The Life and Work of Niels Bohr – A Brief Sketch

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The life and work of Niels Bohr are briefly reviewed covering: his family life, background, and education; the importance of his stay in England after PhD, and the crucial contact with Rutherford; the period of the Old Quantum Theory initiated by his work on atomic structure; and his role as mentor to the next generation of physicists through his Institute in Copenhagen. The contacts with Einstein, their debates on quantum mechanics, their deep mutual respect, and their personalities, are described.

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The Atomic Hypothesis

The idea of atoms as the ultimate indivisible building blocks of matter is about 2500 years old. In India it was suggested by Kānada (6th century BC), and in Greece by Leucippus (~450 BC) and his student Democritus (460 BC–370 BC). Over the centuries there have been both supporters and opponents of this idea. After the advent of modern science in the 17th century, the atomic hypothesis was revived in quantitative terms by John Dalton around 1803. However the actual experimental discovery of atomic structure and the foundations of its theoretical understanding resulted from the work of Ernest Rutherford and Niels Bohr about a century ago. Together they truly ushered in the atomic and nuclear age. Bohr along with Albert Einstein, by general consent, were the two greatest physicists of the 20th century.

The Early Years

Niels Henrik David Bohr was born to affluent parents on 7 October 1885 in Copenhagen in the small country of Denmark. Other notable physicists of his generation were Max Born, Hermann Weyl and Erwin Schrödinger. Niels' sister Jenny was two years older; while his brother Harald, to whom he was

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extremely close, was two years younger. Their father Christian Bohr was a professor of physiology at the university, and an important cultural figure in Copenhagen. In the father's eyes, Harald was 'brilliant' but Niels was 'special'! Family life was close, highly cultured and intellectual, with Niels and Harald being exposed to scientific, literary and philosophical discussions from a very young age. This may well be contrasted with the cases of Einstein and Paul Dirac, for example.

Niels and Harald attended the Gammelholm School in Copenhagen, then went on to the university. From the beginning it seemed understood that they would both pursue academic careers in physics and mathematics respectively. Niels completed undergraduate and master's degrees in 1907 and 1909, and the PhD in 1911 for a thesis based on a profound study of the Lorentz–Drude electron theory of metals. During his years at the university he was influenced by the philosophical ideas of Benedict Spinoza and Denmark's own Søren Kierkegaard. He was also concerned from an early age with the difficulties of communication, problems of words and language, and ambiguities in understanding. This led to his being extremely careful in writing and in the choice of words, all through his life.

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Trip to England

At this point, Niels (hereafter Bohr) was very keen to work with J J Thomson – the discoverer of the electron – at the Cavendish Laboratory in Cambridge in England, and to describe his own work to the great man. Bohr reached Cambridge in the autumn of 1911 and met Thomson soon after. However things did not go well, partly because Bohr began by pointing out mistakes in Thomson's papers, and partly because Thomson took an inordinate amount of time to read Bohr's paper. Earlier that year, in May 1911, Rutherford at Manchester had announced the discovery of his model of the atom, with a massive but tiny nucleus at the centre and electrons a great distance away, like a miniature solar system. By June 1911 the famous Rutherford scattering formula

was also in hand. At the end of 1911 Rutherford visited Cambridge, and Bohr was deeply impressed by his work as well as his personality. (A wonderful account is given by R F Peierls, 'Rutherford and Bohr', *Resonance*, Vol.15, No.5, 2010). Bohr decided to go to Manchester to work with Rutherford. The immediate and deep friendship and mutual respect between the two were to flower greatly in the coming years. On the physics front, Bohr saw very soon that the Rutherford atom model would lead to the explanation of the properties of chemical elements, the structure of the Periodic Table, with the behaviour of electrons determining all of chemistry. On the other hand, he also saw that alpha and beta rays, two forms of radioactivity, originated from the nucleus.

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"In the spring of 1912 I became convinced that the electronic constitution of the Rutherford atom was governed throughout by the quantum of action."

As Paul Dirac would say many years later, the steps taken by Bohr were the most difficult ones in the passage from classical to quantum physics.

In due course Bohr's ideas also led to an understanding of the laws of spectroscopy.

In April 1912 Bohr moved to Manchester. Over the next four months, up to July 1912, he worked incredibly hard on his ideas sketched above, all based on the Rutherford atom model, more precisely on developing his own 'quantum version' of it. Before leaving Manchester the draft of a first paper was done and shown to Rutherford.

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Return to Denmark

Returning to Copenhagen, Bohr and Margrethe Norlund were married on 1 August 1912, the beginning of a 50-year relationship of deep love, harmony and mutual support. They were to have six sons, the eldest of whom, Christian born in 1916, was to die in a tragic boating accident in 1934. Another died in childhood.

In the autumn of 1912, Bohr was appointed assistant professor at the University in Copenhagen. In 1916, after a special Chair was created, he became professor of theoretical physics. Several times in this period Rutherford tried to lure him to Manchester on a more permanent basis, but Bohr only stayed there for a limited period during 1914-1916. Work on his atom model continued, and in 1913 the trilogy of papers: 'On the Constitution of Atoms and Molecules : Parts I, II, III' appeared in the *Philosophical Magazine* in July, September and November. When Einstein came to know about Bohr's results he remarked:

"Then it is one of the great discoveries"

"Then the frequency of the light does not depend at all on the frequency of the electron … And this is an enormous achievement. The theory of Bohr must be then right."

Einstein to Bohr: "Not often in life has a person, by his mere presence, given me such joy as you did … I have the pleasure of seeing your youthful face before me, smiling and explaining. I have learned much from you, especially also about your attitude regarding scientific matters."

The first time Bohr met Einstein (as well as Planck) was in April 1920, when he was invited to Berlin. After this meeting here is what they wrote to one another:

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Bohr in reply said: "To me it was one of the greatest experiences ever to meet you and talk with you and I cannot express how grateful I am for all the friendliness with which you met me on my visit to Berlin."

Period of Old Quantum Theory – Nobel Prize – Later Work

The Old Quantum Theory spanned the quarter century 1900–1924, and clearly the second half was dominated by the impact of Bohr's work of 1912–1913. In this phase there were major contributions by Arnold Sommerfeld, Paul Ehrenfest, and Einstein. This entire effort paved the way for the later development of quantum mechanics proper.

An important event in 1921 was the inauguration of the Institute of Theoretical Physics in Copenhagen in the month of March with Bohr as Director. Bohr had worked tirelessly towards its creation from 1917 onwards. Through the 1920's and 1930's it became a meeting place for talented physicists from many parts of the world, to visit and work for varying periods. In fact, during the period of the Old Quantum Theory and the subsequent discovery and consolidation of the new quantum mechanics, the three centres in Munich, Göttingen and Copenhagen formed an important triangle – Munich emphasizing the physical aspects, Göttingen more mathematically oriented, and Copenhagen the philosophical and interpretational problems. In 1965, the Institute was renamed the Niels Bohr Institute.

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The Nobel Prizes in Physics for 1921 and 1922 were announced jointly on November 10, 1922, and awarded to Einstein and Bohr respectively. Bohr immediately wrote to Einstein:

"… To me it was the greatest honour and joy … that I should be considered at the awarding of the prizes at the same time as you. … I have felt it as the greatest good fortune that … the fundamental contribution that you have made … should be recognized, also quite publicly, before I was considered for such an honour…".

To which Einstein replied two months later: "Your cordial letter reached me shortly before my departure from Japan. I can say without exaggeration that it pleased me as much as the Nobel Prize. I find especially charming your fear that you might have got the prize before me – that is truly 'bohrisch'…"

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After the advent of quantum mechanics in its two forms – matrix mechanics in 1925 and wave mechanics in 1926 – Bohr's role changed to that of a guide and elder statesman. The most rapid advances came from the younger group of Heisenberg, Dirac, Pauli, Fermi (along with crucial contributions by the older Schrödinger and Born); and Bohr concentrated on the problems of interpretation of the new mathematical formalisms. His own later significant contributions to physics include the enunciation in 1927 of his Complementarity Principle; the analysis with Rosenfeld in 1933 of the inner consistency of the mathematical formalism of quantum electrodynamics; the theory of the compound nucleus in 1936; and the study with Wheeler in 1939 of the mechanism of nuclear fission.

Debates with Einstein

Bohr's later interactions and debates with Einstein form an important part of the history of 20th century physics. At the 1927 Solvay Conference, Einstein brought up 'thought experiments' to try and show that Heisenberg's position-momentum uncertainty principle could be violated. At the 1930 Solvay Conference he similarly attacked the time-energy uncertainty principle. On both occasions Bohr was able to answer him and to show the inviolability of these uncertainty principles and the inner consistency of quantum mechanics. In 1935 Einstein (with Podolsky and Rosen) tried to argue that quantum mechanics, while correct, was incomplete. Once again Bohr was able to counter him. (This particular episode is the starting point of a serious study of the phenomenon of entanglement in quantum mechanics, so important today). Later Bohr wrote an extended article in the 1949 volume 'Albert Einstein – Philosopher Scientist' edited by Paul A. Schilpp, reviewing his years of discussions and debates with Einstein, which is also a classic of the physics literature.

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During the second World War, as Denmark was occupied by Nazi Germany, Bohr had to be "smuggled out" to the USA under a false name – Nicholas Baker! In 1941 Heisenberg, who had been so close to him earlier, visited Bohr in Copenhagen, but this

encounter must have been painful to both. Michael Frayn's play 'Copenhagen' tries to reconstruct what might have happened. His attempt in 1944 to talk with Winston Churchill was a fiasco, due to problems of communication.

Some Quotes from Bohr

As mentioned earlier, Bohr was always conscious and concerned about problems of language and communication. His talks and articles are quite dense and difficult to read, prompting Einstein to say: " He utters his opinions like one perpetually groping and never like one who believes he is in possession of definite truth". Nevertheless some of his most famous pieces should be mentioned, to tempt the brave reader: (i) The lecture at Como in September 1927 announcing his Complementarity Principle: (ii) the 1932 lecture in Copenhagen to an audience of light therapists on 'Light and Life'; and (iii) 'Light and Life revisited' on 21 June 1962 at the University of Cologne.

There are many statements of Bohr which are at the same time both profound and often subtly humorous. Here are a few:

- Strictly speaking, the conscious analysis of any concept stands in a relation of exclusion to its immediate application.
- Every sentence I say must be understood not as an affirmation, but as a question.
- It is difficult to predict, especially about the future.
- Tomorrow is going to be wonderful, because tonight I do not understand anything.
- You are not thinking, you are just being logical.
- If quantum mechanics has not profoundly shocked you, you haven't understood it yet.
- There are some things so serious you have to laugh at them.
- The opposite of a fact is falsehood, but the opposite of one profound truth may very well be another profound truth.

On 18 November 1962, a little while after lunch, Bohr passed away.

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– Bohr

... Einstein and Bohr were both scientists without whom the birth of that uniquely twentieth-century mode of thought, quantum physics, is unthinkable.
– Abraham Paris

Comparing Bohr and Einstein

In this brief sketch of his life and work, Einstein has played a very prominent role. It is appropriate then to conclude with some sentences from Abraham Pais, who had known them both very well, taken from an address to the Royal Danish Academy of Sciences and Letters in December 1989 titled 'Reflections on Bohr and Einstein':

"Both would speak with intense enthusiasm and optimism about work they were engaged in, and had enormous powers of concentration... In younger years, Einstein's spectrum of scientific activities was broader than Bohr's ... Both men were indefatigable workers, driving themselves on occasion to states of exhaustion which would lead to illness, more serious in the case of Einstein.

… Their prime concern was always with what they did not understand, rather than with past achievements. … From the point of view of science, Bohr was more spectator than actor in his later years. … Both Bohr and Einstein were a-religious. … Einstein had a lifelong interest in philosophy… . As for Bohr, less well read in philosophy than Einstein, philosophizing was part of his nature from boyhood on… . How to avoid ambiguity – that was the problem that worried Bohr. … They differed in their views regarding the interpretation of quantum mechanics. They argued frequently about it, particularly over the concept of Complementarity. … By and large, however, similarity outweighed disparity. Both had a deep need for simplicity, in thought and in behaviour. … They took science very seriously, but to them it was ultimately a game. The greatest similarity, though, was that Einstein and Bohr were both scientists without whom the birth of that uniquely twentieth-century mode of thought, quantum physics, is unthinkable."

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