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Quantum Dialogue

The Making of a Revolution

Mara Beller

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MARA BELLER is the Barbara Druss Dibner Professor in History and Philosophy of Science at the Hebrew University of Jerusalem.

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CHAPTER 6

The Dialogical Birth of Bohr's Complementarity

His [Bohr's] turn of mind was essentially dialectical, rather than reflective. . . . He needed the stimulus of some form of dialogue to start his thinking.

Leon Rosenfeld 1967, 117

It is, of course, possible to simplify the medium in which a scientist works by simplifying its main actors.

Paul Feyerabend 1975, 19

Introduction

A dialogical analysis of a scientific paper differs from the usual conceptual analysis. The dialogical approach is opposed to static structures and fixed meanings—it is inherently contextual and historicist.

Such an analysis, as we saw in the previous chapter, can change our understanding of a scientific text: we uncover diversity of meaning, complexity of argumentation, unresolved tensions. When we perceive that the text is populated with invisible interlocutors, we realize what the central issues of the paper are. This realization modifies our understanding of the content of the paper. Dialogical analysis is a potent tool for deciphering opaque and obscure texts. Such is the case, I argue in this chapter, with respect to the analysis of Bohr's Como lecture (1927c)—Bohr's initial formulation of his complementarity principle.

The usual reading of the Como lecture identifies the announcement of wave-particle duality as the main message of Bohr's initial presentation of complementarity. My dialogical reading challenges the accepted reading: Bohr continues to reject pointlike light quanta, and his discussion is heavily asymmetrical in favor of waves. The usual reading of Bohr's paper assumes the similarity of Bohr's and Heisenberg's positions, while a dialogical analysis reveals an incompatibility between their positions at the time. The usual reading also assumes the centrality of measurements and of operational definitions of concepts, while the dialogical reading of the Como lecture uncovers Bohr's more modest emphasis on the "harmony" between the wave theoretical definition of concepts and the possibilities of observation. Significantly, the dialogical reading discloses that the central message of Bohr's paper was not the resolution of wave-particle duality by the complementarity principle but rather an extensive defense of his concept of stationary states and discontinuous energy changes, or "quantum jumps."

As with Heisenberg's uncertainty paper, plurality of meaning permeates Bohr's initial elaboration of complementarity. An analysis of Bohr's discussion of the complementarity between space-time and causality reveals different, even incompatible uses of this concept. Scholars have attempted to find an unequivocal connection between wave-particle complementarity and space-time–causality complementarity (Murdoch 1987). Some have argued that causal description is associated with particles and space-time with wave propagation, while others conversely connect space-time with particles and causality with waves. In fact, both of these contradictory readings are present in the text.[1] They occur in different dialogues and address different issues. Complementarity between space-time and causality is an imprecise umbrella concept that allows Bohr to cope locally with interpretive issues while entrenching his initial conception of stationary states and discontinuous energy jumps.

A dialogical reading of Bohr's Como lecture also brings back to life "lesser" scientists. We will see that the work of Campbell triggered Bohr's deliberations on interpretive issues as it did Heisenberg's (chapter 4). Campbell's name figures in a draft of Bohr's paper (1927b, 69), as well as in the published text (1927c, 131).

A dialogical reading of Bohr's Como lecture also provides a new perspective on the famous clash between Heisenberg and Bohr over the uncertainty paper. A dialogical analysis reevaluates Bohr's and Heisenberg's intellectual positions so that the confrontation between them becomes conceptually meaningful, no longer merely the result of "misunderstandings" and "confusion." Such a presentation allows us to merge the "conceptual" and "anecdotal" aspects of the history of quantum physics (Beller 1996b).

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[1] While discussing the Compton effect, Bohr associated conservation laws—causality—with particles and space-time descriptions with wave propagation. Yet while discussing the complementarity between space-time and causality in the case of stationary states of an atom, Bohr associated causality with waves (a stationary state is described by a proper vibration and has a definitive unchanging value of energy) and space-time descriptions within the atom with particles. See the analysis below.

Bohr's first presentation of the complementarity principle took place at the International Congress of Physics, held in the Italian city of Como. In the history of scientific thought it is hard to find another contribution about which opinions continued to differ sharply more than half a century after its appearance. Some physicists, such as Leon Rosenfeld, considered complementarity the most profound intellectual insight of the twentieth century, the pinnacle of the physical understanding of nature, no less inevitable than "the emergence of man himself as a product of organic evolution" (1961, 384). Others criticized Bohr's complementarity as an obscure "double-think" that impeded clear thinking and scientific progress, or as a crutch that helped initially but was eventually no longer needed (Landé 1967; interview with Alfred Landé, AHQP).

Attitudes toward Bohr's complementarity principle even in the camp of "believers" were more ambivalent than the published sources disclose. As Dirac expressed it: "I never liked complementarity. . . . It does not give us any new formula. . . . I believe the last word was not said yet about waves and particles" (interview with Dirac, AHQP). Similarly, Heisenberg disclosed, "I know that, besides Landé, many other physicists had been upset by this situation, and they felt it was a dualistic description of nature" (interview with Heisenberg, AHQP).

Despite the strong reactions it provoked, what exactly Bohr's complementarity means continues to be an enigma. Jammer, commenting on the difficulty of comprehending Bohr's complementarity principle, described Carl Friedrich von Weizsäcker's extensive effort to elucidate the original meaning of complementarity. However, when Weizsäcker asked Bohr "whether his interpretation accurately presents what Bohr had in mind, Bohr gave him a definitely negative answer" (Jammer 1974, 90). Recent students of Bohr's thought continue to face the "formidable difficulty," even incomprehensibility, of his writings dealing with complementarity. Thus Folse claimed, "Even with almost one full year's work on this paper, innumerable rewrites, two public deliveries, and three different sources of publication, the essay contains many obscurities and never makes very clear what this new 'viewpoint' is supposed to be" (1985, 108).[2] Don Howard recently proclaimed that "now there are signs of growing despair . . . about our ever being able to make good sense out of his [Bohr's] philosophical view" (1994, 201).

A dialogical perspective allows us to decipher Bohr's philosophy in general and the meaning of Bohr's original presentation of the comple-

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[2] Similarly pessimistic is the conclusion of Gibbins: "Niels Bohr went to great lengths to refine and then to clarify his thoughts on quantum mechanics, but, sad to say, his writings do not appear to have benefited from these efforts. It is very difficult to say . . . how his ideas hang together" (1987, 53).

mentarity principle in particular. Without identifying the interlocutors of each sentence of the Como lecture, it is impossible to understand the meaning of these sentences and the connections among them. Yet when we realize that the text is filled with implicit arguments with the leading physicists of the time—Einstein, Heisenberg, Schrödinger, Compton, Born, Dirac, Pauli, and the lesser known Campbell—the fog lifts and Bohr's presentation becomes clear.

A dialogical reading reveals that the central message of Bohr's Como lecture was the announcement of a compatibility, indeed, a "happy marriage," between Schrödinger's successful continuous wave mechanics and the quantum postulate, especially Bohr's original notion of discrete stationary states. In Bohr's presentation, the de Broglie-Schrödinger wave packet was sufficient to resolve the paradoxes of atomic structure, of the interaction of radiation with matter, and of the interaction of matter with matter—paradoxes that had confounded Bohr since his brilliant and troublesome debut into atomic theory in 1913. The existing accounts of complementarity center almost exclusively on the "wave-particle duality" of a free particle, while the significant physical problems—those that invoke physical interactions (bound electrons in atoms, collisions)—are neglected. Yet it was the paradoxical, nonclassical aspects of these problems that were central to the efforts of physicists at the time.

The Como lecture announced a resolution of these long-standing problems by harnessing the wave theoretical framework to the quantum postulate. In fact, each of the dialogues centers on Bohr's solution of one of these problems—atomic structure, the interaction of radiation and matter, and collisions. In each case, Bohr implied that the abstract idea of a point-mass particle is inadequate and must be replaced by a wave theoretical superposition of light waves or matter waves. The fertility of this idea for Bohr's skillful weaving of the argumentation in the Como lecture clearly demonstrates why, from the very beginning, he ascribed physical significance to Schrödinger's theory, unlike his younger colleagues Heisenberg and Jordan. Bohr's implicit argument for the superiority of wave concepts over particle concepts does not mean that waves represented for him a literal picture of reality. Rather the fruitfulness of the wave model is in the English tradition: the wave model is both heuristically useful and theoretically adequate. Bohr's Como lecture constituted a striking contrast to Heisenberg's efforts to develop an exclusively corpuscular ontology.

The fruitfulness of the concept of wave packets is especially evident in the case of interactions. Because we never observe either an isolated particle or a monochromatic wave (both are "abstractions"), but only cases of superposition of light or matter waves, the idea of a wave packet is particularly suitable for demonstrating the harmony between the possibilities of wave theoretical definition and those of observation (Bohr 1927d). The agreement claimed between the possibilities of definition and observation was initially much weaker than the operational assertion that measurement is the primary and indispensable part of the interpretation of concepts—the stand later taken by Bohr. Mere "harmony" between observation and definition of concepts is, of course, a necessary part of any interpretive attempt.[3]

My claim that Bohr's original announcement of complementarity was not a symmetrical solution of the wave-particle dilemma, and that in all physically interesting cases—those of interactions—one must necessarily deal with wave packets (light waves or matter waves), will be substantiated by discussing Bohr's dialogues with Einstein, Compton, and Campbell. It is generally assumed that the roots of Bohr's complementarity lie in the experimental refutation of the Bohr-Kramers-Slater theory. This theory used the wave theoretical framework of light exclusively rather than Einstein's theory of light quanta. After the Bothe-Geiger experiments, many authors assume, Bohr had no choice but to assimilate light quanta, which he had rejected vigorously beforehand. The foundations of Bohr's complementary framework, they hold, lay in his acceptance of light quanta in 1925, before all the subsequent breakthroughs—Heisenberg's matrix mechanics and Schrödinger's wave mechanics—occurred (Jammer 1966; MacKinnon 1982).

I argue for a substantially different perspective. Bohr did not adopt the idea of pointlike light quanta (as used in the explanation of the Compton effect), even after the Bothe-Geiger experiments. Bohr's complementarity principle implied further *rejection,* not acceptance, of the idea of pointlike material particles. It is incomprehensible that Bohr would have developed his interpretation of quantum physics without responding in a significant way to the pivotal theoretical developments that occurred during the years 1925–27. I will discuss the nature of Bohr's response in the Como lecture to Heisenberg's matrix mechanics and to Schrödinger's wave mechanics. In particular, I will describe Bohr's understanding of the space-time problem in the interior of the atom, and his defense and elaboration of his idea of a stationary state. This description further substantiates my claim that it is around Bohr's concepts of stationary states and quantum jumps—which Schrödinger aimed to eliminate—rather than around the wave-particle dilemma or indeterminism, that the new philosophy of physics was erected. Bohr's full-fledged defense of his own idea of stationary states is elaborated in

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[3] This was argued by both Born and Heisenberg in 1927 for their respective statistical and indeterminacy interpretations.

paragraph 5 of the Como lecture—a part either neglected or considered the most obscure (the opinion of the editors of Bohr's collected works; *BCW*, 6:30).

Bohr's defense and elaboration of the idea that an atomic system is adequately represented by a sequence of stationary states that are, in turn, adequately described by Schrödinger's wave function reveals a deep conceptual gap between Bohr's wave theoretical and Heisenberg's particle-kinematic interpretations of atomic systems—a gap that was circumvented rather than resolved by subsequent developments. This incompatibility between the positions of Bohr and Heisenberg is one of the historical roots of the inconsistencies that plague the Copenhagen interpretation of physics. My discussion of this gap also provides an insight into Einstein's and Schrödinger's early dissatisfaction with the Copenhagen interpretation. I argue that their initial criticism focused on the inconsistency of amalgamating the incompatible positions held by Bohr and Heisenberg. Part of the incomprehensibility of the Como lecture derives from Bohr's attempt to conceal this gap by uniting forces against the opposition.

Dialogue with Schrödinger: The Structure of Atoms

My discussion of Bohr's predisposition to de Broglie–Schrödinger concepts is based on the text of the Como lecture (Bohr 1927c), together with two manuscripts written before the lecture (Bohr 1927a, 1927b). I will also quote from a manuscript (1927d) written only three weeks after the Como conference. These three manuscripts are conveniently available in Bohr's *Collected Works*, volume 6.[4] As is clear from these writings, Bohr in his original struggle with the physical interpretation of quantum theory leaned heavily on the idea of a wave packet—a superposition of waves of different frequencies that results in a wave field limited in space and time. Bohr used the imagery of a wave packet whenever he described light quanta or electrons, both in cases of free individuals and in cases of interactions between them. The position of the light quantum is the position of such a limited wave field, rather than that of a mass-point.[5] Using the idea of wave packets, Bohr directly derived the uncertainty relations, a derivation that is opposed to Heisenberg's, based on the idea of pointlike electrons and photons.

In a manuscript written just a few days before the Como lecture (Bohr 1927a), Bohr introduced de Broglie wave packets to represent both light quanta and electrons. Bohr described de Broglie's ideas "of ascribing a frequency to any agency carrying energy" and consequently "a phase-wave to a material particle." According to Bohr, the matter wave theory, or "the representing of a particle by means of a wave-packet, represents a direct generalization of the light quantum theory." Such a point of view strongly suggests not only that the pointlike corpuscular light quantum is an abstraction but that a singular harmonic light wave is similarly merely an abstraction that is never actualized by itself in any physical situation: "As emphasized by de Broglie the abstract character of the phase-wave is indicated by the fact that its velocity of propagation . . . is always larger than the velocity of light *c*." All this suggests also that "a light wave may be considered as an abstraction, and that *reality can only be ascribed to a wave group*" (Bohr 1927a, 78, my italics).

Recognizing the physical significance that Bohr attached to a wave packet allows us to see the following often-quoted sentence in a different light: "Radiation in free space as well as isolated material particles are abstractions . . . their properties on quantum theory being observable and definable only through their interaction with other systems" (Bohr 1927c, 116).

This sentence does not imply, or at least did not originally imply, a strong instrumentalist approach, where no reality can be ascribed to atomic systems in themselves—the view Bohr gradually developed by countering later objections. Neither does it indicate a symmetrical solution of the wave-particle dilemma. Rather only the idea of a wave packet represents the "real thing" that allows the untangling of the mysteries of the atomic world.

My interpretation is confirmed by Bohr's analysis of the possibilities of observation in principle, as well as by his analysis of actual physical interactions—the interaction of radiation and matter and the Davisson-Germer experiments. According to Bohr, any observation necessarily involves superposition. In the case of light, "as stressed by de Broglie the only way of observing an elementary wave is by interference" (Bohr 1927a, 78). Here the possibilities of definition of a wave packet and the possibilities of observation are in close harmony. On the other hand, "the only way to define the presence of the waves is through analysis of the interaction between light and matter" (Bohr 1927b, 70). It was from this phenomenon that the corpuscular character of light was deduced. Here, according to Bohr, the discussion "was until recently most unsatisfactory" because "the behaviour of the so-called material particles rested so entirely on corpuscular ideas," that is, on the idea of localized pointlike particles. All the difficulties are removed "through the

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[4] Page references for Bohr (1927a, 1927b, 1927c, 1927d) are to *BCW*, vol. 6.

[5] "Only by the superposition of harmonic waves of different wavelengths and directions is it possible at a given time to limit the extension in space of the wave-field. . . . If we ask about the position of a light quantum, we find that no more than in the case of its energy and momentum, we can define a position of a light quantum at a given time, without consideration of complementary waves" (1927b, 69–70).

introduction of an *essential wave feature in the description of the behaviour of material particles* due to the work of de Broglie and Schrödinger" (Bohr 1927b, 70, my italics). The Davisson-Germer experiments, according to Bohr, directly confirm the matter wave theory in the spirit of de Broglie–Schrödinger: "The discovery of Davidson [*sic*] and Germer . . . prove[s] the necessity of applying a wave-theoretical superposition principle in order to account for the behaviour of electrons. . . . the wave character of the electrons is by these experiments shown just as clearly as is the wave character of light. . . . As [is] well known the experiments are in *complete accordance* with the ideas of de Broglie" (1927a, 77, my italics). Though reference to these experiments is omitted in the text of the Como lecture, this discussion, written just a few days before Bohr's presentation in Como, forms a necessary background for understanding his argument in the lecture.

According to Bohr, an adequate visualizable interpretation of physics is possible only with the help of the idea of a wave packet: "The possibility of identifying the velocity of a particle with a group velocity indicates the applicability of space-time pictures in the quantum theory" (1927c, 118).

The idea of a wave packet allowed Bohr, following de Broglie, to rationalize the "irrationality" of the basic quantum relation $E\tau = I\lambda = h$, where "corpuscles of light" with energy E and momentum I had the characteristics of infinitely extended waves (period of vibration τ and wavelength λ). It was this irrationality that Bohr cited in his earlier work as the reason for his opposition to the idea of light quanta. The concept of a wave packet demonstrates that one is dealing not with two "rivalizing [competing] concepts" but rather with a description of two "complementary sides of phenomena (Bohr 1927b, 69). The relation $\Delta t\Delta E = \Delta x\Delta I_x = \Delta y\Delta I_y = \Delta z\Delta I_z = h$ indicates the reciprocal accuracy with which the space-time and energy-momentum vectors of such wave packets can be defined, suggesting the complementarity of space-time and causality descriptions. The relation indicates "the highest possible accuracy" in the definition of "individuals associated with wave fields." In general, the wave packet would "in the course of time be subject to such changes that [it would] become less and less suitable for representing individuals" (Bohr 1927c, 119). Here, according to Bohr, is the source of the "paradoxes" of quantum theory.

As we will see, Bohr did not accept the particle-kinematic interpretation of an atom in a given stationary state (as Heisenberg, Pauli, and Born would have it), nor did he entertain the idea of wave packets moving along visualizable Keplerian orbits (as Schrödinger at some point had hoped). In Bohr's interpretation of the interior of the atom, the possibilities of visualization were closely connected with the possibilities of experimentation. The wave theoretical model allowed Bohr finally to decipher the limits of the application of space-time to the atomic domain—a problem that had occupied him since 1913, when he himself had introduced the incomprehensible quantum leaps into an inexplicable space-time abyss. On the other hand, the wave model enabled Bohr to resurrect his idea of the stationary states of an atom—an idea that seemed to have been abandoned in the matrix approach and to be in danger of elimination by Schrödinger's attempts at interpretation.

The problem of stationary states and the problem of the application of space-time description in the atomic domain are closely connected. The idea of stationary states (when out of all classical mechanically realizable motions, only certain motions were assumed to be actualized), and especially the idea of instantaneous transitions between such states, implied from the very beginning a radical departure from classical space-time models. Yet how radical the departure would eventually become nobody initially grasped, not even Bohr. Both his 1913 and 1918 papers show that Bohr did not rule out the possibility that the mechanism of the transitions would eventually be understood. The concept of the stationary states of an atom was beset with conceptual inconsistencies from the start (Beller 1992b). Still, Bohr and other physicists used this idea, which successfully explained the stability of atoms and powerfully deciphered the structure of spectral lines (Heilbron and Kuhn 1969; Jammer 1966). As far as Bohr and his followers (but not Schrödinger) were concerned, the idea of stationary states and discontinuous transitions between them was fully and definitely corroborated by the Franck-Hertz experiments.

In retrospect, we can see how, step by step, the conceptual price of the utility of this idea rose. In the Bohr-Kramers-Slater theory the idea of stationary states and quantum jumps necessitated such major departures as nonconservation of energy and momentum, as well as the introduction of the strange "virtual field" that an atom in a definite stationary state emitted. The Bohr-Kramers-Slater theory also implied further departures from ordinary space-time visualization, for example, in the explanation of the Compton effect. Similarly, the analysis of the phenomenon of collisions, when a fast-moving particle collides with an atom in a certain stationary state, demanded resignation from strict conservation of energy and momentum (Bohr 1925). When Bohr learned of the results of the Bothe-Geiger experiments, confirming strict conservation, he did not question the formulas of the wave theory of light or the adequacy of the description of atoms in terms of stationary states. Rather it was a further departure from classical space-time models for the interior of the atom that Bohr found mandatory. Bohr was supported in this direction by the wave theoretical ideas of de Broglie and Einstein. The paper Bohr wrote on these matters was published in 1925, just before Heisenberg's reinterpretation paper—the paper that provided a panacea for all the ills of the old quantum theory by eliminating the classical space-time container from the interior of the atom.

Heisenberg's solution, however, was too radical. Matrix mechanics could not theoretically describe the states of atomic systems and the evolution of phenomena—the main reason for the lukewarm reception it received initially (chapter 2). Schrödinger indeed perceived the matrix mechanical formalism as eliminating Bohr's concept of separate stationary states. Schrödinger himself attempted a continuous wave description that would further eliminate the concept of stationary states with definite energies, and discontinuous transitions between these states, by suggesting instead a resonance model in terms of frequencies. As I have argued, the Göttingen and Copenhagen physicists joined forces in response to the perceived threat from Schrödinger—his attempt to reduce Bohr's concepts to the status of Ptolemaic epicycles. It was around the adequacy of Bohr's concepts of stationary states and quantum jumps that the crucial interpretative attempts revolved.

Bohr, who accepted the great usefulness of Schrödinger's formalism, could not see initially how solutions to Schrödinger's wave equation, in terms of the superposition of different proper vibrations, could be reconciled with the idea of separate stationary states. His heated argument with Schrödinger, during the latter's visit to Copenhagen in the fall of 1926, had centered on quantum jumping. After Schrödinger's visit, the direction of Bohr's efforts became clear: to achieve compatibility between wave theoretical ideas and the quantum postulate. As Heisenberg put it: "Bohr realized at once that it was here we would find the solution to those fundamental problems with which he had struggled incessantly since 1913, and in the light of the newly won knowledge he *concentrated all his thought on a critical test of those arguments which had led him to ideas such as stationary states and quantum transitions*" (1967, 101, my italics).

Bohr's Como lecture was the culmination and resolution of these efforts. Bohr criticized Schrödinger's attempts to replace "the discontinuous exchange of energy . . . by simple resonance phenomena" (1927c, 127; 1927d, 97). Schrödinger's theory must necessarily "be interpreted by an explicit use of the quantum postulate," and "in direct connection with the correspondence principle." Moreover, "in the conception of stationary states we are . . . concerned with a characteristic application of the quantum postulate" (1927c, 130). Countering Schrödinger, Bohr asserted: "The proper vibrations of the Schrödinger wave-equation have been found to furnish a representation of the stationary states meeting all requirements" (1927c, 126; 1927d, 97). If characteristic vibrations represent stationary states, then "a fundamental renunciation of the space-time description is unavoidable" (1927c, 129). The reason for this is the fact that "every space-time feature of the description of phenomena is based on consideration of interference taking place inside a group of such elementary waves" (1927c, 129; 1927d, 97). Stationary states, having definite energy, are adequately described by a single elementary wave (because "the definition of energy and momentum is attached to the idea of [a] harmonic elementary wave"; 1928, 113). The above sentences clearly indicate that no particle-kinematic description can be applied to a separate stationary state in principle, and that "a consistent application of the concept of stationary state excludes . . . any specification of the behavior of the separate particles in the atom" (1928, 112). Here lies a crucial retrospective insight into the past failures of the old quantum theory, which assumed visualization of these stationary states in terms of mechanical electron orbits. Since no time mechanism for the description of these states can be conceived, no prediction of the time of the transition is possible. This, in turn, discloses why, for describing these transitions, one must be content with probabilities—another crucial insight into the source of past struggles!

The initial difficulty of reconciling the idea of stationary states with the Schrödinger wave function was the fact that the general solution of Schrödinger's equation is a superposition of proper vibrations, and at first it seemed "difficult to attribute a meaning to such a superposition as long as we adhere to the quantum postulate" (Bohr 1927d, 97), according to which an atom is always in some definite stationary state. Schrödinger regarded this difficulty as conclusive, arguing that an atom exists in a superposition of several proper vibrations, and that the appropriate characteristic of a proper vibration is its frequency and not its energy. Bohr's ingenious resolution of this difficulty centered on an exploration of the compatibility of the possibilities of definition and observation. A superposition of proper vibrations is an adequate description in the case of interactions (observations). An atom in a definite stationary state with precise energy is, however, a closed system, not accessible to observation, and therefore it can be correctly described by a single proper vibration. As such, the idea of a stationary state becomes an abstraction, both because it is represented by a single wave and because a system "not accessible to observation . . . constitutes in a certain sense an abstraction, just as an idea of an isolated particle" (1927d, 97). Despite its being an abstraction, the concept of a stationary state is indispensable in the interpretation of phenomena (1927d, 97). Because "the conception of a stationary state involves, strictly speaking, the exclusion of all interactions" (1928, 115), the constant energy value associated with such states "may be considered as an immediate expression for the claim of causality contained in the theorem of conservation of energy" (1927c, 130). Thus the complementarity of space-time and causality in the quantum domain follows. The idea of an atom in a stationary state as a closed system with constant energy accords well with Bohr's initial introduction of this idea to explain the stability of matter: "This circumstance justifies the assumption of supramechanical stability of the stationary states, according to which the atom, before as well as after an external influence, always will be found in a stationary state and which forms the basis for the use of the quantum postulate" (1927c, 130). Schrödinger's interpretive aspirations are deficient precisely because they cannot deal with the stability postulate, for which the assumption of stationary states is essential.

Bohr devoted all of paragraph 5 of the Como lecture to arguing for the consistency of the concept of a stationary state. Bohr's strategy was to demonstrate that complementarity between stationary states and corpuscular space-time descriptions—or between causality and space-time, for the interior of an atom—accords fully with the possibilities of observation. For example, if one is to inquire about the behavior of separate particles in an atom, then one has to neglect their mutual interaction during the observation, thus regarding them as free. This necessitates a very short time of observation, shorter than the periods of revolution of electrons. This, in turn, implies a big uncertainty in the energy transferred during the observation, and thus the impossibility of ascertaining the energy values of stationary states.

The concept of complementarity between stationary states and corpuscular space-time descriptions, however, seems to present a serious difficulty when large quantum numbers are approached. According to Bohr's correspondence principle, in the limit of large quantum numbers the concept of stationary states must approach the classical space-time orbits along which intraatomic particles revolve. This problem occupied Bohr from the time matrix mechanics emerged with its total renunciation of space-time descriptions. Nor was the problem ignored by Heisenberg, who though not reluctant to abandon space-time description in the interior of the atom, was nevertheless eager to understand how the transition from the micro- to the macrodomain might be achieved. Because an electron moving along an orbit with a large quantum number should necessarily be represented by a wave packet (a superposition of many vibrations), the idea of a stationary state as a single proper vibration seemed to Schrödinger basically inadequate. How, then, can complementarity, or the mutual exclusion of the concepts of stationary states and individual particles, possibly be maintained in the case of large quantum numbers, where these ideas are not only no longer contradictory but simultaneously applicable?

Here again the harmony between the possibilities of observation and definition comes to the rescue, and Bohr demonstrates with characteristic ingenuity how even in this case his conception of stationary states and transitions between them can be preserved.[6]

The possibility of describing stationary states by means of Schrödinger's wave function, in contrast with the inadequacy of matrix mechanics on this score, indicated to Bohr the profound physical significance of wave mechanics. The fact that such a definition of a stationary state is theoretically adequate is demonstrated, according to Bohr, by Born's work, which provided "a complete description of the collision phenomena of Franck and Hertz, which may be said to exhibit the stability of st[ationary] states" (1927b, 71). Bohr's enthusiasm for Schrödinger's wave mechanics was manifest in his correspondence at the time. Shortly after Schrödinger's visit to Copenhagen, Bohr wrote to Ralph Fowler: "Just in the wave mechanics we possess now the means of picturing a single stationary state which suits all purposes consistent with the postulates of the quantum theory. In fact, this is the very reason for the advantage which the wave-mechanics in certain respects exhibits when compared with the matrix method." Two days later Bohr argued the same point in a letter to Kronig. Bohr made this point again in his first written attempt at interpretation leading to the Como lecture (Bohr to Fowler, 26 October 1926, AHQP; Bohr to Kronig, 26 October 1926, AHQP; Bohr 1927b, 70).

Closely connected with the idea of the quantum postulate and the concept of stationary states was the idea of quantization. The rules of quantization determined the choice of certain mechanical motions, to be associated with the stationary states, from a manifold of all possible classical motions. In this way a set of integers—quantum numbers—was associated with every stationary state. This choice by dictating integers seemed at best arbitrary, at worst a return to Pythagorean mysticism. Matrix mechanics, which dispensed with the description of stationary states, also eliminated the idea of quantization. Initially, as I have argued, Heisenberg and Born were quite happy to get rid of a postulate of quantization, deducing all the quantum effects, including the existence of the sequence of discrete stationary states, from the mathematical formulas of the matrix formalism. The concept of quantization reappeared, however, in Dirac's version of quantum mechanics,

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[6] When we identify the exact value of the energy of a stationary state by means of collisions or radiation reaction, we inevitably imply "a gap in the time description, which is at least of the order of magnitude of the periods associated with transitions between stationary states. In the limit of high quantum numbers these periods, however, may be interpreted as periods of revolution. Thus we see that no causal connection can be obtained between observations leading to the fixation of a stationary state and earlier observations of the behavior of the separate particles in the atom" (Bohr 1927c, 135).

indicating that perhaps this idea might have deeper significance than that conceived by matrix physicists.

Schrödinger's version of quantum mechanics allowed the resurrection not only of stationary states but also of the idea of quantization. According to Bohr, visualization in terms of the wave theoretical model points to the physical interpretation of quantization: "The number of nodes in the various characteristic vibrations gives a simple interpretation to the concept of quantum number which was already known from the older methods but at first did not seem to appear in the matrix formulation" (1927c, 126). While matrix mechanics defied any attempt at physical interpretation, Schrödinger's wave mechanics allowed an understanding of the electric and magnetic properties of atoms. The wave model also allowed an understanding of the failure of the concept of mechanical orbits: "From characteristic vibrations with only a few nodes no wave-packages can be built which would even approximately represent the motion of a particle" (Bohr 1928, 113).

Bohr's discussion of the problem of interaction, and especially of the problem of bound particles in the interior of an atom, is particularly instructive for seeing both the advantages of a wave ontology and its limitations. Because of the complementarity of the space-time and energy-momentum coordinates, for a free particle (and even more so for a bound one) precise knowledge of its momentum and energy excludes exact specification of its space-time coordinates. This implies the inadequacy of a particle-kinematic framework and the inapplicability of the classical concept of mutual forces and potential energy in Heisenberg's approach. This difficulty is "avoided by replacing the classical expression of the Hamiltonian by a suitable differential operator" (1928, 111). However, it is this advantage that shows the limits of visualization in the interior of the atom in terms of waves, because the Schrödinger equation contains imaginary numbers and is associated with a multidimensional space that is "in general greater than the number of dimensions of ordinary space." Therefore, intraatomic particles, though adequately represented by a wave theoretical framework, cannot be visualized in terms of ordinary space-time pictures. It is only a three-dimensional wave packet of a free particle that can represent a particle's space-time location. It is here that the most striking difference between classical and quantum mechanics lies: while in the former "particles are endowed with an immediate 'reality,' independently of their being free or bound" (1928, 114), in quantum mechanics intraatomic, bound particles are not visualizable. Consequently, Born's interpretation of the wave function as denoting the probability of position should not be applied uncritically to the interior of the atom.

This analysis was addressed simultaneously to Schrödinger and to Heisenberg, who were engaged in a controversy over the relative merits of wave and matrix mechanics. Schrödinger claimed superiority for his version, due to its greater visualizability, or intuitiveness. To counter Schrödinger, Heisenberg, in his uncertainty paper, presented an exclusively corpuscular interpretation. Bohr found both approaches inadequate. Bohr agreed with Heisenberg that Schrödinger's waves in multidimensional space could hardly be considered immediately intuitive. But neither was Heisenberg's approach satisfactory: the intraatomic reality was not a particle-kinematic one. We begin to see the depth of the gulf between Heisenberg's and Bohr's positions. Only with extreme caution, argued Bohr, can one employ ordinary categories in the interior of the atom; for example, the particle concept may be used only during very short times of observation. A consistent interpretation in such situations is possible only when the compatibility of the possibilities of observation and definition is closely analyzed. In general, the idea of individual particles has "just as much or as little 'reality'" as the idea of stationary states.

Not surprisingly, what Schrödinger perceived as the focus of Bohr's argument in the Como lecture was Bohr's defense of the concept of a stationary state. Schrödinger struck back with Bohr's own weapon, arguing that the combination of uncertainty relations and the idea of stationary states destroys compatibility between definition and observation: "It seems to me that there is a very strange relation between Heisenberg's uncertainty relation and the claim of discrete quantum states. On account of the former the latter can really not be experimentally tested" (Schrödinger to Bohr, 5 May 1928, AHQP; Schrödinger also discussed this issue in a letter to Einstein, 30 May 1928, Przibram 1967). This controversy was not resolved. In the 1950s, Schrödinger (1952a) criticized Bohr's idea of stationary states and quantum jumps extensively (see chapter 10).

Dialogue with Einstein and Compton

Another central problem in atomic physics at the time was that of the interaction of radiation and matter. More than any other, this problem cried out for nonclassical treatment. Nonclassical departures had already been made in Max Planck's and Albert Einstein's early work, including Einstein's idea of light quanta (Jammer 1966; Kuhn 1978). For Bohr the problem of the interaction between radiation and matter led to the famous Bohr-Kramers-Slater proposal. When certain conclusions of this theory were refuted by the Bothe-Geiger experiments, many physicists considered the reality of quanta to have been proved unequivocally (Klein 1970; Stuewer 1974). According to the usual accounts, Bohr accepted the failure of the Bohr-Kramers-Slater theory, as well as the existence of light quanta, striving from this point on to incorporate quanta into his interpretive framework. The principle of complementarity, announced by Bohr in his Como lecture, was the culmination of these efforts, resulting in a symmetrical solution of the wave-particle dilemma.

But you must know that he rejected waves!

In what follows I argue for a substantial revision of this reading. I see no evidence of Bohr's having accepted pointlike quanta. In fact, by using the de Broglie–Schrödinger idea of a wave packet, Bohr gained a dramatic insight into past difficulties, enabling him to rehabilitate the apparently discredited Bohr-Kramers-Slater theory.

The Bohr-Kramers-Slater paper, a programmatic rather than a technical work, had mapped out a comprehensive framework for the general problem of the interaction of radiation with atoms, eliminating the need for the idea of light quanta. In this theory, the kinematic model of the atom was replaced with a virtual oscillator model.[7] The virtual field produced by the atom determined its own probability for spontaneous emission, as well as the probabilities for the processes of emission and absorption induced in other atoms. Such a probabilistic description implied not only renunciation of exact conservation laws but—contrary to the light quanta point of view—independence of the processes of emission and absorption in atoms that are far apart.

The conflict between Bohr and Einstein on the nature of radiation caught the attention not only of the scientific community but of the general public as well (Klein 1970). The results of the Bothe-Geiger experiments, which were reported in April 1925, did not accord with the ideas of Bohr-Kramers-Slater. These experiments detected correlations between Compton recoil electrons and scattered X-rays, a result more in keeping with the light quanta concept of radiation that with the wave concept. Most physicists took the experiments as crucial evidence in favor of the corpuscular idea of light quanta. Pauli, for example, declared that from then on light quanta were "as real" as material electrons. There is no indication that Bohr ever considered the Bothe-Geiger and Compton-Simon experiments crucial with respect to the nature of light, even though it was clear to him that the program outlined in the Bohr-Kramers-Slater theory could not be retained without modification. Bohr explained his position in a letter to Hans Geiger, who had informed Bohr of the results of his experiments. Bohr further argued for the renunciation of ordinary space-time pictures—a necessity that was already apparent, according to Bohr, from an analysis of collision phenomena.[8]

The need to depart from ordinary space-time pictures has a clear meaning in Bohr's discussion of the interaction of radiation with matter. Wherever Bohr used the notion of space-time pictures, he discussed models using material particles traversing continuous spatial trajectories. The Bohr-Kramers-Slater theory clearly indicated why such ideas could no longer be applied. In the case of the interaction of light with free electrons (the Compton effect), the wave picture of light indicated kinematic peculiarities in the description of the electron's motion. In the Bohr-Kramers-Slater theory, the notion of the atom as a kinematic system of orbiting electrons was replaced by a virtual oscillator model. The visualization of a stationary state of the atom as a state in which electrons move along well-defined orbits was abandoned (a step also indicated by Bohr's analysis of collision processes).[9] Bohr's reaction to the "crucial" Bothe-Geiger experiments was greater conviction that the ordinary space-time concepts of material particles were inadequate, and that a still more far-reaching revision of such concepts was necessary. Perhaps, he argued, de Broglie's modification of the idea of material particles might help to resolve this situation (Bohr 1925).

This thought, entertained as early as 1925, found its full expression in the Como lecture. The instantaneous interaction of light (wave phenomena extended in space and time) with matter (pointlike particles) is not reconcilable with exact conservation laws—the reason for introducing statistical conservation in the Bohr-Kramers-Slater theory. However, if the space-time and energy-momentum vectors of electrons are not sharply defined (as in the case of a wave packet, as opposed to a localized particle), the wave picture of light can be reconciled with the conservation laws. This idea is expressed in all the manuscripts preceding the Como lecture, as well as in the lecture itself. It is the complementarity of the space-time and energy-momentum vectors of a wave packet that makes it possible to unite space-time coordinates and

How?

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[7] In each of its stationary states, an atom continuously emits a virtual wave field, which is "equivalent to the field of radiation which in the classical theory would originate from the virtual harmonic oscillators corresponding with the various possible transitions to other stationary states" (Bohr, Kramers, and Slater 1924, 164).

[8] "Conclusions concerning a possible corpuscular nature of radiation lack a sufficient basis" (Bohr to Geiger, 21 April 1925, AHQP; *BCW*, 5:353). A similar position was expressed in other letters by Bohr at the time, as well as in the postscript to his "Über die Wirkung" (Bohr 1925), where he attempted to extend the nonconservation ideas of Bohr-Kramers-Slater to collisions between atoms and material particles.

[9] Bohr 1925. The misinterpretation that Bohr accepted light quanta is related, in my opinion, to the fact that many authors assume Bohr's statement about "space-time pictures" applies to the wave propagation of light as well and consequently conclude that the failure of space-time pictures applies to classical wave theory. However, I am not aware of anything in Bohr's writings at the time supporting this point of view: wherever Bohr used the phrase "failure of space-time pictures," it referred to the failure of models using pointlike material particles.

conservation principles. What seemed a contradiction is now removed through the introduction of an essential wave feature in the description of the behavior of material particles: "The general character of this relation [the complementarity of the sharpness of definition of the space-time and energy-momentum vectors] makes it possible to a certain extent to reconcile the conservation laws with the space-time coordination of observations, the idea of a coincidence of well-defined events in space-time points being replaced by that of unsharply defined individuals within finite space-time regions" (Bohr 1927d, 93). As opposed to the earlier description of the Compton effect, where "in the change of the motion of the electron . . . one . . . is dealing with an instantaneous effect taking place at a definite point in space," the new wave theoretical view of matter indicated that "just as in the case of radiation . . . it is impossible to define momentum and energy for an electron without considering a finite space-time region" (Bohr 1928, 96).

All these ideas signaled nothing less than the resuscitation of what seemed a discredited (Bohr-Kramers-Slater) theory, and a further rejection of the idea of light quanta. Though Bohr did not argue this point explicitly in his Como lecture, the message is implicit in his analysis. What Bohr only hinted at, Hendrik Kramers, his faithful disciple, chose to announce unambiguously in the discussion following Bohr's lecture. Kramers opened his remarks by saying that he "shall not be able to add anything fundamental to Professor Bohr's exposition." Kramers intended only to call the attention of the audience to the examples, which illustrated the resolution of past paradoxes and difficulties with the help of the wave theory of matter: "I am thinking especially of the principle of conservation of energy and momentum, which seemed to contradict the wave-theory of light. . . . The difficulty, that the *results of these experiments* [Bothe-Geiger and Compton-Simon] *were at variance with the wave theory of light, disappears definitely,* if the de Broglie wave theory of matter is taken into account" (*BCW,* 6:139, my italics).[10]

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Thus the victory of Einstein and his conception of light quanta, in the view of Bohr and Kramers, was only apparent. Bohr was more outspoken about this issue in private correspondence and discussions than in formal addresses. As Bohr informed Einstein: "In view of this new formulation . . . it becomes possible to reconcile the requirement of energy conservation with the implication of the wave-theory of light, since according to the character of the description the different aspects never manifest themselves simultaneously" (Bohr to Einstein, 13 April 1927, AHQP; also *BCW,* 6:420, my translation).[11]

Bohr's complementarity viewpoint, formulated in the Como lecture, represented a "second phase" in his lifelong dialogue with Einstein. This dialogue was, in Pais's incisive phrase, "Bohr's inexhaustible source of identity" (1967, 219). Bohr never yielded; his entire epistemological edifice was constructed in dialogical response to Einstein's ceaseless challenge.

Dialogue with Campbell

We now turn to another central problem of the atomic domain—the interaction of matter with matter—and to yet another crucial dialogue with the lesser known Campbell. Bohr's first notes for the Como lecture were triggered by an exchange of letters between Campbell and Jordan on the interpretation of quantum theory (Campbell 1927; Jordan 1927c). Campbell took an early interest in Bohr's theory and its interpretation. In 1913, Campbell published a review of Bohr's new atomic theory. In the 1920s, Campbell suggested that the idea of orbiting electrons in stationary states was a purely formal assumption and that no reality could be ascribed to Bohr's planetary model. At the time, Bohr was not ready to consider such a suggestion—a stand he modified gradually when mechanical visualization led to a crisis of the old quantum theory. In 1921 Campbell suggested that the paradoxes of quantum theory could be avoided by modifying the concept of time and endowing it with statistical significance only. Again, Campbell's idea was not greeted with enthusiasm, probably because at the time Bohr's theory was scoring impressive successes. Encouraged by recent developments that acknowledged the need to modify space-time concepts and to renounce visualization (Bohr 1925; Heisenberg 1925), Campbell repeated and extended his earlier suggestion that time be treated statistically in

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[10] Kramers repeated Bohr's considerations, emphasizing that similar considerations apply to the question of the correlation of processes of emission and absorption in distant atoms: while an exact correlation (emission of a light quantum from the source and absorption of the "same" light quantum in the absorbing matter) is out of the question, an "approximate" correspondence is, in fact, maintained, in agreement with the basic ideas of wave mechanics (*BCW,* 6:139–40).

[11] Similarly, in discussions following Compton's talk at the fifth Solvay conference, held a month after the Como meeting, Bohr continued to argue against the idea of point-like light quanta, using explicitly de Broglie–Schrödinger wave concepts. According to Bohr's description of the scattering process, "we must work with four wave-fields of finite extension" (two for electrons, before and after the phenomenon, and two for the incident and scattered light quanta), which are localized in the same space-time region. This modification of space-time concepts of particles preserves the ideas of the wave picture of light (and matter) together with conservation laws. Moreover, as Bohr pointed out, in the Compton experiment "the frequency shift produced is measured by means of instruments, the functioning of which is interpreted according to the wave theory" (*BCW,* 5:211). Compton (1927) apparently did not find Bohr's arguments conclusive, arguing that the last word on this issue had not yet been said.

the programmatic paper "Time and Chance," published in 1926. This paper spurred Bohr's reasoning, as it did Heisenberg's (chapter 4), leading to the formulation of Bohr's complementarity principle.

Campbell (1926) reminded his readers both of his earlier proposal that the quantum and classical theories be reconciled by abandoning the concept of time in the interior of the atom and of Bohr's recent declarations (arrived at "of course quite independently") that the description of the quantum domain in terms of space and time might be impossible. Campbell referred to Bohr's famous postscript to his paper on the behavior of atoms in collisions, where Bohr took this stand (Bohr 1925). The paper itself was written before Bohr was familiar with the results of the Bothe-Geiger and Compton-Simon experiments, and it constituted Bohr's attempt to provide further guidelines for resolving the difficulties of quantum theory by extending the idea of nonconservation of energy from the realm of interactions between radiation and matter (Bohr-Kramers-Slater theory) into the realm of interactions between matter and matter (scattering, atomic collisions, ionization). Bohr's paper clearly displayed his thinking in terms of concrete models of atoms where stationary states were represented by mechanically orbiting electrons, and where processes were categorized as "reciprocal" or "irreciprocal" depending on whether the interaction time of particles passing by the atom is longer or shorter than the natural periods of revolution of the atomic electrons. When an atom collides with an electron of slow velocity, the time of collision is comparable to the periods of revolution of the intraatomic electrons; so during the time of collision, the passage of the atom into its final stationary state can be completed and energy is conserved (a "reciprocal process"). In the case of swiftly moving particles (such as α- and β-particles), "the collision [with the atom] must probably be regarded as finished long before one can speak of the completion of a possible transition of the atom from one stationary state to another" (Bohr 1925; *BCW*, 5:198).

Bohr suggested that, as in the case of radiation, so also in the case of collisions of swiftly moving particles with atoms, only statistical laws of energy conservation apply. This consideration was also connected with the fact that, while the reaction of an atom upon a particle is adequately expressed by continuous parameters, the change of state of the atom is described by discontinuous values. Bohr applied similar considerations to the case of collisions between atoms. The discussion and the conclusion of nonconservation were firmly based on space-time imagery in the interior of the atom. It was the limitation of this imagery that Bohr acknowledged in the postscript, after he became familiar with the results of the Bothe-Geiger experiments implying strict conservation. This point is also stated explicitly in Bohr's nontechnical paper, summarizing recent developments: "For impacts in which the time of

collision is short compared to the natural periods of the atom . . . the postulate of stationary states would seem to be irreconcilable with any description of the collision in space and time based on the accepted ideas of atomic structure" (Bohr 1926; *BCW*, 5:851).

This conclusion formed the necessary background to the development of matrix mechanics, as well as a starting point for Campbell's discussion. Campbell's proposal that time be treated as statistical in nature was intended to provide a way out of this predicament, indicating how the space-time description of atomic phenomena must be modified. Campbell tackled Bohr's concern with collisions of fast-moving particles with atoms, suggesting that if time is statistical, the paradox resulting from the comparison of "short" collision times with "long" periods of electron revolution does not arise: "The conclusion that it [time] is short depends entirely on the assumption that the motion of the particle and the oscillation of the atom are uniform. This, of course, we deny. Particles moving with uniform velocity or oscillating in fixed orbits are undergoing fortuitous transitions between the points of their paths" (1926, 1111).

Campbell's discussion played an important role, as I have argued, in the emergence of Heisenberg's uncertainty paper. It also provided impetus to Bohr's further retreat from the reality of stationary states in his Como lecture. However, Bohr could not accept a statistical conception of time, for it would threaten his overall research program in the atomic domain, which was intimately connected with classical electromagnetic theory. In this theory periodicity in time is explicitly assumed. The new quantum theory, advocated by Campbell, clearly "cannot be deduced from Maxwell's equations in their present form" (Campbell 1926, 1113). Bohr, who vigorously defended Maxwell's electrodynamics against Einstein's idea of light quanta, and who even after the Bothe-Geiger results would only admit a need to modify space-time imagery rather than to revise electromagnetic theory itself, could not agree with Campbell's assertion.

However, Campbell's focus on the nature of time in dealing with the space-time problem in the interior of the atom turned out to be very suggestive: "The singular position of time in problems concerned with stationary states is . . . due to the special nature of such problems" (Bohr 1927c, 131). As for the conflict between space-time descriptions and conservation laws, discussed by Bohr in 1925 and subsequently treated by Campbell, the resolution of this conflict constituted another example of the complementarity between space-time and causality.[12]

[12] "If the definition of the energy of the reacting individuals is to be accurate to such a degree as to entitle us to speak of conservation of energy during the reaction, it is necessary . . . to coordinate to the transition between two stationary states a time interval long compared to the period associated with this process. This is particularly to be re-

Clash with Heisenberg: Setting the Historical Record Straight

We are now better equipped to evaluate the clash between Heisenberg and Bohr over Heisenberg's uncertainty paper, and to determine the effect this clash had on the consolidation of Bohr's position. An understanding of the wide gap between Bohr's and Heisenberg's interpretive positions and professional interests illuminates the intense emotional strain that surrounded the Bohr-Heisenberg dialogue. The strain was so acute that Bohr and Heisenberg needed to spend some time away from each other, during which Heisenberg was able to write his uncertainty paper, and Bohr to elucidate his formulation of complementarity. Intense also was the confrontation between Bohr and Heisenberg over the uncertainty paper: Bohr found the paper mistaken and premature, forcefully urging Heisenberg not to rush into print. Heisenberg did not yield, though occasionally "bursting into tears" as a result of immense emotional pressure coming from Bohr (interview with Heisenberg, AHQP). Heisenberg (1927b) merely agreed to append a postscript that acknowledged Bohr's criticism without revising the content of the paper itself. One of the mistakes Bohr found occurred in Heisenberg's analysis of uncertainty during measurement in the γ-ray thought experiment. In his analysis Heisenberg treated both photons and electrons as regular point particles (!), arguing that during their collision (interaction!) a photon transfers a discrete and uncontrollable amount of energy to the electron (Compton recoil). Yet the Compton recoil of point-mass particles would not lead to indeterminacy, as I discussed in chapter 4, but to precisely calculable changes, as Bohr pointed out. The correct explanation, Bohr insisted, relies on the wave nature of light and matter in an essential way. I have argued earlier that in opposition to Schrödinger's accusations, Heisenberg's uncertainty paper was aimed at demonstrating that the "frightfully" abstract matrix mechanics is amenable to a visualizable, intuitive interpretation. As opposed to Schrödinger's program of wave ontology, aimed at eliminating the matrix approach, Heisenberg in his uncertainty paper used exclusively particle-kinematic concepts. In this effort, Heisenberg wanted to avoid Schrödinger's waves altogether (interview with Heisenberg, AHQP; interview with Klein, AHQP). Clearly, correcting the mistakes in the way that Bohr suggested, which involved essential reliance on wave concepts, would undermine Heisenberg's aims. Nor would the intensely ambitious Heisenberg withdraw his paper and miss the opportunity to make another pivotal contribution by letting Bohr reap all the fruits of their interpretive struggle. As Heisenberg himself put it: "Perhaps it was also a struggle about who did the whole thing first" (interview with Heisenberg, AHQP).

In the postscript to the uncertainty paper, Heisenberg acknowledged several mistakes in his argument and included Bohr's objection to his analysis of the Compton effect—Compton recoil applies rigorously only to free and not to bound electrons. Given this mistake, Bohr must have thought, Heisenberg had completely failed to provide a physical interpretation for the interior of the atom. We have seen in this chapter what an ingenious conceptual web of arguments Bohr had spun in order to comprehend "intuitively" intraatomic structure. No wonder Bohr found Heisenberg's paper unsatisfactory. Even in the case of free electrons in the Compton effect, as we saw earlier, Bohr found particle-kinematic concepts inadequate. In any type of physical interaction, reliance on wave concepts (superposition of waves) was essential, according to Bohr. Electrons and photons treated as point-masses in Heisenberg's discussion not only led to technical mistakes in the discussion; they were "abstractions," insufficient for the description of real physical situations. This was the focus of the confrontation between Heisenberg and Bohr.[13] The issue was not metaphysical preferences (wave-particles as opposed to the mathematical structure of the formalism), as Heisenberg's recollections would lead us to believe, but Bohr's dissatisfaction with Heisenberg's exclusively particle-kinematic interpretation. The mistake Heisenberg made in the discussion of the γ-ray experiment, as well as his failure to correct this mistake in the particle framework, strengthened Bohr's position. Bohr's elucidation of the concept of the stationary state, and his resolution of past paradoxes of the Bohr-Kramers-Slater theory in the wave theoretical framework, made the gap between himself and Heisenberg unbridgeable. Bohr's Como lecture clearly displays his dissatisfaction with Heisenberg's position, though in a subtle way. When discussing the uncertainty principle, Bohr pointed to the mistake in Heisenberg's derivation of uncertainty in the γ-ray thought experiment: "Such a change [momentum change during a position measurement] could not prevent us from ascribing accurate values to the space-time coordinates, as well as to the momentum-energy components before and after the process. The reciprocal uncer-

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membered when considering the passage of swiftly moving particles through an atom. According to the ordinary kinematics the effective duration of such a passage would be very small as compared with the natural periods of the atom, and it seemed impossible to reconcile the principle of conservation of energy with the assumption of the stability of stationary states" (Bohr 1928, 116).

[13] "I argue with Bohr over the extent to which the relation $p_1q_1 \sim h$ has its origin in the wave—or the discontinuity aspect of quantum mechanics. Bohr emphasizes that in the gamma-ray microscope the diffraction of the waves is essential; I emphasize that the theory of light quanta and even the Geiger-Bothe experiments are essential" (Heisenberg to Pauli, 4 April 1927, *PC*).

tainty . . . is an outcome of the limited accuracy with which changes in energy and momentum can be defined, provided the wave-fields used for the determination of the space-time coordinates of the particle shall be sufficiently limited" (1927c, 120–21).

Some contemporary physicists understood well the point Bohr was making. Ehrenfest, in a remarkable letter to Goudsmit, Uhlenbeck, and Dieke, referred to Bohr's derivation of uncertainty, relying on "wave kinematics" and "amending the error running through the Heisenberg paper" (*der durchlaufenden Fehler von Heisenberg;* Ehrenfest to Goudsmit, Uhlenbeck, and Dieke, 3 November 1927, AHQP, translated in *BCW,* 6: 37–41, quote on 39). Born, in a discussion following the Como lecture, accepted Bohr's derivation of uncertainty as following, not from uncontrollable changes during measurement, but from the wave nature of matter (*BCW,* 6:137–38). If, for Heisenberg, uncertainty followed from discontinuity (discontinuous changes), for Bohr, uncertainty followed from a dialectical combination of continuity and discontinuity, or "individuality and superposition." For Bohr, at this point, not the operational definition of concepts, but agreement between the possibilities of definition and observation was essential.

The Como lecture contains other, more subtle hints of Bohr's past disagreements with Heisenberg. The clash over uncertainty was not the first time Bohr had reason to be dissatisfied with Heisenberg's position. As Bohr's secretary, Betty Schultz, recalls (interview with Schultz, AHQP), Heisenberg was not very helpful to Bohr, certainly not as useful as the ever loyal Kramers or, later, the agreeable Klein (about Kramers's crucial role in Bohr's research program, see Dresden 1987). Nor was Heisenberg always scrupulous about acknowledging his debt to Bohr. In his reinterpretation paper (1925), Heisenberg does not cite Bohr's work at all, despite the fact that the paper was built on Bohr's correspondence principle in a fundamental way. Nor does Heisenberg mention Bohr's conclusion from his 1925 paper about giving up space-time visualization inside the atom. Instead, Heisenberg presented his work as flowing from the positivist principle of elimination of unobservables. I have argued that this was not a guiding principle, but a justification after the fact, and that the conceptual package—correspondence principle, nonconservation, wave theory of light—seemed to be discredited by the Bothe-Geiger results. It is likely that Heisenberg chose not to mention the correspondence principle for strategic reasons. Bohr must have been unhappy about this, as well as about the fact that Heisenberg's matrix mechanics suppressed the idea of quantization and "swallowed" the idea of stationary states.

In his Como lecture Bohr set the historical record straight. After citing work by Kramers and Rudolf Ladenburg as a "characteristic example of the correspondence," Bohr presented matrix mechanics as the culmination of his own research program, based on the correspondence principle: "It is only through the quantum theoretical methods created in the last few years that the general endeavors laid down in the [correspondence] principle . . . have obtained an adequate formulation" (1927c, 124). Bohr also expressed his reservation about the initial emphasis on observability in papers on matrix mechanics, finding this emphasis not only historically misleading but physically inadequate. Only in "a certain sense" may matrix mechanics be described as a "calculus with directly observable quantities," because it is "limited just to problems, in which in applying the quantum postulate the space-time description may largely be disregarded, and the proper question of observation therefore placed in the background" (1927c, 125). The correspondence principle, according to Bohr, continued to serve as a necessary basis for the interpretive framework of physics, together with the indispensability of classical concepts. This is the reason for the amalgamation of "historical" and "philosophical" aspects in the Como lecture, which has puzzled some scholars of Bohr's work (Folse 1985; Gibbins 1987). Bohr's subtle message registered fully with Heisenberg, who from that time on, in his historical expositions, presented his reinterpretation paper as following from Bohr's correspondence principle.

Confrontation with Pauli

According to the usual historical accounts, the confrontation between Heisenberg and Bohr ended when each comprehended the other's point of view, realizing that there was no real contradiction between their positions. But the text of the Como lecture, as well as Bohr's and Heisenberg's scientific correspondence at the time, reveals the continuing gap between their interpretations of the atomic interior. For Bohr, the Heisenberg-Born-Pauli statistical kinematic interpretation of particles ("abstractions") was not sufficient for a consistent interpretation of quantum physics; the wave nature of free "individuals" (electrons, photons) had to be taken into account in an essential way. The uncertainty relations, according to Bohr, apply rigorously only to free particles (as a direct consequence of the limitation of the associated wave fields) and in general cases of interaction "must always be applied with caution" (Bohr to Schrödinger, 23 May 1928, AHQP, translated in *BCW,* 6:49). In particular, the uncertainty relation between position and momentum for discrete stationary states of an atom cannot hold true without modification. According to Bohr, the application of the concept of a stationary state and the tracking of the behavior of individual particles in the atom are mutually exclusive.

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As one of the main architects of the particle-kinematic interpretation of the interior of the atom, Pauli did not agree with Bohr. For Pauli it was meaningful to talk about the uncertainty relation for particles in the case of individual discrete stationary states, as was discussed in Heisenberg's paper. Nor did Pauli agree with Bohr that a visualizable, intuitive interpretation is possible only in three dimensions, arguing that his own interpretation of the wave function could "in principle be empirically ascertained by statistical utilization of results of observation" (Pauli to Bohr, 17 October 1927, *PC*). The Bohr-Pauli dialogue had a crucial effect on further elaborations of complementarity. Pauli, an early critic of continuous field theories, was not as enthusiastic as Bohr about the indispensability of classical electrodynamics. He did accept the Bothe-Geiger results as conclusive evidence of the physical reality of Einsteinian light quanta. Bohr's complementarity of space-time and causality was not always clear to Pauli (Pauli to Bohr, 13 January 1928, *PC*). The first comprehensive discussion of wave-particle duality, as far as I know, is presented in Pauli's 1933 encyclopedia article. Pauli, then, was most likely the architect of the symmetrical complementarity of waves and particles, as distinct from Bohr's different notion of the complementarity of space-time and causal descriptions.

Bohr's and Pauli's versions of the interior of the atom were not, as far as I know, ever reconciled. Subsequent elaborations of complementarity (two-slit experiments, interaction of atomic objects with measuring devices) centered on individual particles. Bohr and Pauli did, however, agree entirely on the importance of elucidating the concept of measurement for the interpretation of quantum physics (Pauli to Bohr, 17 October 1927, *PC*). Subsequently, the *Nature* version of the Como talk (Bohr 1928), which was conceived in dialogue with Pauli, placed heavier emphasis on measurement than had the original version delivered at the conference, written in collaboration with Klein and Darwin. If the Como lecture stressed harmony between the possibilities of definition and observation, the later *Nature* version ushers in the key theme of the "uncontrollable element" introduced by observation. Bohr's and Heisenberg's positions seem to have become closer. In addition, Bohr's enthusiastic praise of Schrödinger's theory was subdued in the *Nature* version. Bohr's claim in the Como lecture that "just Schrödinger's formulation of the problem of interaction seems particularly well-suited for the illustration of the nature of the quantum theory" was eliminated from the *Nature* article. Similarly eliminated was the claim about the utility of Schrödinger's wave mechanics for a "demonstration of the consistency of symbolic [matrix] methods" (1927c, 128). With Pauli's skillful assistance, the Göttingen-Copenhagen front was uniting and consolidating its stand.

Conclusion

The united public front did not imply that the Copenhagen interpretation was coherent or consistent. The "interpretation" was actually an amalgamation of the different views of Bohr, Born, Heisenberg, Pauli, and Dirac. There is no indication that Heisenberg fully accepted Bohr's views. Unlike Bohr, the "mathematical physicist" Heisenberg preferred one coherent set of concepts, rather than two incompatible ones.[14] In this respect, Heisenberg was much closer to the "enemy" Schrödinger, who considered Bohr's solution merely a judicious escape. Heisenberg's position was that wave language and particle language, being equivalent descriptions of the same reality, were mutually convertible. One could therefore use either language at will, that of particles or that of waves, without needing to use them simultaneously, as Bohr claimed (interview with Heisenberg, AHQP).

According to the usual accounts, soon after their heated arguments over the uncertainty paper, Bohr and Heisenberg reached complete agreement. Yet genuine unanimity of opinion between the two men never occurred. Rather they realized that "all that mattered now was to present the facts in such a way that despite their novelty they could be grasped and accepted by all physicists" (Heisenberg 1971, 79). The need to offer a unified explanation, capable of countering the opposition, was ? one of the reasons for the obscurity of Bohr's Como lecture, where the differences between Bohr's and Heisenberg's positions were subdued. Such obscurity was necessary in order to conceal the conceptual gap between their interpretations of physics for the interior of the atom. The uncertainty principle for the position and momentum of a particle ? cannot easily be reconciled with the representation of separate stationary states by harmonic partial vibrations. This difficulty was one of the early targets for Schrödinger's criticism. Einstein agreed fully with Schrödinger that the particle-kinematic framework, even when supplemented by the uncertainty principle, was deficient, and that the "shaky" concepts p and q should be abandoned: "The whole thing was invented for *free particles* and suits only this case in the natural way." It was not because of their "classical nostalgia" that Einstein and Schrödinger were not persuaded by the "Bohr-Heisenberg tranquilizing philosophy" (Einstein to Schrödinger, 31 May 1928, Przibram 1967).

Years later, Heisenberg conceded that Bohr's matter wave interpretation for the interior of the atom was perhaps "much closer to the truth"

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[14] "If one immediately starts with the supposition there are both waves and particles, everything can be made contradictory free," Heisenberg wrote disapprovingly to Pauli two months after the uncertainty paper appeared (May 1927, *PC*). See chapter 11 for further discussion of this issue.

than his own (1958, 51). Yet the conflict between Bohr and Heisenberg on this issue had been circumvented rather than resolved. Subsequent interpretive developments shifted the emphasis to the measurement problem, the algebra of Hilbert spaces, quantum logic—areas of inquiry dissociated from the initial struggles over what happens inside the atom. As Heisenberg revealed, the physicist had no choice but "to withdraw into the mathematical scheme" when the vague use of classical concepts, encouraged by Bohr's complementarity, led to difficulties and inconsistencies (1958, 51). This sort of escape was not open to Bohr—a "natural philosopher" rather than a "mathematical physicist" (see chapter 12). To the end of his life Bohr struggled to clarify and extend his complementarity framework. In order to comprehend further developments, as well as the numerous contradictions in the orthodox interpretation of quantum physics, a historical perspective on the initial interpretive efforts is necessary.

Nor is the genesis of Bohr's complementarity principle fully comprehensible without taking into account such psychosocial factors as ambition, professional interest, group dynamics. It is remarkable, though not surprising, how much the cognitive positions of different contributors coincided with their professional and personal interests. Thus Bohr, in his Como lecture, emphasized the wave aspect of matter and light; the wave ontology allowed him to preserve and entrench his major contributions to science—the idea of stationary states, the approach of the Bohr-Kramers-Slater theory, the statistical description of atomic collisions. Heisenberg, who had no direct investment in these ideas, was ready to dispense with the wave aspect altogether, in order to argue the superiority of matrix mechanics, to which he had contributed so decisively. Emotional intensity in a scientific dialogue is not an aberration; it is vital fuel for the shaping of ideas, the formation of stands, the achievement of breakthroughs. In dialogical accounts that acknowledge the essential formative role of scientific controversies, the line between the "cognitive" and the "social" becomes blurred.

Equally problematic becomes the idea of a definable research program. A simplistic division between "orthodox" and "opposition" is not adequate for describing a living, creative stage in the formation of ideas. We see, rather, flexibility, simultaneous openness to different conceptual options, at times genuine dialogue, at times "infiltration" or selective appropriation of opponents' ideas. We saw that on certain points Bohr was closer to Schrödinger than to Heisenberg, while on other issues Heisenberg was closer to Schrödinger than to Bohr. At times, emotions become fierce, but no concessions are made; this is what happens at the crossroads of vital interests.