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Helge Kragh
Editor

Niels Bohr

On the Constitution of Atoms and Molecules

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Preface

About a century ago, on 3 March 1921, Niels Bohr inaugurated the famous institute of theoretical physics in Copenhagen which a few years after his death became officially named after him. On 10 December the following year he received the Nobel Prize in Stockholm after first having been nominated in 1917. The two events, and generally Bohr's status as one of the leading physicists during the first half of the twentieth century, had their background in a series of three papers published between July and November 1913 in the prestigious English journal *Philosophical Magazine* (despite its name, the journal was since its foundation in 1798 devoted to physics and not to philosophy). The three papers carrying the common title "On the Constitution of Atoms and Molecules" are often referred to as Bohr's trilogy. The radically new model of atomic structure introduced in the first instalment came as a bolt out of the blue, written by a young Danish physicist who was practically unknown outside his own country. On the other hand, he was not completely unknown, for at the time he had published two papers in *Philosophical Magazine* (1912, 1913), one in the *Proceedings of the Royal Society* (1910) and one more in the *Philosophical Transactions of the Royal Society* (1909).

All the same, it was the trilogy which changed the scene of physics. It was only with this work that physicists realized that quantum theory was an essential ingredient in atomic physics, and it was also only with this work that Rutherford's nuclear model dating from 1911 was transformed into a proper theory of atomic structure. About ten years later theoretical atomic physics without Bohr's quantum atom was generally regarded as nonsense, almost oxymoronic. Even more important in the longer perspective, the theory created in 1913 contained the germ to the later Heisenberg–Schrödinger quantum mechanics, if more in Heisenberg's version than in Schrödinger's. In one sense, modern quantum mechanics grew out of Bohr's theory and its associated correspondence principle, and yet it grew out of the theory only by negating some of its essential elements such as electrons moving in definite orbits.

Bohr's trilogy of 1913 unquestionably deserves the label "classical text". Given its significance it is only natural that it has previously been reproduced and scrutinized by physicists, historians and philosophers. There also exist translations to languages other than English, such as Chinese. Somewhat strangely, perhaps, Bohr's atomic theory is not among the treatises reproduced in the nearly 300 volumes of Wilhelm

Ostwald's famous series *Klassiker der exacten Wissenschaften* (Classics of Exact Sciences) published between 1889 and 1987. The reason may have been that a complete German translation of the trilogy was published as early as 1921, translated by the physicist Hugo Stintzing (Bohr, 1921). Most of the modern reproductions, whether in print format or as found on the internet, cover only the first instalment of the trilogy, whereas the two other parts are today less visible. Although this is understandable, it is also unfortunate given that Bohr thought of the trilogy as a whole and conceived the main content of Parts II and III before he wrote the draft that became Part I.

The entire trilogy was reproduced together with pertinent archival sources in Rosenfeld (1963) and later in volume 2 of Bohr's *Collected Works* (Bohr, 1981). Among the several works in which Bohr's original atomic theory have been analysed from a historical point of view, Heilbron and Kuhn (1969) is one of the earliest and still most valuable. Hoyer (1974) is another early and detailed analysis based on archival sources. Other works including insightful considerations on the birth of the Bohr atom and the content of the trilogy are Mehra and Rechenberg (1982, pp. 181–258), Darrigol (1992, pp. 81–100), Arabatzis (2006, pp. 112–150), Kragh (2012a, pp. 39–139), Aaserud and Heilbron (2013), Darrigol (2016), and Duncan and Janssen (2019, pp. 143–204).

The central parts of the present work are annotated reproductions of five of Bohr's publications on the quantum theory of atoms published between July 1913 and February 1914. The first three texts (3.a, 3.b, 3.c) are Bohr's trilogy papers, which here appear in versions retyped from the original because of copyright problems. The fourth text (3.d) is an English translation of a paper published in Danish in *Fysisk Tidsskrift* and based on an address to the local Physical Society which Bohr gave in late December 1913. Although this paper was not generally known at the time, it belongs to the same cluster of articles as the three trilogy papers. The fifth of the included texts, here reproduced as 3.e, is a brief paper in *Nature* of 23 October 1913 in which Bohr discussed his theoretical predictions in relation to apparently problematic spectroscopic data. This text is immediately followed by a response by the British astrophysicist Alfred Fowler.

The present work starts with a condensed biographical account of Bohr's life and scientific career, from his birth in Copenhagen in 1885 to his death in the same city 77 years later. This mini-biography is of course highly selective. Chapter 2 outlines some of the important developments in atomic physics prior to Bohr's seminal contribution, such as the theories of J. J. Thomson and Rutherford, and it traces Bohr's route from his doctoral dissertation in 1911 over his stays in Cambridge and Manchester to the submission in April 1913 of the first part of the trilogy. In Chapter 4, the articles reproduced in the previous chapter are followed by a limited number of notes and commentaries related to the texts. The purpose of the notes is primarily to clarify some of the textual passages and to explicate names and subjects that are not immediately clear or well known. One thing is the actual content of the new quantum theory of atoms and molecules, another is how it was received by contemporary physicists and chemists. This is discussed in Chapter 5, which deals with the immediate reactions to Bohr's theory 1913–1915 mostly among British, German and American scientists. The book ends with a bibliography of relevant primary and secondary sources. I am grateful to the Niels Bohr Archive for its permission to use the included figures and to the publisher Birkhäuser for having arranged the retyping of the trilogy.

Copenhagen 2022 *H. Kragh*

Contents

Fig. 1 Albert Einstein and Niels Bohr in conversation during the 1930 Solvay congress in Brussels. Courtesy of the Niels Bohr Archive, Copenhagen.

Chapter 1
Bohr in Brief

"That ... a man of Bohr's unique instinct and tact [could] discover the major laws of spectral lines and of the electron-shells of the atoms together with their significance for chemistry appeared to me like a miracle and appears as a miracle even today. This is the highest form of musicality in the sphere of thought" (Einstein 1949, p. 4). Thus wrote Albert Einstein in 1946 about his six-year younger colleague, whom he first met in 1920 and much appreciated as both a physicist and a human being. As one of the leading scientists of the twentieth century, Niels Bohr has often been portrayed by physicists, historians of science, and other authors. On the other hand, compared to other giants of science – say Darwin, Pasteur, Einstein and Feynman – relatively little has been written about Bohr's life. There is but a handful of full and seriously researched biographies.[1] This section merely offers a fragmentary sketch of some of the more important events in Bohr's life and career.

1.1 Early Years

Niels Henrik David Bohr was born in central Copenhagen on 7 October 1885, the second of three siblings. His mother, née Ellen Adler, belonged to a wealthy and influential Jewish banking family and his father, Christian Bohr, was a promising physiologist who five years later was appointed professor at Copenhagen University, the country's only university. Internationally recognized for his important work on blood gases and related areas of physiology, Christian Bohr was nominated for the Nobel Prize in 1907 and again in 1908, although with no success. Niels Bohr had an elder sister, Jenny, and a younger brother, Harald, who were born on 9 March 1883 and 22 April 1887, respectively. Niels and Harald had and continued to have until Harald's death in 1951 a very close relationship. Harald Bohr chose mathematics as his calling and made an international career even before his older brother. In 1910 he defended his doctoral dissertation on Dirichlet series, a subject which he later

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[1] Major biographical works on Bohr include Moore (1966), Röseberg (1992), Blaedel (1988), and Pais (1991). Heilbron (2020) is a short but useful introduction. There is also much biographical information in, for example, Rozental (1967) and French and Kennedy (1985). The most important source is *Niels Bohr Collected Works* published in 12 volumes between 1972 and 2007.

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extended to what was his most outstanding contribution to mathematics, the theory of almost-periodic functions dating from the mid-1920s.

In 1903 Niels Bohr entered Copenhagen University to study physics as his major subject and mathematics, chemistry, and astronomy as his minor subjects. His physics teacher was Christian Christiansen, a close friend of Bohr senior. Christiansen had since 1886 occupied the country's only chair in physics and was internationally known as the author of the widely used *Elemente der theoretischen Physik*, a textbook which in 1897 appeared in an English translation as *Elements of Theoretical Physics*. In addition, Christiansen was known for his experimental works in areas of optics and thermodynamics. Niels Bohr wrote his first scientific paper in 1909, a predominantly experimental investigation of the surface tension of liquids published in the *Philosophical Transactions of the Royal Society*. The paper grew out of a prize investigation proposed by the Royal Danish Academy of Sciences and Letters in 1905, and two years later the Academy notified Bohr that he had won the prize and the associated gold medal. In the absence of a university physics laboratory, Bohr did the experiments in his father's physiology laboratory.

The paper in *Philosophical Transactions* was followed the next year by a purely theoretical analysis of the same topic which was published in the *Proceedings of the Royal Society*. However, the young physics student did not continue his studies of surface tension. At the time when Bohr obtained his master's degree, also in 1910, he had become seriously interested in a very different topic, namely the electron theory of metals on which he wrote his 1911 doctoral dissertation (Section 2.4). A few months before the defence of the thesis, his father Christian Bohr died by a heart attack at only 55 years old.

In 1909 Niels Bohr first met his future wife, Margrethe Nørlund, the daughter of a pharmacist in the town of Slagelse, and in the summer of 1910 the two were formally engaged. About two years later, after Bohr had returned from his fruitful stay in Manchester, Margrethe and Niels were married on 1 August 1912. The wedding ceremony took place at the Town Hall of Slagelse and not in a church, the reason being that shortly earlier Bohr had resigned his membership of the Lutheran Danish State Church. In letters to his fiancé and her mother Bohr explained that although he once had firmly believed in the Christian faith, he no longer did. "I can and will not believe what is not true", he wrote to Margrethe, "and what is not true means to me what would affect the meaning of life... [and] that a human being has to beg and deal with imagined powers that are infinitely many times stronger than itself" (Aaserud and Heilbron 2013, p. 78). Bohr was non-religious, possibly an atheist, and he remained so throughout his life. In the words of Léon Rosenfeld, Bohr's close collaborator: "He never found any occasion in later life to depart from the position of the freethinker, which he maintained with tolerance and humanity" (Rosenfeld 1972, p. xxi).

The ever-ambitious Bohr endeavoured from an early date to obtain an academic position in Denmark (Pais 1991, pp. 132–134, 163–166). When Christian Christiansen resigned from his physics professorship in 1912 and a successor had to be found, 27-year-old Bohr optimistically applied, but as expected the vacancy was filled by the older and more experienced Martin Knudsen, a capable experimental physicist of the old school who took on Bohr as his teaching assistant.[2] Although Bohr did not get the position, he was rated highly, as indicated by a recommendation from the Science Faculty of the University: "If a teaching position in mathematical physics were at issue – a position which our university unfortunately lacks – then there could hardly have been any doubt that Dr Bohr would have been the right choice" (Aaserud and Heilbron 2013, p. 88).

In September 1912 Bohr left for England to do postdoctoral work, first in Cambridge and next in Manchester (Sections 2.5 to 2.7). He returned in late July 1913 to take on his position under Knudsen. While in Copenhagen, Bohr gave on 20 December 1913 a brilliant lecture to the Danish Physical Society in which he exposed his atomic theory in a clear and partly novel manner. In this paper, published in Danish in 1914 but only translated into English eight years later, for the first time he made use of arguments based on a primitive version of the correspondence principle (Bohr 1914a; Bohr 1922, pp. 1–19; see Section 4.d). Dissatisfied with the humble position, which scarcely left him time for research, in October 1914 Bohr returned to Manchester, where Rutherford had arranged a readership for him. The desired professorship in Copenhagen became a reality two years later, when a new chair in theoretical physics was established. Bohr returned to Denmark in 1916, to remain in the position as physics professor until his retirement in 1955. Shortly after his return he got his first assistant and collaborator, the 21-year-old Dutchman Hendrik Kramers, who would soon emerge as a leading figure in theoretical physics.[3] Another of Bohr's early assistants was the Swede Oskar Klein, who came to the institute in 1918 at the age of 24. He too became an important figure in twentieth-century theoretical physics.[4]

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[2] Martin Knudsen (1871–1949) was employed as lecturer of physics at the University of Copenhagen in 1901. In 1909 he was elected a member of the Royal Danish Academy of Sciences and Letters, and from 1912 to his retirement in 1941 he served as professor. His research activities focused on two very different areas, one being the behaviour of gases at very low pressure and the other physical oceanography. A leading figure in the international organization of hydrography and oceanography, from 1930 to 1936 he served as president of the International Association of Physical Hydrography. Knudsen's experimental work on highly rarefied gases was much appreciated in the early twentieth century, as illustrated by his several nominations for a Nobel Prize between 1914 and 1921. Christiansen nominated him three times. The nomination for the 1917 prize made by the Russian physicist Orest Chwolson is of interest because it proposed a shared prize between Knudsen and Bohr. Chwolson nominated Knudsen for his "researches on very rarefied gases" and Bohr for "his labours, which shed light on the internal structure of atoms" (Aaserud 2001, p. 281). As another indication of Knudsen's international recognition, in 1912 he was appointed secretary of the Solvay Institute. He participated in the 1911 Solvay congress and also in those of 1913, 1921, 1927 and 1930, in the latter two together with Bohr. During the 1911 congress he delivered an address on rarefied gases which attracted the attention of Nernst and Einstein, among others (Mehra 1975, p. 42).

[3] Hendrik Anthony Kramers (1894–1952) stayed in Copenhagen until 1926, after which he returned to the Netherlands. The same year he developed an important approximation method in quantum mechanics today known as the WKB method, where the other letters refer to Gregor Wentzel and Léon Brillouin. In 1937 Kramers stated particle-antiparticle symmetry or charge conjugation as a general principle of physics, and about the same time he formulated the basic idea of so-called mass renormalization in quantum electrodynamics. On the occasion of Kramers's early death in 1952, Bohr wrote a memorial article on his earlier assistant and collaborator (Bohr 2007, pp. 355–360).

[4] Oskar Benjamin Klein (1894–1977) may be best known for his pioneering attempts to unify relativity theory and quantum mechanics. In 1926 he proposed a five-dimensional theory of rela-

1.2 Developments of the Quantum Atom

Bohr's quantum theory of atoms soon turned out to have even greater explanatory force than what was demonstrated in his trilogy of 1913. The theory gained further experimental support through its remarkable interpretation of a wide range of experiments, most of which were new. The splitting of spectral lines in an electric field known as the Stark effect was announced by Johannes Stark in November 1913 and provisionally explained by Bohr in a paper of 1914. The full explanation based upon Arnold Sommerfeld's extension of the Bohr theory followed in two complex papers of 1916, the one by Karl Schwarzschild and the other by Paul Epstein.

Another and no less impressive success was the explanation of experiments with electron collisions in gases conducted by the physicists James Franck and Gustav Hertz. The Franck–Hertz experiments were unrelated to the quantum atom and when they conducted their first experiments, the two physicists were still unaware of Bohr's theory. However, Bohr quickly realized that the experimental results could be interpreted in beautiful agreement with his theory and that they confirmed the central relation $E_n - E_m = h\nu$ (Bohr 1915; Robson et al. 2014). Without knowing it, Franck and Hertz had provided strong support for Bohr's atomic theory. Had it not been for this connection, the two physicists would not have shared the Nobel Prize in 1925.

Still other successes were mainly due to Sommerfeld, who in 1916 brilliantly solved the problem of the fine structure of the hydrogen spectrum that Bohr had considered but without obtaining quantitative agreement between theory and experiment. Sommerfeld's deduction of the fine structure splitting of the Balmer lines agreed perfectly with Friedrich Paschen's measurements, thereby serving as impressive confirmation of the Bohr–Sommerfeld atomic model. In a letter to Sommerfeld of 3 August 1916, Einstein wrote: "Your investigation of the spectra belongs among my most beautiful experiences in physics. Only through it does Bohr's idea become completely convincing. If I only knew what little bolts the Lord had used for it!" (Sommerfeld 2000, p. 563).

In order to extend Bohr's theory to the more general case of elliptic orbits, Sommerfeld made use of two quantum numbers given by quantization conditions relating to both the angular and the radial momentum (Eckert 2013a; Seth 2010; see also Section 4.a). The one quantum number corresponded to Bohr's n whereas the k number expressed the quantized eccentricity of the elliptic orbit. Since the energy depends only on the sum of n and k, in Sommerfeld's version there was no unique relationship between the energy and the stationary orbit, as there was in Bohr's original theory. Another innovative feature was Sommerfeld's consideration of the three-dimensional case, which led him to introduce the concept of space quantization,

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tivity, electromagnetism and quantum theory which included a characteristic "Klein length" given by $(4h/e)\sqrt{\pi G}$ = ca. 10^{-32} m, where h is Planck's constant, e the elementary charge, and G the gravitational constant. In this context he suggested a relativistic version of the Schrödinger equation known as the Klein–Gordon equation because it was also suggested by the German physicist Walter Gordon. In the late 1930s Klein formulated the first tentative theory unifying the strong, weak and electromagnetic interactions, and later in life he turned to general relativity and plasma cosmology. His early work on five-dimensional theory became known as the KK or Kaluza–Klein theory, where the first K refers to the German mathematician Theodor Kaluza.

or *Richtungsquantelung* in German. In his influential monograph *Atombau und Spektrallinien*, first published in 1919, Sommerfeld gave a full exposition of his theory and its relation to Bohr's. The book, the third edition of which appeared in an English translation, was an authoritative and much used source of the old quantum theory (Sommerfeld 1923; Eckert (2013c)). Bohr never contemplated to write a similar textbook based on his own ideas.

During the years 1916 and 1917 Bohr was busy developing what he thought of as a rational understanding of the quantum atom. The result was a lengthy and complex treatise in three parts titled "On the Quantum Theory of Line-Spectra" of which the first two parts appeared in 1918 and the third only in 1922. Bohr had in April 1917 been elected a member of the prestigious Royal Danish Academy of Sciences and Letters, and he published the treatise in the transactions of the Academy rather than submitting it to *Philosophical Magazine* or some other international journal. In the second part of the treatise he developed in great detail a "formal analogy" between classical and quantum physics, or what he since 1920, first in a conference in Berlin, called the correspondence principle (Bohr, 1918). By using the correspondence principle or approach he was able to calculate intensities and polarizations of spectral lines and thus go beyond the limitations of the earlier theory of 1913.

In the years to come, the correspondence principle stood in the centre of Bohr's development of the quantum theory of atoms. The new approach strengthened Bohr's conviction that light was emitted as electromagnetic waves and that Einstein's hypothesis of light quanta was quite wrong. It also resulted in an important revision of the postulate of stationary states. While in Bohr's original theory the energy levels of the stationary states were sharply defined ($\Delta E_n = 0$), according to the new version, the energy would vary over a small interval ($E_n \pm \Delta E_n$). It followed that discrete spectral lines must have a so-called natural line width independent of temperature and other external circumstances. Yet another consequence of the fruitful correspondence approach was that it predicted certain quantum predictions to be "forbidden" and thereby functioned as a selection principle.

Armed with the correspondence principle and other theoretical weapons, Bohr suggested atomic models that differed significantly from the simple planar ring structures he had proposed in 1913. According to Bohr's new theory of atomic structure, as he presented it in his Nobel Prize lecture of 1922 and at other occasions, the state of an electron was governed by the principal quantum number n and the azimuthal quantum number k with the values $n = 1, 2, \ldots$ and $k = 1, 2, \ldots, n$. The electron moved in three-dimensional elliptic orbits whose eccentricity was given by the ratio n/k. An electron moving in an outer orbit might penetrate the inner core of the atom and thereby give rise to a coupling of the electrons. Moreover, he adopted the rule that the number of electrons in the outer shell remained unchanged during the completion of an inner shell. What Bohr called the *Aufbauprinzip* (construction principle) stated that the addition of electron number p to a partially completed atom with $(p - 1)$ bound electrons leaves the quantum numbers of the $(p - 1)$ electrons unaffected; the principal quantum number n of the newly added electron differs from that of the already bound electrons only if the atom belongs to a new period of the periodic system (Darrigol 1992, p. 165).

Bohr's theory of complex atoms rested heavily on general principles such as the correspondence principle and the *Aufbauprinzip*. However, the way in which he used these principles to derive precise electron structures of the elements remained obscure. Nonetheless, Bohr believed that he could reproduce the entire periodic system and even extend it to hypothetical transuranic elements (Kragh 2012a, pp. 272–297). He argued that the unknown element 72 must be a homologue to zirconium and not a rare earth metal as claimed by French scientists. When George von Hevesy and Dirk Coster, working in Bohr's institute, identified the element in zirconium minerals by means of X-ray spectroscopy in late 1922, it was widely considered a confirmation of Bohr's atomic theory. Although Bohr at first preferred "danium" for the new element, it was named "hafnium" after the Latin name for Copenhagen (Kragh and Robertson, 1979).

The discovery of hafnium was made at Copenhagen University's Institute for Theoretical Physics (in Danish *Universitetets Institut for Theoretisk Fysik*), a unique and highly innovative research institution which Bohr had originally proposed to the Faculty of Science in April 1917. In this proposal Bohr argued that the new kind of theoretical physics that he wanted to cultivate needed to be supplemented by experimental work. "In order that theoretical investigations ... can be conducted to advantage, it is necessary however that the scientists occupied in this way are given the opportunity to also undertake experimental investigations", he wrote (Robertson 1979, p. 21). Later in the proposal he returned to the same point:

> In the elaboration of the theories referred to, one is faced at each moment with having one or another consequence of the theory tested experimentally, before the choice between the various possibilities presented can be made, and therefore it is as mentioned necessary that the practitioners of the subject have the opportunity to carry out and guide scientific experiments in direct connection with the theoretical investigations.

The institute was planned to open officially in the summer of 1920, but economic and other problems caused a delay to 3 March 1921. As Bohr reiterated in his inauguration speech of this date, the term "theoretical physics" should be understood as fundamental physics and not as excluding experimental physics. Informally the new Institute for Theoretical Physics was since its beginning known as "Bohr's institute" and in 1965, three years after the death of its founder, it was officially renamed the Niels Bohr Institute. During the two decades between the world wars, Bohr's institute was unquestionably the world's premier institution for atomic and quantum physics, attracting a large number of visitors from abroad. From its very beginning the institute was thoroughly international, as illustrated by its first staff which, apart from Bohr as the director, consisted of two Danes, one Swede, one German, and one Dutchman.

At about the same time that hafnium revealed its existence, Bohr received the Nobel Prize in physics, another moment of glory for the young institute. Bohr had first been nominated in 1916, and in 1919 and again in 1920 he received nominations from several outstanding physicists, among them previous Nobel laureates such as Rutherford and Wilhelm Wien. However, the Nobel Committee in Stockholm turned down the proposals with the argument that "the assumptions on which Bohr's atomic model has been built stand in contradiction to physical laws that are still indispensable" (Aaserud 2001, p. 283). When Bohr was awarded the 1922 prize, it was for "his services in the investigation of the structure of atoms and the radiation emanating from them". In his Nobel lecture delivered in Stockholm on 11 December 1922, Bohr gave a popular yet comprehensive and fairly detailed account of his latest ideas about atomic structure and how they explained the periodic system of the elements (Bohr, 1923). He paid particular attention to the correspondence principle and its use in areas such as atomic and molecular spectroscopy. In addition to the Nobel Prize, Bohr was also honoured for his atomic theory with the Royal Society's Hughes Medal in 1921 and the Matteuci Medal from the Italian National Academy of Sciences in 1923; in Denmark, he received the Ørsted Medal in 1924.

Einstein too received a full physics Nobel Prize in 1922, but in his case for the year of 1921. Bohr was delighted to receive the prize at the same time as Einstein, whom he greatly admired as both a physicist and a human being. Bohr and Einstein first met personally in April 1920, when Bohr was invited to give a lecture to the German Physical Society. Later the same year Einstein visited Oslo – or what at the time was called Kristiania – and on his way home also Copenhagen, where he lectured on his general theory of relativity and its astronomical consequences. In a letter to Lorentz, Einstein reported: "The journey to Kristiania was really beautiful, but the most beautiful was however the time I spent with Bohr in Copenhagen. He is a highly intelligent and excellent man" (Einstein 2006, p. 364).

Einstein was once more in Copenhagen, but then only briefly and *en route* to Gothenburg to give his delayed Nobel lecture. On 9 July 1923 he came to Copenhagen, where he spent several hours in intense discussions with Bohr, possibly about their disagreement with respect to the nature of radiation and its interaction with matter.[5] While Einstein maintained his belief in light quanta, Bohr contemplated at the time a new anti-photon theory. About half a year later, Bohr's thoughts crystallized in the so-called Bohr–Kramers–Slater theory, an important but wrong theory proposed by Bohr jointly with Kramers and the American physicist John Slater, who at the time worked at the Copenhagen institute.

A few months after having said farewell to Einstein, Bohr left for America, where he had been invited to give several lectures. He also attended the annual meeting of the American Physical Society in Chicago. Bohr lectured on atomic theory in Toronto, at Harvard University and at Columbia University, and in November 1923 he gave the six Silliman Memorial Lectures at Yale University. Earlier Silliman lecturers included J. J. Thomson, Rutherford, and Walther Nernst, and the 1922 Silliman lectures were given by Bohr's compatriot August Krogh, a physiologist and Nobel Prize laureate of 1920. Although Bohr found his first visit to the New World an interesting experience, he also found the unfamiliar American way of life a little disturbing. After having returned to Copenhagen, he wrote to Rutherford: "Although a strenuous time my visit to America was a very refreshing experience. ... [But] I do not think I should like to live there all my life and to miss the traditions which ... give the colour to the life in the old countries" (Bohr 1984, p. 487).[6]

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[5] In an unpublished interview of July 1961 conducted by Aage Bohr and Léon Rosenfeld, Bohr recalled about Einstein's brief visit: "I naturally fetched him from the railway station ... [and] we took the street car from the station and talked so animatedly about things that we went much too far past our destination. ... I can't remember how many stops, but we rode back and forth in the street car because Einstein was really interested at that time ... what people thought of us, that is something else" (Pais 1991, p. 229).

[6] Like many other European physicists, at the time Bohr did not rate American science highly. Shortly after his return from America, he had a conversation with Harold Urey, a young American visitor who would later be awarded the Nobel Prize in chemistry for his discovery of deuterium. In a letter to G. N. Lewis of 1 January 1924, Urey reported that Bohr "said he found so much

1.3 From Crisis to Crisis

In July 1923 the journal *Die Naturwissenschaften* celebrated in a special issue the tenth anniversary of the Bohr atom. Although the development since 1913 had clearly been progressive, at the time problems of an empirical and conceptual nature began to accumulate, leading to a growing dissatisfaction with the otherwise successful Bohr–Sommerfeld theory of atomic structure. One year later it became evident that the theory was plainly unable to account for simple systems such as the helium atom and the H_2^+ ion. There were several other anomalies of which the so-called anomalous Zeeman effect (which is the common form) was the most discussed and most frustrating. By the end of 1924 experts recognized that the Bohr–Sommerfeld theory was inadequate and that the concept of electrons moving in fixed orbits might have to be abandoned (Darrigol 1992, pp. 175–212; Kragh 2012a, pp. 313–355). Max Born and Wolfgang Pauli declared the orbits fictitious and wanted to replace Bohr's more pictorial models with abstract mathematical models based solely on observable quantities. In 1924 Born coined the term "quantum mechanics" for the supposedly superior new theory, but unfortunately, no one knew what this quantum mechanics of the future would look like.

The growing crisis in quantum theory was discussed by Bohr, Kramers, Heisenberg, and Pauli at a meeting in Copenhagen in March 1925. Half a year later 23-year-old Werner Heisenberg published his seminal paper in *Zeitschrift für Physik*, generally considered to be the beginning of modern quantum mechanics. Heisenberg's paper was followed by a more elaborate one by Born, Heisenberg and Pascual Jordan in which the new mechanics was formulated in the language of matrix calculus. Bohr was not actively involved in the creation of quantum mechanics in the summer and early fall of 1925, but he soon realized that it was an extraordinary advance if not a complete break with the earlier atomic theory. After all, the fundamental postulates of stationary states and the frequency condition survived in the new theory and so did Bohr's cherished correspondence principle. Instead of burying himself in the technical and mathematical problems of quantum mechanics – whether in the German version or in Erwin Schrödinger's alternative wave mechanics – Bohr decided to focus on the physical and philosophical interpretation of the new theory. He wanted to know what it meant and what its wider implications were.

Heisenberg's introduction of the famous uncertainty or indeterminacy principle in the spring of 1927 was indebted to intense discussions with Bohr concerning the foundation of quantum mechanics. As Heisenberg recalled in a commentary of 1967, Bohr was at first dissatisfied with how he stated the principle, but then, "After several weeks of discussions, which were not devoid of stress, we soon concluded ... that we really meant the same, and that the uncertainty relations were just a special case of the more general complementarity principle" (Wheeler and Zurek 1983, p. 57). Bohr's ideas of complementarity grew out of reflections about quantum mechanics he entertained even before his discussions with Heisenberg. He first presented the concept of complementarity at an international congress in Como, Italy, in the fall of 1927. "The very nature of the quantum theory", he said, "forces us to regard the

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enthusiasm and wealth in America but that science lacked the prestige which it has here" (Shindell 2019, p. 61).

space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition, respectively" (Bohr 1928, p. 580). The complementarity principle eventually became the cornerstone in the so-called Copenhagen interpretation of quantum physics, a term dating only from the mid-1950s.

Shortly after the Como congress Bohr again lectured on his ideas of complementarity, this time at the legendary fifth Solvay conference devoted to the conceptual foundation of quantum mechanics (Bacciagaluppi and Valentini, 2009). The meeting in Brussels is famous not least because of the profound discussions between Bohr and Einstein. Whereas Einstein doubted the absolute validity of the uncertainty relations and the Bohr–Heisenberg interpretation generally, Bohr maintained that quantum mechanics was a complete theory that exhausted all possibilities of accounting for observable phenomena. Most of the participants agreed with Bohr rather than Einstein, and the same was the case when the second round of the Bohr–Einstein debate which took place during the 1930 Solvay congress. Yet the majority view in no way swayed Einstein, who in a letter to Schrödinger of May 1928 sarcastically referred to "the Heisenberg–Bohr tranquilizing philosophy – or religion?" (Schrödinger 2011, p. 459). Many years later, in a volume celebrating Einstein's 70th birthday, Bohr described in detail his discussions with Einstein during the two Solvay conferences and at later occasions (Bohr, 1949).

Schrödinger shared to some extent Einstein's reservations about standard quantum mechanics. In October 1926 he visited Bohr's institute in Copenhagen, where he had long but fruitless discussions with Bohr and Heisenberg concerning quantum jumps and more. Although Schrödinger did not convert to the Copenhagen quantum philosophy, he held Bohr in great esteem. Just a few days after his return to Vienna, he wrote in a letter to Wilhelm Wien: "There will hardly again be a man who will achieve such enormous external and internal success [as Bohr], who in his sphere of work is honoured almost like a demigod by the whole world, and who yet remains – I would not say modest and free of conceit – but rather shy and diffident like a theology student" (Schrödinger 2011, p. 320; Kragh 2013a).

In the late 1920s Bohr was not only occupied with the general interpretation of quantum mechanics, but also with the apparently nonsensical behaviour of nuclear electrons. The problem of the continuous spectrum of the electrons emitted by beta-radioactive decay was particularly discomforting. Bohr had been the first to point out that beta electrons have their origin in the atomic nucleus and now, about seventeen years later, the insight caused much worry. According to quantum mechanics, which incorporated energy conservation, the beta electrons should be emitted with discrete energies, contrary to experiments. This and other problems, some of them relating to the spin quantum number and others to Paul Dirac's relativistic wave equation for electrons, led to a kind of crisis in parts of the physics community.

The problems caused Bohr to suggest the radical solution that energy conservation failed in beta decay and other nuclear processes, including those going on in the interior of stars. In an unpublished note of 1929, he wrote that "the behaviour of electrons bound within an atomic nucleus would seem to fall entirely outside the field of consistent application of the ordinary mechanical concepts, even in their quantum mechanical modification" (Bohr 1986, p. 88). Bohr followed this blind