A TRIBUTE TO NIELS BOHR ›››DOI 10.1051/epn:2008505

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It is hard to imagine, in 2008, the attraction exerted in the 1920's and 1930's by the Institute of Theoretical Physics, at Blegdamsvej 17, Copenhagen, an institute conceived and created by Niels Bohr, the young professor in the newly created chair of theoretical physics of Copenhagen University. Even before it opened its doors, the inventor of the new atomic model, in which J. J. Thomson's electrons, Rutherford's nucleus and Planck's quanta had been merged together to explain the line spectra, was a celebrity who attracted young physicists anxious to make the physics of the future. Hans Kramers from Leiden was the first to come to see Bohr and to join forces in the exploration of the atomic structure; many would follow.

The student

Niels Henrik David Bohr was born in 1885 as the second child of the physiologist Christian Bohr, the professor-in-chief of the Medical Faculty, and Ellen Adler, a banker's daughter and former student of Christian. There was an elder sister, Jenny, and a younger brother, Harald: Jenny was to become a teacher of Danish and history, Harald grew to become Denmark's most distinguished mathematician. From his youth onwards Niels Bohr was the practical man of the family. He loved working wood and metal and put together mechanical constructions, at a special bench with tools – at home – and equipped with a lathe. His father promoted an English way of life – with strong German literary accents – and so it came that 'football', a most recent novelty, became part of the extra-curricular student activities; his own boys were to excel at it, Harald, it is true, more than Niels. The two closely followed each other: in 1910, Harald expanded in his thesis on the theory of Dirichlet series; Niels passed his doctorate on the electron theory of metals. Typically, Harald preferred working alone, whereas Niels was always searching for company to discuss scientific subjects and, eventually, to dictate the texts of publications. Indeed, for some of his later guests it was an unforgettable experience to serve as the writer – pencil or fountain pen and paper, at hand – of the often exasperating number of successive drafts of a publication. Bohr's kind joviality, though, in a way more than outweighed his barely hidden inclination to dictate.

The doctor

Armed with a provisional translation of his thesis, Bohr left for Cambridge in order to try to win J. J. Thomson's support for his novelties. Bohr's electron theory was built upon that of Lorentz, in which the velocities of the electrons obeyed a normal distribution. The statistics involved was that of the kinetic theory of gases, the electrons taking the place of the molecules of Maxwell and Boltzmann. Thomson himself, however, went not that far; assuming a steady velocity he had calculated in 1908, roughly, the velocity of those electrons: about 100 km.sec⁻¹. A metal was conceived of as a rigid structure of metallic atoms enclosing, as a porous container, the 'gas' of electrons moving hither and thither. The encounter with Thomson was much of a disaster. Bohr himself later acknowledged his awkwardness: it had perhaps not been really the best first move to try to convince his host of errors in the latter's publications. The youthful Bohr, renowned for his frankness, had to acquire some diplomatic skills, and so he did. At Cambridge he made the acquaintance of Ernest Rutherford, who had come over from Manchester for a talk. In moving on to Manchester, Bohr was made familiar with the latest trends in atomic physics, more specifically the assumption of a tiny *nucleus* at the heart of the atoms, a carrier of a huge positive charge, huge enough to cause the backscattering of α-particles, 1 out of every 20.000. A thin foil of e.g. gold thus was somewhat like a 2D grid of nuclei and electrons. Rutherford himself had referred to the Saturn-like system, formerly suggested by the Japanese physicist, Nagaoka; others had followed. In 1912, a flat system of electrons circling around the nucleus was in the air.

Atomic spectra and structure; professor

The simplest atom of all was claimed to have just one such electron. Crucially, its emission spectrum was renowned, since a long time, for its simplicity: four razor-sharp lines, hinting at four discrete light emissions. The numerical relationship had been analyzed by the mathematicians Balmer and Rydberg: the latter had translated the former's formula in terms of wave-numbers (cm⁻¹), σ (= $10^8.v/c$):

$$\sigma = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \qquad (1)$$

In a flash of genius, Bohr realized its bearing on the atomic structure, when the energy of the emitted light was considered, in Planck and Einstein's way, as the product of Planck's constant, h, and the light's frequency, v. When the normal hydrogen atom is considered as having its electron in an orbit of lowest energy, states of higher energy could be imagined as brought about by the electric current through the gas discharge tube. The four lines of the hydrogen spectrum, then, correspond to discrete losses of energy stemming from electrons 'falling' from orbits of higher energy to that of lowest energy. The 'energy' of an orbit could also be expressed as $h\omega$, in which ω is the frequency of revolution. The kinetic energy of an electron in an orbit, then, corresponds to $\frac{1}{2}h\omega$. Supposing the occurrence of a series of orbits determined by τ = 1, 2, 3, .. their kinetic energies correspond to $\tau(\frac{1}{2}h\omega)$. The normal, 'permanent' state of an atom, then, is that for which τ = 1. On the other hand, the

kinetic energy of an orbiting electron equals its potential energy: $\frac{1}{2}mv^2 = eE/r \ (= W)$, in which $v = 2\pi r\omega$. So, the frequency of revolution, ω, may be expressed as:

$$\sqrt{\frac{2}{m}} \cdot \frac{W^{3/2}}{\pi eE} \tag{2}$$

With $W = \tau(\frac{1}{2}h\omega)$ one obtains expressions for the atom's radius, r, and the frequency of revolution, ω, while W_τ, the energy of a particular orbit is fully determined. The energy difference between two orbits, $W_{\tau 1} - W_{\tau 2}$, that is, the energy of the light emitted, thus leads to:

$$v = \frac{2\pi^2 me^4}{h^3}\left(\frac{1}{\tau_2^2} - \frac{1}{\tau_1^2}\right)$$

Considering the symmetry of formulae (1) and (3), Rydberg's constant R, rewritten as $c/10^8$ times its original value, may be calculated as $3,1.10^{15}\ s^{-1}$, an outcome that accurately verifies Rydberg's own: $3,290.10^{15}\ s^{-1}$.

In this way Bohr succeeded in linking the various spectral lines of hydrogen (12 experimental, and 33 stellar). For the 33rd line of the stellar spectrum, the radius of the hydrogen atom would correspond to $1,2.10^{-5}$ cm, in magnitude corresponding to the mean distance between molecules in a gas at 2.10^{-2} mm Hg. All kinds of phenomena were at once explicable, among which the photoelectric effect and the production of X-rays and canal rays. In two following articles Bohr went on to assess more complex atoms – to begin with helium, lithium and beryllium – and molecules.

Drafts of his papers, meant for *Philosophical Magazine*, were submitted to Rutherford who advised to cut them down, but Bohr insisted. In order to fully convince his mentor Bohr took leave and went directly to Manchester. Rutherford was won over in the end and the first instalment appeared in the May issue of 1913. From then onwards the Bohr-Rutherford atomic model went irresistibly its own way. Van den Broek's suggestion, used by Bohr, was confirmed that very autumn by Moseley. In chemistry the new model was elaborated by Walter Kossel, a student of Sommerfeld, who stressed the importance of the noble gases as possessing stable electronic configurations. Sommerfeld himself addressed the splitting of spectral lines under magnetic and electric influence, known as the Zeeman and the Stark effect. Sommerfeld's *Atombau and Spektrallinien* (1919) became the manifesto of the new atomic theory.

Nobel Prize 1922

At home, Bohr's success led to his nomination, in 1916, as professor of theoretical physics. Unfortunately the material circumstances were extremely poor and Bohr started thinking of mobilizing public funds in order to create an Institute worth that name. The Carlsberg Foundation, which had previously funded his travels to Cambridge and Manchester, became interested. Bohr's association with the greatest physicists of the time, already Nobel laureates or soon to become, paid itself out. He was among the invités of the Belgian philantropist Ernest Solvay, during the first post-War Conference on Physics, that of 1921, where 'Atoms and electrons' featured on the agenda, Bohr's subject, that is. Because of ill health Bohr was unable to attend, but his friend Ehrenfest was kind enough to read his report on 'The application of the quantum theory to atomic problems'. Already in 1917 Bohr was proposed for the Nobel Prize [1]. It was to be that of 1922. In his conference on that occasion he could report on the very-latest success of his theory, a hot find that had been cabled from Copenhagen to Stockholm. It concerned the identification of number 72 of the elements by his guests Hevesy and Coster, an element to be baptized *hafnium*, after Denmark's capital. It concerned an analog of zirconium and not the rare earth that others had postulated. For the European community of physicists Bohr's credentials were unsurpassed and countless PhD students and senior scientists flocked to the Institute of Theoretical Physics. It is important to realize that 'theoretical', with Bohr, just meant 'fundamental', embracing both theoretical and experimental studies, in which physics and chemistry alternated in the most fruitful of interdisciplinary labours. Backed by the Carlsberg Foundation, Bohr became a model of scientific hospitality. In 1929, he received George Gamow from Odessa who had come, on a wild card, just to shake hands, and procured him a fellowship for a year. In much the same way Hendrik Casimir, a student of Ehrenfest, came over. Bohr's magnanimity is reflected in the open-mindedness of his guests. It is told, for instance, that on a warm summer evening Casimir, in trousers and waistcoat, took the trouble to swim across the Sortedams Sø, one of the lakes-in-a-row crossing Copenhagen, in order to check that it was indeed the shortest way. In so doing he won a bet made with Georg Placzek [2].

Compound nuclei; the drop model 1936-1937

Early in the 1930's Bohr tended to drift away in a more speculative direction, but the discovery of *artificial* radioactivity put atomic, more particularly nuclear, physics again on his agenda. Up until then the 'nucleus' had been regarded as a solid-like close packing of α-particles, protons and electrons. Rutherford had suggested, in 1920, the involvement of neutral particles, composed of a proton and an electron. His was a new physics, with a wholly new terminology centering on 'bombardments' with 'projectiles', mostly α-particles, the 'cross-sections' of 'beam' and 'target' defining the probability of atomic and nuclear reactions. Chadwick, his experimental confidant, had deduced, in 1932, the very existence of such neutral particles, slightly heavier than a proton, escaping from $^9Be_4$ when bombarded with α-particles. The context was the following. Bothe and Becker had studied, at Berlin-Charlottenburg, the effect of a polonium-preparation through silver foil upon a platelet of beryllium on top of a counter [3]. This powerful source of (almost) exclusively α-particles was expected to liberate protons from Be, the free protons, so to speak. Instead Bothe and Becker noticed a highly penetrative radiation, apparently unusually hard γ-rays. When lead through paraffin wax, this radiation was sufficiently energetic to liberate high-speed protons, as Irène Joliot-Curie, at Paris, established (speeds of at maximum $3 \cdot 10^7$ m.s^{-1}) [4]. However, what Joliot-Curie interpreted as an extremely energetic variant of the Compton effect was, in Chadwick's view, more probably the consequence of a classical collision of particles, that is of *neutral* particles capable of expelling protons, recoil protons, energy and momentum being conserved [5]. These *neutrons* appeared not to produce tracks of their own in Wilson's expansion chamber, but revealed their presence through abruptly emerging tracks, that is, tracks without an origin.

Bohr had followed, from a certain distance, the debate on the Be-radiation and the later findings of the Joliot-Curies and Fermi. In 1936 he proposed a model of his own for the mechanism of nuclear reactions. In essence, Bohr claimed the production, by the impact of a projectile, of an 'intermediate state', a 'compound nucleus', as he called it. This 'compound nucleus' would have a rather long lifetime: the entering projectile would hit one or more of the nucleons, its energy and momentum being spread over all of them. It could be considered as an 'excited state', in the classical atomic way. After a while, then, one of the nucleons obtained sufficient energy and escaped. What Bohr described in his characteristic mechanical way, could of course also be translated in the new quantum mechanical terms, a job carried out by Gamow [6]. Gamow took the nucleus as featuring a potential well, allowing for the nucleons a whole range of quantum states: outside the well the Coulomb field

of the nucleus reigned, inside something new of a short-range, whose nature was left to be determined. If the entrance of a neutron is unhampered, the later ejection of a recoil particle is a matter of statistics, a tunneling process through the well. In 1937, Bohr would propose, together with Kalckar, the celebrated drop model, presenting the nucleus as behaving like a liquid, with modes of surface and volume oscillations of its own, ready to become excited isotopes by incoming neutrons. With this in mind the nuclear 'fission' of uranium-nuclei by slow neutrons, as deduced in 1938 from the appearance of barium, was nothing short of a confirmation of Bohr's drop model.

Science and policy

From the very beginning of his career Bohr sought the stance of a scientist-statesman, displaying his responsibility whenever necessary. In the 1920's, he was the host who provided many of his guests from all over Europe with Carlsberg fellowships. In the 1930's he became the elder scientist who actively engaged in procuring safehavens for sacked German physicists. After the invasion of Denmark, Bohr remained at his post, as the embodied symbol of Danish academic non-collaboration who refused whatever honours his former student Werner Heisenberg had in mind. On 29 September 1943, though, he had to flee himself, via Stockholm to Great Britain and the United States. His appeals to Churchill and Roosevelt revealed his last great moves, this time as the distinguished statesman-scientist, second only to his friend Albert Einstein. ∎

Acknowledgement

About the author

Henk Kubbinga (University of Groningen) is a member of the EPS-History of Physics Group. His latest book concerns '*The molecularization of the world picture, or the rise of the Universum Arausiacum*' (Groningen University Press, 2008).

◀ **FIG. 2:** 'And now our honoured guest will give his famous lecture on chain reactions', cartoon by B. O. Bøjensen, in: Politiken (1958) (courtesy and ©: Niels Bohr Archive, Copenhagen).

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