eased by John Bell's work pointing to non-locality as the irreducible quantum feature), the insight from a TV program in which he saw the demonstration with ink and glycerin, and the fruitful interaction with mathematicians and mathematical physicists. The question remains of how much Bohm was influenced in the early 1960s by his dialogues with the writer Jiddu Krishnamurti. Bohm once acknowledged some influence from Krishnamurti's psychological ideas on the non separability between observer and observed, which reinforced his ideas on the analogous problems in quantum measurement (Bohm, 1982). Later, however, he did not mention such influence again in his research (Bohm, 1987). Basil Hiley thinks that these dialogues were not influential in Bohm's physics, rather they played a role in Bohm's thoughts about society, thoughts, and creativity.[3] A reflection on the relationship between observer and observed had been an essential feature of Bohm's

[3]Basil Hiley Oral History, interviewed by O. Freire, 11 January 2008, American Institute of Physics.

early reflections on the foundations of quantum mechanics, see for instance how he treated measurement both in his 1951 book and 1952 causal interpretation. Thus, it seems that the influence of these dialogues on his physics, if any, was superseded by his enduring reflection on measurement in quantum physics (Freire, 1999).

22.4 Returning to the Quantum Potential

In the late 1970s a new stage in Bohm's quest for a new approach to quantum mechanics began; albeit strongly overlapping the previous one. To a certain extent it meant a return to Bohm's 1952 ideas. This return, almost 30 years later, is vividly described by Basil Hiley[4]:

> We had a couple of research students working for us, Chris Dewdney and Chris Philippidis. They came to me one day with Bohm's '52 paper in their hand. And, they said, "Why don't you and David Bohm talk about this stuff?" And I then started saying, "Oh, because it's all wrong." And then they started asking me some questions about it and I had to admit that I had not read the paper properly. Actually I had not read the paper at all apart from the introduction! And when I took it and, so, you know, I was now faced with embarrassment that our research students [Laugh] were putting me in, in a difficult position, and so I went back home and I spent the weekend working through it. As I read it, I thought, "What on earth is wrong with this? It seems perfectly all right. Whether that's the way nature behaves is another matter." But as far as the logic, the mathematics, and the arguments were concerned, it was sound. I went back again to see the two Chrises again, I said, "Okay, let's now work out what the trajectories are, work out what the quantum potential looks like in various situations."

The students and the surprised Hiley went on to calculate the trajectories allowed by Bohm's quantum potential using the recently arrived desktop computer resources to plot these trajectories creating images of quantum phenomena (Philippidis et al., 1979). Thus, motivated by students and collaborators, Bohm returned to his 1952 approach, but now he had a new problem: how to interpret such an approach and its deterministic trajectories shaped by the nonlocal physical interactions resulting from the quantum potential. Here there is a crucial point to consider while charting Bohm's thoughts on quantum mechanics. While he and his colleagues kept the mathematics and the model used in the 1952 paper they changed many of their philosophical and conceptual assumptions. The quantum potential was no longer considered a new physical potential. Instead it was interpreted as an indication of a new order, in particular a kind of "active information." Emphasis was no longer put on the causality embedded in such an approach. According to Bohm and Hiley (1993) in their synthesis book *The Undivided Universe*, after considering terms such as "causal" and "hidden variable" interpretations "too restrictive" and stating that "nor is this sort of theory necessarily causal," they concluded that "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

[4]Basil Hiley Oral History.

or be it stochastic or be it of any other nature." Their main philosophical stance was thus to look for an ontological view of quantum phenomena, while the main scientific challenge remained how to tie such a requirement with the mathematical work related to the idea of an "implicate order." This challenge has survived Bohm and is a task to which Hiley remains focused, as we will see below.

22.5 Bohm's Legacy

Bohm's main legacy for the understanding of quantum physics is his enduring insistence that the foundations of this theory deserves further investigation and that it should be conducted with open minds to see the problems from different perspectives. In addition, his causal interpretation highlighted the non-locality present both in his interpretation and in standard quantum mechanics. The very existence of such an interpretation was the main inspiration for the work that led John Bell to his seminal theorem. Lancelot Whyte once compared Bohm to Kepler (Freire, 2005). As for Bohm's legacy, it is a high accolade for a contemporary physicist to be compared to the great German mathematician and astronomer.

Yet, the meaning of Bohm's quantum potential and implicate order remains controversial. It remains a research program in progress. In fact, subsequent researchers follow one of three lines of research. The first line continues to work on Bohm's original 1952 proposal not only trying to extend the first physical models but also keeping Bohm's early philosophical commitments with determinism and realism. This is, for instance, the path chosen by Peter Holland (1993).

The second line concerns Bohmian mechanics, as coined by Dürr et al. (1992, 1996). They construed Bohm's proposal in a very clean and elegant way. While in his original paper Bohm worked out analogies between Schrödinger equation and classical Hamilton-Jacobi equations, which led to an emphasis on the role of the non-classical potential that Bohm christened quantum potential, Dürr and colleagues adopted just two premises: the state which describes quantum systems evolves according to Schrödinger equation and particles move, that is, they have a speed in the configuration space. With this approach, without quantum potentials, they derived the same results one gets both with standard quantum mechanics and with Bohm's original approach for nonrelativistic phenomena. This approach has been useful for discussing quantum chaos, and for this reason it has received wide acceptance well beyond physicists interested just in foundations of quantum mechanics. One should note that when these physicists define what they understand to be a *Bohmian theory* priority for determinism disappears and they consider that "a Bohmian theory should be based upon a clear ontology", meaning by ontology "what the theory is fundamentally about." While for non-relativistic physics they have adopted a particle ontology, they admitted that they "have no idea what the appropriate ontology for relativistic physics actually is." This way commitment to a quantum ontology comes before an engagement with a causal pattern for physical theories, a position analogous to that has been adopted by David Bohm and Basil Hiley since the 1960s.

The third line of Bohm's scientific legacy is represented by Basil Hiley, who continues to work on research that he and Bohm had been carrying out before Bohm's death. This research tries to connect the insights of implicate order and active information with the quest for algebraic structures able to underpin space-time geometry and standard quantum mechanics. This program has inherited from the causal interpretation the major challenge of obtaining a fully relativistic treatment in order to match the level attained by standard quantum mechanics with Dirac equation. Bohm had once promised that "the day that we defeat the Dirac equation, we are going to have a special victory party, with a case of champagne".[5] Recently Hiley announced that he has "now found a complete description of the Dirac theory in the Bohm tradition, Bohm momentum, Bohm energy and even a quantum potential which reduces to the Pauli QP in the non-relativistic limit".[6] Only time will tell if the case of champagne should be opened.

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Chapter 12
Orthodoxies on the Interpretation of Quantum Theory: The Case of the Consistent History Approach

Olival Freire

Most of the historical narratives about the foundations of quantum theory center on the themes of orthodoxies and heterodoxies. Niels Bohr's and John von Neumann's early approaches were considered the orthodox views on the issue. In the 1950s, this research was marked by David Bohm's and Hugh Everett's heterodoxies, and according to such physicists who led the field in subsequent years as John Bell and John Clauser, its development faced the stigmas associated with this research. Since the blossoming of this research in the late twentieth century, warnings against the revival of old orthodoxies have been heard. A poignant alert was launched by Jeffrey Bub in *Interpreting the Quantum World*, published in 1997, when he dubbed the weaving of strands including decoherence, Everett's interpretation, and the consistent history approach the "new orthodoxy." Bub pointed to Roland Omnès writings as examples of this new orthodoxy.

Here, I analyze these claims, particularly the consistent history approach. I consider not only the rhetorical strategies adopted by its proponents and critics, such as Bub himself, but also the effective influence achieved by this approach. Bub's claim that the consistent history approach is a new orthodoxy is an overstatement. This paper presents a summary of the use of terms such as "orthodoxy" and "heterodoxy" in reference to quantum mechanics. In addition, it deals with the polysemic manner in which the concept of orthodoxy appears in Bub's book; and I present a synopsis of the consistent history approach, of its claims and rhetorical strategies. The final part is dedicated to the analysis of the effective influence of this approach on physicists. Further, I draw some conclusions from this history about the uses of the terms orthodoxy and heterodoxy in debates on the foundations of quantum mechanics.

12.1 Orthodoxies and Heterodoxies in Quantum Physics

Between 1925 and 1927, a polyphony of interpretations of the newly-born quantum theory emerged. This concurrence was narrowed in October 1927 when Bohr presented his complementarity principle at the Solvay Conference. Bohr's interpretation was not accepted by such physicists as Albert Einstein and Erwin Schrödinger. However, it was supported by a number of others, including Werner Heisenberg, Wolfgang Pauli, and Max Born. While the term orthodoxy was not commonly used at the time, its meaning hung in the air. Louis de Broglie, who arrived at the conference suggesting a causal interpretation of quantum mechanics which was at variance with the notion of complementarity, left disillusioned with his own proposal. When faced with the duties of teaching quantum mechanics in Paris, he "joined the ranks of the adherents to the orthodox interpretation which was accepted by the overwhelming majority of the participants at the Solvay meeting" (Jammer 1974, 114). In 1928, Einstein wrote to Schrödinger, both men in a clear-cut minority among the founding fathers of this physical theory, on complementarity: "The Heisenberg-Bohr tranquilizing philosophy—or religion?—is so delicately contrived that, for the time being, it provides a gentle pillow for the true believer from which he cannot very easily be aroused. So let him lie there."[1]

In the early 1930s, the mathematician von Neumann presented a fully consistent treatment of quantum theory in terms of Hilbert spaces. Together with complementarity, von Neumann's treatment conveyed the feeling that both the philosophical implications and the mathematical formalism of the theory were settled forever. Moreover, in the 1930s, physicists failed to exploit the differences between Bohr's and von Neumann's views regarding completeness and measurement problems.

In the 1950s, the manner in which physicists referred to the dominant view of the interpretation of quantum mechanics began to change. Critics of complementarity referred to it as the "usual" interpretation, as Bohm (1952), or "Copenhagen interpretation," as Everett (Osnaghi, Freitas, and Freire 2009, 105, footnote 111). Later, the historian of physics Max Jammer (1974, 250) dubbed the orthodoxy "the monocracy of the Copenhagen school." The term "Copenhagen interpretation," apparently created by Heisenberg, was not consensually accepted by adepts of Bohr's complementarity. Most importantly, it was used by critics of Bohr's views in general (Osnaghi, Freitas, and Freire 2009, 99). In the early 1960s, Eugene Wigner conspicuously called von Neumann's mathematical presentation of the measurement problem "the orthodox view" in quantum mechanics, only to say that either quantum mechanics was incomplete and could be complemented by a nonlinear modification or one should accept the mind's role during measurement processes (Wigner 1963). If Bohr were alive, it is unlikely that he would accept either of Wigner's choices. As I have argued elsewhere, Wigner indeed became a heterodox in the foundations of quantum mechanics and supported most

[1]Einstein to Schrödinger, 31 May 1928 (Jammer 1974, 130).

of the research in this field during the late 1960s (Freire 2007). From 1970 on, the term “Princeton school” was used to distinguish Wigner and von Neumann’s views from Bohr’s as well as to signal that the monolithic support behind what was once considered the orthodox view had waned or had been split (Freire 2007).

In the 1960s, a new meaning for orthodoxy was emerging among the new generations of physicists interested in the foundations of quantum mechanics. Bell, who would play a key role in subsequent years in this research, co-authored a paper with Michael Nauenberg in 1966 saying:

> [W]e emphasize not only that our view [that quantum mechanics is, at best, incomplete] is that of a minority but also that current interest in such questions is small. *The typical physicist feels that they* [issues on foundations of quantum mechanics] *have long been answered*, and that he will fully understand just how if ever he can spare twenty minutes to think about it. (Freire 2006, 583, emphasis added by OFJ)

The same sentiment was conveyed by Abner Shimony, in a later recollection:

> [T]he preponderance of the physics community at that time accepted some variant of the Copenhagen interpretation of quantum mechanics and believed that satisfactory solutions had already been given to the measurement problem, the problem of Einstein-Podolsky-Rosen, and other conceptual difficulties. (Shimony 1993, XII)

Thus, when research on the foundations of quantum mechanics began to appeal to a larger number of physicists in around 1970 (Freire 2004; 2009), orthodoxy was a polysemic term meaning Bohr’s complementarity, von Neumann’s mathematical presentation, and the vague but influential idea that problems in the foundations of quantum mechanics had already been solved by the founding fathers of the discipline.

A conclusion may be drawn from this short review. Orthodoxy is a term that was never used by the supporters of the complementarity view to refer to themselves. Often it is currently used without implicit assumptions, but mostly orthodoxy is used by critics of the complementarity view or Bohr’s legacy. Such assessments suggest that Bohr and adepts of the complementarity view were closed-minded to the diversity of possible interpretations of quantum mechanics, and their authority helped suffocate debate on the subject. Heinz-Dieter Zeh sharply criticized the inappropriateness of authority’s role: “I have always felt bitter about the way how Bohr’s authority together with Pauli’s sarcasm killed any discussion about the fundamental problems of the quantum.”[2] The term orthodoxy has been

[2] Zeh to Wheeler, 30 October 1980, Wheeler Papers, Series II, Box Wo–Ze, folder Zeh. Cited in (Freire 2009, 282).