

Preface

This book offers a comprehensive introduction to Niels Bohr's interpretation of quantum phenomena and quantum mechanics, based on his concept of "complementarity," his arguably most significant conceptual contribution to physics and philosophy. The term "complementarity" carries three interrelated but distinct meanings in Bohr's writings:

- (1) a general philosophical concept;
- (2) a set of physical concepts, specific to quantum mechanics (as against both classical physics and relativity)—concepts that are instantiations of the general philosophical concept of complementarity but that also have independent significance as physical concepts; and
- (3) a particular interpretation of quantum phenomena and quantum mechanics, in part based on this concept and its instantiations.

In this study, I shall, for the sake of clarity, only use the term "complementarity" as referring to the first two meanings of the term, and just speak of Bohr's interpretation of quantum phenomena and quantum mechanics, or Bohr's interpretation of quantum mechanics (which includes an interpretation of quantum phenomena), or Bohr's interpretation. Using the phrase "Bohr's interpretation" requires, however, the following additional qualification. Bohr's views underwent, sometimes significant, changes, which led him to changing his interpretation, in some cases in conjunction with different instantiations of his general concept of complementarity (this concept itself has remained pretty much the same), or with new concepts, such as and in particular those of "phenomenon" and "atomicity." There is, thus, more than one "Copenhagen interpretation" even in Bohr's case, not to speak of a number of other interpretations associated with this rubric, often quite different from any of Bohr's own interpretations. I shall avoid this overused and sometimes still abused rubric, although more recent commentaries have been more cautious in using it. On the other hand, it is, I think, legitimate to speak, following Werner Heisenberg, of the spirit of Copenhagen, "the Copenhagen spirit of Quantum Theory [*Kopenhagener Geist der Quantentheorie*]," defined by certain

features shared by some of these interpretations and especially pronounced in Bohr's interpretation (Heisenberg 1930, p. iv).

There are several reasons to pursue the project undertaken by this book, three of which I would especially like to stress here:

- (1) The first is Bohr's contribution to our understanding of quantum phenomena and quantum mechanics, and the shaping impact of his thought on the history of quantum mechanics and its interpretation. The significance of this contribution and the pervasiveness of this impact are hardly in question, although the resistance to Bohr's ideas has been considerable, beginning with Albert Einstein, who debated the foundations of quantum theory with Bohr throughout his life.
- (2) Offering a discussion of the Bohr–Einstein debate is the second reason for undertaking the project, with an additional aim of better explaining Bohr's position in this debate, which has not always been adequately addressed by commentators on this debate. Einstein's position has fared much better, in part because it has had a greater appeal to most of these commentators than Bohr's position did.
- (3) The third reason is that, as one of the contributing factors to the resistance to Bohr's thinking and writings, there has been much confusion concerning the meaning of complementarity and of Bohr's ideas in general, and hence his interpretation or, again, interpretations of quantum phenomena and quantum mechanics. Thus, Einstein said that, "despite much effort [he has] expended on it," he was "unable to achieve [a] sharp formulation of [Bohr's principle of complementarity]," which is not uncommon (Einstein 1949b, p. 674).

One of the sources of this confusion is the difficult nature of Bohr's writings on complementarity and quantum mechanics, most of which are assembled in the volumes collectively entitled, *The Philosophical Writings of Niels Bohr* (Bohr 1987; Bohr 1995). These writings are sometimes criticized for their vagueness and elusiveness, a view that the present author does not share and that this book aims to dispel. Bohr's writings are, as I shall argue, lucid and precise, although (this would be hard to deny) they could be difficult and are, in some respects, unconventional, and hence understanding them requires additional effort even on the part of experts in foundations of quantum theory.

Their difficulty is in part due to the complex and counterintuitive character of quantum phenomena and quantum mechanics, which may not be that inhibiting in presenting the mathematics of the theory, but which makes a physically or philosophically explanatory exposition difficult. If anything, Bohr's writings are sometimes excessively cautious and, hence, frequently qualified. Bohr, who strongly believed that a clear and unambiguous exposition of the complexity of quantum phenomena and quantum mechanics was possible and aimed to offer it (the very concept of complementarity was designed to help this task), grappled with this complexity throughout his life. The fact that this struggle is sometimes reflected in Bohr's writings contributes to their difficulty. Bohr commented on these difficulties on several occasions, for example, in his 1949 "Discussion with Einstein on Epistemological Problems in Atomic Physics." Bohr spoke there of

“the inefficiency of expression which must have made it very difficult to appreciate the trend of [his] argumentation” because of certain epistemological complexities specific to quantum phenomena that his writings struggled to capture and to express, complexities that I shall address in detail in this study (Bohr 1949, p. 61).

Some of the difficulties of Bohr’s writings are, however, due to their particular character, especially insofar as Bohr’s key terms, such as “complementarity,” “phenomena,” or “atomicity” have unconventional meanings. Although this and several other aspects of Bohr’s writings are not uncommon in philosophical discourse, they appear to demand more substantial interpretive effort than is customary in scientific texts. Reading Bohr’s works requires paying special attention to particular formulations, carefully adhering to the particular meanings of his terms, understanding the philosophical (rather than only physical and mathematical) structure of his concepts, negotiating the different languages involved, and so forth. These demands have diminished these writings’ appeal to many physicists, although there have been notable exceptions, especially among those who were close to Bohr, such as Heisenberg and Pauli.

Only a minimal reliance on mathematics in Bohr’s arguments did not help either. This reliance characterizes the practice of theoretical physics and the very way of thinking of most physicists and philosophers of quantum theory. The majority of books and articles in the philosophy of quantum mechanics are marked by a strong presence of technical mathematics, thus in a manifest contrast to Bohr’s writings. Bohr’s writings are sometimes taken to task for their insufficient attention to the mathematics of quantum mechanics, which, so it is claimed, inhibits the effectiveness of Bohr’s argumentation or even makes it inadequate. This criticism is, as I shall argue, not justified either and is often based on misunderstanding. The fact that the technical use of formalism is sparse in Bohr’s writings does not mean that Bohr did not give sufficient attention to the *role* of mathematics in quantum theory; quite the contrary.

It is not of course that one cannot disagree with Bohr’s views or criticize his arguments, which the present study will do on several occasions. The point instead is that not paying proper attention to the aspects of Bohr’s writings indicated above prevents one from an effective reading or, when necessary, meaningful criticism of his arguments. Part of my aim in this study is to take these factors into account as much as possible in order to convey the physical and philosophical content of Bohr’s views and ideas more effectively.

This aim notwithstanding, this study can only offer *an* interpretation, one of several possible interpretations, of Bohr’s argumentation and of his interpretation, or again, his several interpretations, of quantum phenomena and quantum mechanics. Nothing else is possible. Carl Friedrich von Weizsäcker remarked that Bohr’s interpretation “needs an interpretation itself, and only that will be its defense” (Weizsäcker 1971, p. 25). The first part of the sentence is self-evidently true. An interpretation of quantum phenomena and quantum mechanics always involves an *interpretation* of this interpretation. A given interpretation only functions or even exists when somebody interprets it, especially beyond its existence and functioning for its author, although ultimately this is true even in this case.

As will be seen later in this study, Bohr reinterpreted his earlier interpretations on later occasions, even if without expressly acknowledging or perhaps realizing that he was doing so. I am not saying that Weizsäcker was unaware of this general situation: he might have been or, in any event, would have probably acknowledged the pertinence of these considerations. His contention instead appears to be that there is a degree of incompleteness to Bohr's argument for his interpretation, and thus that this argument needs to be supplemented (consistently with what Bohr expressly says) by further elaborations, explanations, argumentations, and so forth. As any scholarly study of Bohr, this study will provide this type of supplementation as well. However, I do not think that Weizsäcker's contention and, hence, his claim that Bohr's interpretation requires a special defense is true, at least when it comes to Bohr's ultimate interpretation, discussed in [Chap. 9](#), when Bohr revises and corrects his earlier interpretations, of which there are, again, several, the circumstance that Weizsäcker does not address. At least, Weizsäcker's contention and claim are, again, no more true in the case of Bohr's interpretations than those of most other interpretations, except for the initial version of his interpretation, offered in the so-called Como lecture of 1927. As I shall argue in [Chap. 4](#), some parts of this version are difficult to defend, and Bohr significantly modified his interpretation shortly thereafter. Bohr was not God. He struggled hard with the complexities of quantum phenomena and quantum mechanics, and he revised and changed his views, and made mistakes. Nor, as he acknowledged, could he have fully controlled his texts, hard and even obsessively as he tried to do so. Nobody could achieve this either, especially, again, in dealing with subjects of that magnitude of difficulty.

In view of the circumstances just outlined, the task of making Bohr's thinking and work more broadly accessible may not be easy. It is not insurmountable, however, and this book aims to pursue this task. While aware of the difficulties his own writings may present, Bohr insisted that it is possible to make what is fundamentally at stake in quantum physics available to a willing and open-minded layperson, and this book aims to do so as well. There are a few technical mathematical details in this book, but they are minimal and can be skipped without missing the main points of the elaborations where they occur.

This book is a *philosophical* introduction to Bohr. However, it represents a different aspect or even a different *form* of a philosophy of physics, vis-à-vis most forms of the institutional philosophy of physics and specifically the philosophy of quantum theory, or even most philosophical studies of Bohr. The difference is reflected in my emphasis, beginning with this Preface, on Bohr's *thinking* about quantum mechanics or complementarity. Physics is a product of human thought under complex material (nature), technological (our experimental capacities), psychological, historical, and sociological or cultural conditions. Accordingly, one can pursue a philosophy of physics that attempts to understand how physicists think under these conditions, especially at the time of, and in the process of making, new discoveries.

The present approach is, thus, different from dealing, as is more common, especially, again, in the institutional philosophy of physics, with the logical-axiomatic structure of quantum theory or with broader epistemological or

ontological questions, such as reality and causality. These questions were of course a major part of Bohr's thinking, too, and will be considered here, but considered as part of his *thinking*, which, I shall argue, approaches these questions in a new way, demanded, Bohr argued, by the new situation of physics brought about by quantum phenomena. Physics is thinking, thinking about nature or the ontology of nature—of how nature is. It is thinking about what is true or probable about nature or those aspects of nature that physics could consider. In all modern, post-Galilean physics, classical or quantum (or relativity), this truth or probability is determined by means of mathematics, that is, by means of mathematical theories connected, descriptively or predictively, to the suitably configured numerical data obtained in experiments. How close we come to the ultimate constitution of nature in this way may depend on a given theory or, possibly, on nature itself, that is, on how far nature would allow our mathematical theories and experimental technologies to reach in this regard. It is this last question that is ultimately at stake in the Bohr–Einstein debate on, to return to Bohr's title phrase of his account of this debate, “epistemological questions in atomic physics” (Bohr 1949, p. 32).

A physicist can also explore the *nature* of thinking in physics, sometimes simultaneously with creating new physics, and in this sense become a philosopher of physics in the present sense, which tends to happen at the time of crisis, as it happened in Bohr's work. First, creating a proper theory of quantum phenomena and, second, offering a proper interpretation of both quantum phenomena and quantum mechanics presented exceptionally difficult problems for physics, which led to a crisis. The first problem was essentially solved by Heisenberg's and Schrödinger's invention of quantum mechanics in its respectively matrix and wave form in 1925 and 1926. From that point on, Bohr's thinking, which had confronted this crisis for over a decade by then, was directed toward the second problem, which the concept of complementarity helped him to address and ultimately to solve, or at least to reach as far as it was possible for him in solving it, although this took a while (roughly another decade). For some, especially those whose view is closer to that of Einstein's and who are not satisfied with the kind of solution of this problem Bohr offered, the second and, for some, beginning, again, with Einstein, even the first problem has not yet been solved and, hence, the crisis, at least the epistemological crisis, of quantum physics is still ongoing. The debate concerning quantum phenomena and quantum mechanics continues with undiminished intensity, and given the irreconcilable nature of opposing philosophical positions, such as those of Bohr and Einstein, this debate may be interminable. This situation, however, by no means inhibits the project of philosophy of physics defined by the exploration of the nature of thinking in physics.

This study is an attempt at this type of philosophy of physics, as specifically applied to Bohr's thinking, which continues, just as does Einstein's thinking, to shape this debate. Given the scope of this study, I will not be concerned with psychological and sociological aspects of Bohr's thinking or quantum-theoretical thinking in general. On the other hand, history will play a significant role in my argument. History is unavoidable in physical thinking, which always builds on preceding thinking in physics, even at the time of new discoveries, however

revolutionary or historically unexpected the latter may be. Every physical idea has a history, some trajectories of which may be short and others quite long, sometimes, as in the case of the idea of motion, extending to ancient thought. Thus, Bohr's 1913 atomic theory is inconceivable apart from Planck's and Einstein's earlier work. Heisenberg's thinking concerning quantum mechanics was significantly indebted to Bohr's 1913 atomic theory, and conversely, Heisenberg's thinking concerning quantum mechanics, or that of Schrödinger and Dirac, was crucial to Bohr's thinking. There is also a long history of philosophical thinking behind this thinking, extending, again, to ancient thought for example, the atomism of Democritus and Lucretius. More modern philosophical trajectories extend from the critique of causality in Hume and Kant, and traverse via the thought of Kierkegaard, Nietzsche, and William James, among others. Bernhard Riemann's theory of the functions of complex variables was mentioned by Bohr as one of the earlier sources of complementarity, and, as will be seen in [Chap. 10](#), it might have been one of the most important ones. It would be impossible to explore most of this history, but it is equally impossible to bypass it here or in any earnest attempt at understanding Bohr's thinking, which embodies this history, as does our thinking concerning quantum theory, at this point with this thinking itself as part of this history.

A qualification is in order, however. When I speak of the thinking of Bohr or any given author, such as Einstein or Heisenberg, I do not claim to have a determinable access to this thinking. Such an access is limited even when the author is alive and could, in principle, provide one with as much information as possible concerning this thinking. Instead, I refer to thinking that one can follow and can engage on one's own accord on the basis of certain statements or works of a given author, and then in a particular reading or interpretation, since these works can be interpreted differently, and, in the process, related to different ways of thinking. A proper name, such as Bohr, Einstein, or Heisenberg, is the signature underneath a given work or set of works, a signature that attests to one's role as a creator of these works, which serve as a guidance for the thinking that we can pursue as a result of reading them.

In the process, one can also gain insights into how a given author might actually have thought, but claims to that effect are, again, hard to make with certainty, although they may be probable and even highly probable. Such claims are, I would contend, not necessarily less certain when they are made, as for the most part they will be here, on the basis of published works or available manuscripts presenting their authors' arguments in detail rather than from other evidence—letters, notes, diaries, recorded conversations, etc. Historical scholarship tends to rely more on such sources as providing a more reliable evidence concerning or insights (in particular, eureka-like insights) into the thinking of a given figure, often forgetting that this type of evidence is also comprised of texts that require reading and interpretation, sometimes as much as do published works. Such sources will be used by this study as well, which will, however, exercise some extra caution concerning Bohr's reported statements, sometimes unduly relied upon by commentators. I shall primarily focus, however, on Bohr's published essays or more extended unpublished manuscripts, which are, I would contend, reliable sources

for understanding his thinking, in part because, as is well known, Bohr paid a particularly careful attention to his published work, albeit never quite finished to his satisfaction. The very concept of a finished manuscript was alien to Bohr, who saw any of his manuscripts, even already published, as an occasion for further thinking, a set of new questions, rather than of conclusive answers. In any event, even apart from their easier availability, Bohr's published works are especially suited for my main concern in this study: what Bohr's thinking, as manifested in his available texts does for *our thinking*, also when our thinking aims to reach beyond Bohr's own.

An interpretation of quantum phenomena and quantum mechanics only becomes effective or, again, operative to begin with when it becomes part of our thinking, and it advances physics, or the philosophy of physics, when it moves this thinking beyond this interpretation, beyond our interpretation of this interpretation. Bohr might be argued to encourage this approach to his writings, an approach that he even adopted himself in dealing with his writings and that his writings invite us to continue. He *reportedly* said that his "every sentence ... must be understood not as an affirmation, but as a question" (Rosenfeld 1967, p. 63). One must, as I said, be cautious concerning such reported statements. However, although not strictly true factually (there are affirmations, or conversely, negations, in Bohr's arguments), this particular statement does correspond to the spirit of Bohr's thinking and writings.

This does not of course mean that, helpful as it might be, Bohr's thinking and writings, or, again, *interpreting* these writings and thus Bohr's interpretations of quantum phenomena and quantum mechanics, is the only path toward a better understanding of them and, especially, advancing this understanding or quantum theory itself. When it comes to advancing physics one's faithfulness or loyalty to Bohr's or anyone's thinking becomes a secondary matter and only counts insofar as it helps this advancement. While my reading of Bohr must and aims to be faithful to his writing as much as possible and while my project is motivated by my belief in the helpfulness of Bohr's thinking for understanding quantum theory and potentially advancing it, this project is not driven by loyalty to Bohr's ideas themselves. At a certain point, our thinking concerning quantum physics will inevitable have to move beyond Bohr, and there is no special reason to assume that it will do so following the path established by Bohr's thinking. An entirely different trajectory, either already in place or yet to be discovered, may be necessary for this task. The project of this book is an introduction to Bohr's thinking concerning quantum phenomena and quantum theory, and it aims to facilitate our understanding of this thinking. This project will succeed most, however, if it will help our thinking to move beyond that of Bohr, either by still following the trajectory of his thinking or, guided by what quantum phenomena and quantum physics tell us, by finding a different trajectory of thinking.

The conception of the book as outlined here makes it different from most previous approaches to Bohr. There are a number of available comprehensive studies of Bohr, a few of which are cited in the special section of the bibliography under the heading, "Suggested Further Readings." Two previous works by the present author offer extensive discussions of Bohr as well, *Reading Bohr: Physics*

and *Philosophy* (2006) and *Epistemology and Probability: Bohr, Heisenberg, Schrödinger and the Nature of Quantum-Theoretical Thinking* (2009), although the latter study is only partially devoted to Bohr. While I shall rely here on some of the research used in these earlier studies, especially *Epistemology and Probability*, the present book is very different from them, in part by virtue of its conception as an *introduction* to Bohr's thinking concerning quantum mechanics and complementarity. My aim here is a streamlined discussion maximally centered on Bohr's thinking, concepts, and arguments in their historical development.

In part for this reason, my discussion of the works of other authors, even Heisenberg and Einstein, who were especially germane to Bohr's thought, is limited, and my engagement with secondary literature on Bohr is reduced to bare minimum. Bohr did not of course think in a vacuum, nor does the present author, and this study will address the ideas of other key figures, such as Heisenberg and Einstein, and Bohr's responses to these ideas, and will refer and engage with secondary sources whenever necessary. However, these engagements will play only an auxiliary role here, that of helping the exposition of Bohr's thinking and argumentation. As just mentioned, in addition to the works actually cited by this study, the Bibliography contains a section, "Suggested Further Reading," which lists both the primary works of some of the major authors and scholarly literature on Bohr. This list is not complete and somewhat selective. This selection, however, is not primarily based on affinities between these works and this book, but on those works that offer comprehensive and engaging accounts of Bohr's thinking and work, sometimes from perspectives quite different from the one adopted here.

I thought that it would be most effective and helpful to the reader to follow the historical developments of quantum theory and Bohr's thinking, and I have arranged the chapters accordingly. Following [Chap. 1](#), which serves an introduction, the subsequent chapters explore those junctures of Bohr's thinking at which his main concepts and arguments concerning quantum mechanics and complementarity emerged or were transformed, as manifest in his key published works, with the date of the publication chronologically marking each chapter. The first, introductory, chapter is an exception and is dated 1900–1962, the years, respectively, of Max Planck's discovery of quantum theory and Bohr's final interview on his life and work, literally on the eve of his death. (This interview itself will be addressed in [Chap. 10](#)). [Chapter 2](#) is a kind of prologue to Bohr's thinking concerning quantum mechanics and complementarity, and briefly traces the development of this thinking to Bohr's 1913 theory of atomic constitution, which, as I shall argue, contains certain key ingredients of his later epistemological approach. The remainder of the book is devoted to Bohr's thinking following the discovery of quantum mechanics. It is not possible to completely map the development of Bohr's thought in this way, in part because some of the corresponding junctures of this development are discussed in later articles. For example, Bohr's initial discussions with Einstein in 1927, leading to major changes in his approach is only discussed by Bohr himself in his 1949 "Discussion with Einstein on Epistemological Problems in Atomic Physics," which presents the development of his thinking concerning quantum mechanics and

complementarity via his lifelong debate with Einstein. Accordingly, the necessary adjustments and qualifications will be made in some of the chapters in order to accommodate these complexities. Nevertheless, I hope that the book's organization will help the reader to follow the trajectory of Bohr's thinking.



<http://www.springer.com/978-1-4614-4516-6>

Niels Bohr and Complementarity

An Introduction

Plotnitsky, A.

2012, XXI, 199 p. 2 illus., Softcover

ISBN: 978-1-4614-4516-6