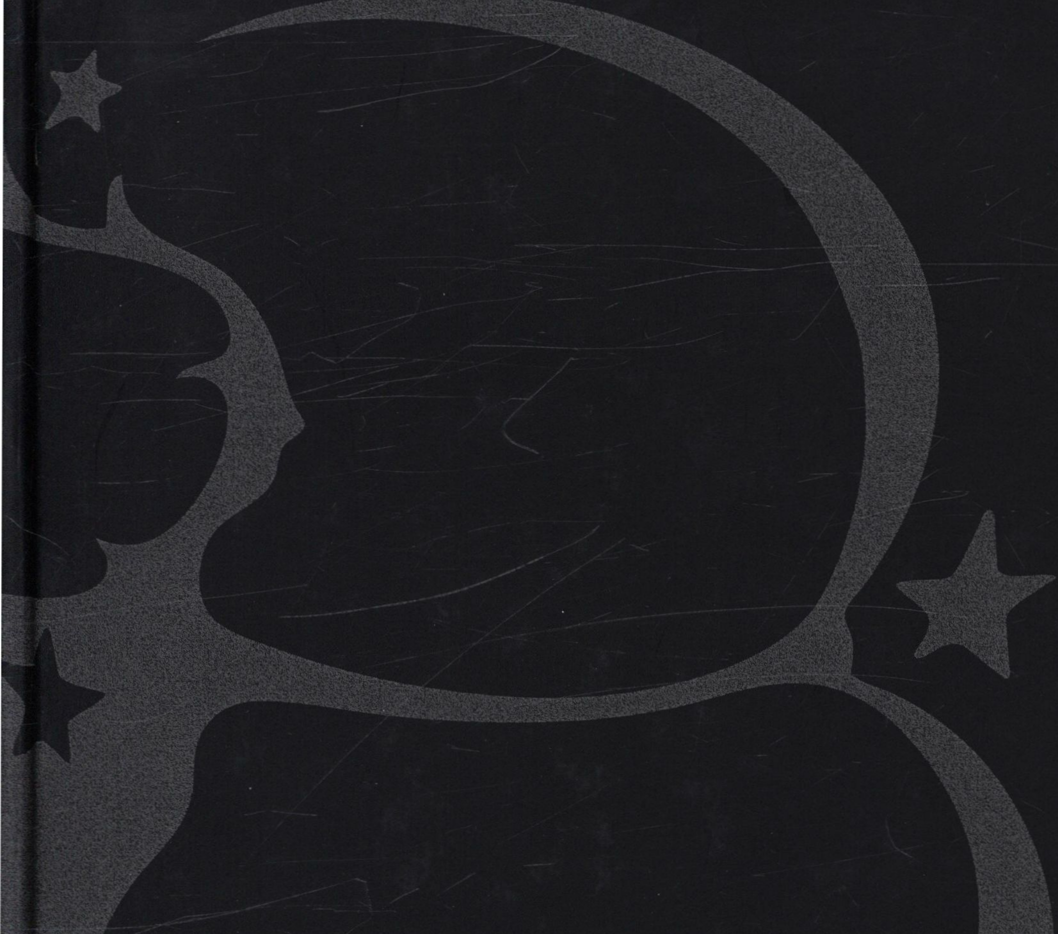

NIELS BOHR AND THE PHILOSOPHY OF PHYSICS

Twenty-First-Century Perspectives

Edited by Jan Faye and Henry J. Folse

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"The thoughtful essays in this rich collection make clear that Niels Bohr's earnest, dogged efforts to grapple with the conceptual implications of quantum theory retain the power to inspire — and provoke — new generations of scholars. The essays look back to Bohr's own intellectual roots, even as they focus on still-open questions at the heart of quantum theory. Brimming with insights, this book will be of interest to physicists, philosophers, and historians of science."

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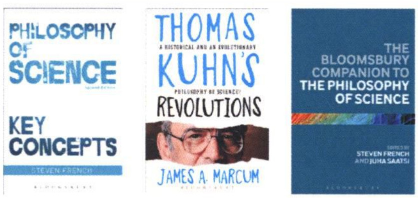

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Introduction

Jan Faye and Henry J. Folse

Roughly a quarter century ago, in the years following the centenary of Niels Bohr's birth in 1885, there was a rather sudden surge in publications presenting somewhat more sophisticated and subtle interpretations of his thinking than—with a few exceptions—had been the general rule in earlier decades. We took advantage of this turn of events to collect a set of seventeen chapters by some of the scholars who had contributed to this new literature. It was published in 1994 in the series *Boston Studies in Philosophy of Science* under the title of *Niels Bohr and Contemporary Philosophy*

Now we are more than a decade into the twenty-first century and approaching the centenary of Niels Bohr's interpretation of quantum mechanics. Meanwhile a whole new generation of scholars writing on Bohr has come to the fore. The issues that were most conspicuous in our previous collection were very different from those that are prominent in the present volume. In the 1990s many of our contributors considered questions related to the then contemporary debates over scientific realism. Now those issues are largely in the background, and our present contributors are much more concerned with Bohr's views on the use of classical concepts, how to draw the distinction between classical and quantum descriptions, and how Bohr's interpretation relates to de-coherence, QBism, and other non-collapse views. Furthermore many new developments in quantum physics naturally lead us to ask how Bohr's views would stand with respect to them. Thus it is appropriate to pause and reflect upon the philosophical traditions that may have nurtured his interpretation as well as its current status in the physics of today. Over the years an astounding number of books and articles have discussed manifold aspects of Bohr's thinking. Nevertheless, like the interpretation of quantum theory itself, the interpretation of Bohr's philosophical viewpoint still remains a matter of lively dispute.

1.

Even though complete consensus concerning the whole of Bohr's philosophy is likely to be unattainable, clarification of his philosophical intentions is a rational goal, for he stood squarely at the center of that iconoclastic transformation in physics that we know as the "quantum revolution." In this context it is encouraging that contemporary scholarship has converged on at least some prominent themes that present great promise for a better understanding of Bohr. For example, more and more scholars point to Kant's philosophy as a possible source for understanding the "viewpoint" Bohr called "complementarity." The contributors to this volume are no exception; among them there are several who see strong similarities between Bohr's philosophy and the Kantian way of thinking. However, other scholars recognize elements of epistemological naturalism in general and of pragmatism in particular in Bohr's approach to quantum mechanics.

These different roots of complementarity need not be regarded as exclusive of each other. Although the naturalistic attitude of most pragmatists is starkly opposed to Kant's transcendental method, and the pragmatists saw themselves as turning the page on epistemology as it was conceived during the Enlightenment, there is undeniable evidence that in his philosophical upbringing Bohr was exposed to both of these influences. Bohr had a long and close relationship to the Danish philosopher Harald Høffding, who not only taught Kant's philosophy but also exhibited Kant's influence in his own thought. Moreover, Høffding corresponded with William James and visited him while Bohr was a student. In the year after Bohr enrolled at the University of Copenhagen, Høffding held a series of seminars about modern philosophical theories that Bohr seems to have attended. Here American pragmatism, focusing on the thought of William James, was one of the topics.

Although they had different goals, pragmatists broadly agreed with Kant that the mind provides a conceptual element that it imposes on a sensory input in generating the empirical world of phenomena with which natural science is concerned. And this is an important theme that appears repeatedly in Bohr's references to the "epistemological lesson" that the quantum revolution has taught. Nevertheless, Kant is working with a conception of knowledge that requires certainty, and this is what leads him to embark on his transcendental approach, which aspires to prove the scheme of categories that Kant claimed to deduce from the nature of Reason are universal and necessary for all human experience. In contrast the pragmatists appealed to a naturalistic account of knowledge, which relinquishes the claim of certainty in favor of a much less stringent criterion of pragmatic justification in terms of successful expectations and actions. In accepting a fallibilist approach to knowledge, pragmatists allow the possibility that what it is reasonable to say we know today may not be reasonable to say we know tomorrow. Thus pragmatism points the way to a dynamic theory of knowledge deeply intertwined with its growth over time. This again is important for appreciating Bohr's thought, for standing at the epicenter of the quantum revolution as he did, he was deeply personally invested in making the case for conceptual change in atomic physics. Kantians and pragmatists agree that we are not merely spectators of an objectively existing world, but that we actively interpret and interact with the world. However, only pragmatists are open to the possibility that the conceptual element in knowledge changes over time as new cognitive standards and goals replace old ones with the expansion of human experience into new domains of phenomena. The pragmatist grounds these changing criteria in human nature as biological, physical beings immersed in the empirical world. While William James was not himself a defender of epistemological naturalism, from its inception with C. S. Peirce pragmatism strongly emphasized scientific knowledge as the paradigm of empirical knowledge and disdained the characteristic nineteenth-century interest in matters transcendent. The methodology of natural science was understood as embodying the key tenets of pragmatism.

Another theme that connects Bohr with Kant and the pragmatists is their rejection of our ability to have knowledge of the world as it is in itself. Both of these traditions accept that our scheme of categories provides non-analytic knowledge only as applied to sense impressions and does not justify any application beyond our sensory experience. We can very well understand the world as it is given empirically, but as soon as we attempt to claim knowledge of the world as it really is independently of our experience of it, we speculate beyond the proper limits of our cognitive faculties. No scientific knowledge is possible about the things-in-themselves, which are empirically inaccessible hidden behind the veil of phenomena. While Kant himself spoke of things-in-themselves as a limiting notion, the name for an unknown realm that the Understanding could not survey, the ink was hardly dry on his first *Critique* before philosophers began to try to find ways around this limit. However, pragmatists, who see the whole of human cognitive apparatus and its products in terms of the needs of natural beings to cope with the world of experience, a realm of objects beyond human experience, transcendent beings, are, quite literally, of no interest. And this also seems to be a view with which Bohr's whole philosophical outlook was in warm accord.

Another theme on which many interpreters have focused is Bohr's insistence on the retention of classical concepts within quantum mechanics. This can be understood as parallel to Kant's claim to have proved that space and time are the forms of intuition necessary for any possible experience. Our sense impressions provide the content for our experience of the world only after they are synthesized in representations with the spatial and temporal forms of intuition and the categories of judgment such as substance, unity, plurality, and causation. In contrast pragmatists seek no such transcendental defense for the unavoidability of the classical concepts, but anchor the indispensable nature of their use in the claim that like all of our faculties, our sensory perceptual faculties are the way they are due to the evolutionary pressure of survival. Thus the classical concepts have evolved for unambiguous communication about the objects of everyday human experience: the objects with which human beings daily interact. According to Bohr, classical physics has been able to define and operationalize these categories to such a degree that their use can be extended beyond the objects of common-sense experience to the physical interpretation of mathematical theories. Our natural language embodies the categories in terms of which we have learned to form a world of causally interacting physical objects in space and time, and it is this use of natural language which allows us to give an empirical meaning to the mathematical symbolism, and thus to use the results of experiments and observation to justify that theoretical structure.

Therefore Bohr held that the classical concepts could not be replaced by other concepts since they are the only concepts by which we can understand and communicate "what we have seen and learned." But at the same time, he was also acutely conscious of the one big obstacle for applying the classical concepts to the results of quantum mechanics. The discovery of the quantum of action, symbolized by Planck's constant, made it impossible to give a classical description of atomic objects. Classical concepts like position, duration, energy, and momentum cannot apply unambiguously to the trajectories of free particles, isolated from any interaction, because in quantum mechanics such trajectories are in principle unobservable since observation requires that the object be interacting with the observing instruments in a way that cannot be ignored or compensated for. But Bohr clearly maintained that the classical concepts could—and indeed must—still be used to describe the outcome of all experiments. There would never be inconsistency in the ascription of incompatible properties to the atomic object based on classical concepts as long as this application was understood to be only in relation to a particular experimental phenomenon. This insistence on the classical concepts while at the same time limiting their proper use gave rise to the viewpoint he called "complementarity." Thus, he argued that the application of the classical concepts is well defined only in relation to a specific phenomenon observed in a particular experimental context and has no physical meaning outside of an experimental context. The consequence is that a quantum system does not have well-defined kinematic or dynamical properties independently of any measurement.

A related theme essential to Bohr's understanding of quantum mechanics is his denial of the representational function of the mathematical formalism. Much of what has been proposed concerning the interpretation of quantum theory fails to follow Bohr's lead in this respect, thus becoming lost in a maze of branching universes and the mystery of what is represented by the nonphysical "collapse" of the wave function. Like all empiricists, Bohr held that the acceptability of a theory is a function of its utility in making successful predictions, but he seems to add to that the pragmatic position that scientific theories are tools or instruments for handling and describing reality as it appears to us, rather than attempts at a representation of the world as it is in itself. So Bohr refused to regard the so-called collapse of Schrödinger's wave function as an issue calling out for interpretation, and he never addressed the "paradox" of Schrödinger's infamous cat. The so-called collapse was beyond any possible experimental inquiry. Where Schrödinger and the anti-Copenhagen physicists saw a paradox, Bohr saw a misunderstanding of the significance of physical theory.

Although Bohr never publically distanced himself from any of the various realist interpretations of the wave function, he repeatedly referred to it as a symbol for calculating probabilities. He seems to have thought that the Born rule that interprets the wave function as a probability amplitude is the only role for the wave function. He certainly never refers to the "collapse" of the wave function as representing a physical process of some abstract, non-empirical form. Moreover, Bohr strongly believed that any attempt to use the quantum formalism to try to characterize a world "behind the phenomena" would be mere metaphysical speculation, and an abuse of the concepts which were well defined for describing the objects of human experience. To him the formalism was a tool for predictions that was "symbolic" and should not be treated as if it gave us a "picture" of what the world looks like when no one is looking at it.

In earlier decades when the influence of Karl Popper was at its peak it was common to treat Bohr as advocating a subjectivistic interpretation, but today no recent scholars or philosophers of science would assume that Bohr understood complementarity to imply that the mind or consciousness of the observer has any influence on experimental outcomes in quantum mechanics. Bohr's philosophical roots in a naturalistic pragmatism make it evident that earlier accusations of subjectivism are without any historical support. While it is easy to find such misinterpretations in the popular press, anyone who reads Bohr carefully can see that his references to "the observer" refer to the observer qua physical system, not qua consciousness. It would appear that this view was often imputed to Bohr by those anxious to discredit the "Copenhagen interpretation," and it is true that at least some physicists—who may or may not have imagined that they were upholding Bohr's position—have indeed held this view. In fact Bohr did emphasize that the physicist makes a free conscious choice in selecting the physical context in which a particular dynamical variable is well-defined, but once that context has been chosen no conscious mind is regarded as having any influence on the result.

At one point he expressed his dismay with what he considered to be Heisenberg's more subjectivist view. Heisenberg had once suggested that the observer partly determines the outcome by his reading of the measuring instrument. Referring to the debate that took place at the Solvay conference in 1927 in "Discussion with Einstein about Epistemological Problems in Atomic Physics" Bohr (1958, 51) writes about this proposal:

> On that occasion an interesting discussion arose also about how to speak of the appearance of phenomena for which only predictions of statistical character can be made. The question was whether, as to the occurrence of individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on the part of "nature" or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the "observer" constructing the measuring instruments and reading their recording. Any such terminology would, however, appear dubious since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, it is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged.

Bohr (1963, 6–7) certainly appreciated the fact that in its emphasis on motion as relative to a frame of reference the theory of relativity was misunderstood by some as injecting subjectivity into the description of motion, and an analogous misunderstanding was common in the case of quantum theory because of its emphasis on the role of the observing instruments:

> Notwithstanding all difference in the typical situations to which the notions of relativity and complementarity apply, they present in epistemological respects far-reaching similarities. Indeed, in both cases we are concerned with the exploration of harmonies which cannot be comprehended in the pictorial conceptions adapted to the account of more limited fields of physical experience. Still, the decisive point is that in neither case does the appropriate widening of our conceptual framework imply any appeal to the observing subject, which would hinder unambiguous communication of experience. In relativistic argumentation, such objectivity is

> secured by due regard to the dependence of the phenomena on the reference frame of the observer, while in complementary description all subjectivity is avoided by proper attention to the circumstances required for the well-defined use of elementary physical concepts.

Thus, although Bohr accepted that the experimenter makes a conscious choice in deciding what experiment to perform, he rejected the observer's influence on the *outcome* without any doubt. What happens in an experiment depends entirely on the physical interaction of the apparatus with the atomic object being investigated.

Nevertheless, at least one reason for mistakenly attributing subjectivism to Bohr's view of complementarity is due to the fact that the label "the Copenhagen interpretation" is often used to cover a broad spectrum of quite different interpretations. Thus when some physicists, who were associated with Bohr and the Copenhagen Institute (and that number included a large portion of the first generation of quantum physicists), proposed that the observer as a conscious mind seems to play an active role in getting a certain measuring result, it came to be mistakenly believed that Bohr himself held this view. It is worth remembering that Bohr never used the phrase "Copenhagen interpretation," nor "orthodox interpretation," although both have now become too entrenched to be in danger of extinction. However, recent scholarship has gone a long way toward demonstrating that the many various versions of the so-called orthodox interpretation or Copenhagen interpretation were often inconsistent with each other and that there was no uniform agreement among all the diverse physicists (and philosophers) who considered themselves to be supporting the Copenhagen point of view.

In this connection, an important point was made at the beginning of our current century by Don Howard (2004) who argued that Heisenberg invented the label "Copenhagen interpretation" as part of his campaign to reconcile himself with Bohr after their break through World War II. He points out that "until Heisenberg coined the term in 1955, there was no unitary Copenhagen interpretation of quantum mechanics" (680). Howard also notes that at the center of Heisenberg's picture of the Copenhagen interpretation was his own "distinctively subjectivist view of the role of the observer." In particular, it seems this came to be the picture of the thus named "Copenhagen interpretation" that a new generation of physicists and philosophers of science began to question. And not uncommonly these critics missed the differences between Bohr and Heisenberg.

Recently Kristian Camilleri (2006, 2007) has cogently argued that sometimes Heisenberg completely misunderstood Bohr's view in his attempt to show that Bohr's and his own understanding were very similar. Camilleri observes that in the Como paper, Bohr defines complementarity as holding between space-time description and the causal description of the stationary states of the atom in terms of well-defined energy. In 1958 Heisenberg claimed that

> Bohr uses the concept of "complementarity" at several places in the interpretation of quantum theory ... The space-time description of the atomic events is complementary to their deterministic description. The probability function obeys an equation of motion as did the co-ordinates in Newtonian mechanics; its change in

> the course of time is completely determined by the quantum mechanical equation; it does not allow a description in space and time but breaks the determined continuity of the probability function by changing our knowledge of the system. (50)

But this interpretation completely misreads Bohr by identifying the continuous evolution of the time-dependent wave function with a "deterministic" causal description. So it was Heisenberg, not Bohr, who identified the causal description with the deterministic evolution of the wave function, since it gave a probabilistic description of a free particle in configuration space. In contrast, Bohr identified a causal description with the dynamical conservation principles. Thus, Heisenberg's misinterpretation of Bohr has generated some important distortions in the general understanding of Bohr's point of view.

The Copenhagen interpretation, often branded as the "orthodox" interpretation to put it in a pejorative light, came to be associated with the "collapse of the wave function" when the measuring process reduces the superposition of possible state values of a system into the actual detected value. This way of speaking—and thinking—would have been common only after J. von Neumann's version of Dirac's formalism in 1932, well after Bohr had already arrived at complementarity. This makes sense if one follows Heisenberg's view that the so-called collapse is an objective physical process. But Bohr never once mentions the "collapse of the wave function." To him the wave function was symbolic because it is not a function of the classical dimensions of space and time, by which we represent to ourselves the world of everyday experience and classical physics. It cannot represent anything visualizable in space and time, so Bohr concluded that at least in the atomic domain it is a mistake to try to demand that a theory represent the world as it is in-itself. And this led him to view quantum theory in a way highly compatible with the current of pragmatism which, as we have noted above, was one of the influences that nurtured his philosophical thinking.

Therefore Bohr held that the wave function, which serves as an invaluable symbolic tool for making statistical predictions concerning all possible observational outcomes, cannot be given an ontological reading by taking it to represent a world existing independently of our interactions with it. Because the unavoidable interaction with the observing instruments in quantum mechanics is an essential condition for the occurrence of the phenomena we seek to describe, the criterion of objective description cannot lie in picturing the world apart from our interactions with it; thus the theory's acceptability must rely on the statistical predictions it makes: "The ingenious formalism of quantum mechanics ... abandons pictorial representation and aims directly at a statistical account of quantum processes" (Bohr 1998, 152), and "the formalism thus defies pictorial representation and aims directly at prediction of observations appearing under well-defined conditions" (172). Moreover, as a complex-valued function the wave function is mathematically defined in an abstract vector space, and not in a real physical space. So to make the collapse of the wave function a real physical process, an abstract vector space would have to transform into real physical space a transmutation that lies outside the scope of physical explanation.

Bohr might have argued instead that the wave function must be given an epistemological reading in the sense that the function represented our total knowledge of the quantum system. In this case the so-called reduction of the wave function does not refer to a *physical* process, but to the *epistemic* event of coming to know the result of a measurement; it is the reduction of a range of possible outcomes we *might* know to what we actually *do* know when we make a measurement. While such a view may have corresponded to Heisenberg's earliest view, Bohr abstained from making any such epistemic claim. Bohr frequently refers to an "epistemological lesson" concerning the recognition that observation requires a physical interaction that produces the phenomena we seek to describe, and that therefore the description of the phenomena is "objective" only when the physical conditions of that interaction are included. But nowhere does he identify this lesson with the symbolism of the "reduction of the wave packet." The predictive utility of the wave function gives us no grounds for holding that it is an ontological representation of reality independently of our experience of it; nor that it represents epistemologically all possible empirical knowledge.

There is an abundance of textual evidence for Bohr's refusal to regard the wave function as *representing* anything and his regarding it as only an abstract symbolic tool. The statistical interpretation of the wave function is stipulated already in Como:

> Another application of the method of Schrödinger, important for the further development, has been made by Born in his investigation of the problem of collisions between atoms and free electric particles. In this connection he succeeded in obtaining a statistical interpretation of the wave functions, allowing a calculation of the probability of the individual transition processes required by the quantum postulate. (Bohr 1934, 75)

Not only is it part of his outlook in Como, it's there from the beginning to the end of his life. Here is an example from his very last year, 1962, recalling the 1927 Solvay meeting:

> A main theme for the discussion was the renunciation of pictorial deterministic description implied in the new methods. A particular point was the question, as to what extent the wave mechanics indicated possibilities of a less radical departure from ordinary physical description than hitherto envisaged in all attempts at solving the paradoxes to which the discovery of the quantum of action had from the beginning given rise. Still, the essentially statistical character of the interpretation of physical experience by wave pictures was not only evident from Born's successful treatment of collision problems, but the symbolic character of the whole conception appeared perhaps most strikingly in the necessity of replacing ordinary three-dimensional space coordination by a representation of the state of a system containing several particles as a wave function in a configuration space with as many coordinates as the total number of degrees of freedom of the system. (Bohr 1963, 89)

In the very next paragraph he clearly connects this symbolic character of the formalism with the claim that not only is the "wave picture" to be considered symbolic, but equally so the "particle picture" is not to be taken as a representation of a real object, as it was used in the classical framework. Thus he continues: