Bohr's Atomic Model

A prime example of Bohr's constrained deductive process is his work on the constitution of the atom while in Ernest Rutherford's (1871-1937) laboratory in Manchester, the initial versions published as a trilogy entitled *On the Constitution of Atoms and Molecules* [544], which for the first time made atomic structure into a subject of scientific inquiry. Bohr had spent the year 1911 with J. J. Thomson (1856-1904) in Cambridge before joining Rutherford in Manchester in 1912. In 1897, Thomson had unraveled the mystery of the nature of cathode rays by discovering the electron and went on to consider atomic structure. The leading atomic theory that Thomson had been developing for several years was a *plum pudding* arrangement of positive charges sprinkled among rings of large numbers of electrons throughout the atom but which did not lead to a quantitative description of atoms. However, the experimental observation by Rutherford's group that α-particles were deflected as they pass through a thin gold foil led Rutherford instead to a planetary picture of the atom in which electrons orbit a massive nucleus according to classical mechanics. Bohr's initial examination found that the electrons could not be mechanically stable in Rutherford's planetary type of orbits. There would also be instability due to radiation of the charged electrons. What keeps the matter of such a configuration from collapsing in a fraction of a second, as it must since any orbiting electrons must radiate? Enforcing stability on the basis of classical physics would have led back to the unsatisfactory Thomson style of model.

From his earlier thesis work on electrons in metals, a detailed mathematical work, Bohr was convinced that Newtonian mechanics and Maxwell's electrodynamics were not adequate for a description of the atomic world. Classical orbits became unstable when populated with more than one electron and nothing in classical physics determines orbital radii or frequencies. Not only did Bohr find that the Rutherford atom was mechanically unstable, he also noticed that it had no characteristic radius to define the size of the atom. As Bohr saw it, this requires introduction of a quantity extraneous to the classical electrodynamics, i.e., Planck's elementary quantum of action, and Bohr noted [442, p. 51]

> *this constant [h] is of such dimensions and magnitude that it, together with the mass and the charge of the particles, can determine a length of the order of magnitude [of the atom's linear dimensions.*
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> S. Petruccioli, Atoms, Metaphors and Paradoxes, Niels Bohr and the construction of a new physics, Cambridge University Press 1993.

This length is of the order of magnitude required to characterize a hydrogen atom and now known as the *Bohr radius* a_0,

$$a_0 = \frac{h^2}{(2\pi)^2 m_e e^2} \cong 0.53 \text{ Ångström} = 0.53x10^{-10} \text{ meter}. \qquad (5.10)$$

However, he also relied heavily on the proposition that classical predictions still apply whenever quantum effects can be ignored, which led him to formulate and extensively exploit a *correspondence principle*. Bohr built up a series of alternative arguments, which were distinct but in part mutually contradictory in Part 1 of his trilogy, each containing a partial deductive truth, which led to a model with the principal feature that energy did not come out through continuous vibrations but discontinuously, in a transition from an orbit more distant to the one closer to the nucleus. As Bohr later recalled [214, p. 17]

> *A clue to the solution of this dilemma was, however, already provided by Planck's discovery of the elementary quantum of action, which was the outcome of a very different line of physical research. As is well-known, Planck was led to this fundamental discovery by his ingenious analysis of just such features of the thermal equilibrium between matter and radiation which, according to the general principles of thermodynamics, should be entirely independent of any specific properties of matter, and accordingly of any special ideas on atomic constitution.*
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The principal postulates of the first model that emerged from Bohr's deductive path were:

- The dynamic equilibrium of the systems in stationary states can be discussed via ordinary classical mechanics while the passing of the systems between different stationary states cannot be treated on that basis.
- The transitions between the stationary states is followed by the emission of a homogeneous radiation whose frequency and energy are related by Planck's quantum relation, $\mathrm{E_n} = \mathrm{nh}\nu$.

The result was a new atomic theory that unexpectedly mixed classical and quantum ideas based on postulates that could be justified only by their empirical success. Bohr emphasized its preliminary and hypothetical character and admitted that [421, pp. 12-13]

> *I am by no means trying to give what might ordinarily be described as an explanation; nothing has been said here about how and why the radiation is emitted.*
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> Niels Bohr, The Theory of Spectra and Atomic Constitution, Three Essays, Cambridge University Press, 1924.

However, application of Bohr's model was a spectacular success, giving quantitative agreement with the hydrogen atom spectral series seen in laboratory experiments and in stellar observations and it predicted other spectral series that were soon verified. It also identified the He^+ ion from stellar spectral lines that had been mistakenly attributed to atomic hydrogen. Bohr's theory gave us such concepts as the screening number and the self-consistent atomic field, and the order of building up of the elements in the periodic table. Bohr's approach had further success for about a dozen years with extensions by Arnold Sommerfeld and others to include elliptical orbits and relativistic effects, which produced fine structure in agreement with observations. And it was within the context of Bohr's struggle to understand atomic constitution via his models that: Wolfgang Pauli (1900-1958) in 1924 made his epic discovery of the exclusion principle, that no two electrons could exist in the same quantum state, and George Uhlenbeck (1900-1988) and Samuel Goudsmit (1902-1978) in 1925 discovered the electron spin. Bohr's was the first theory of atoms and molecules that addressed their structure in terms of the configurations of electrons. It initiated a quite new and productive development in the study of atomic, subatomic, molecular, and chemical phenomena along a path that eventually led to a consistent theory of quantum mechanics. The Nobel Prize in Physics was awarded to Bohr in 1922 "because of the assured results and because of the powerful stimulus which this theory has given to experimental as well as theoretical physics."

Despite these successes, many contemporary scientists objected to the apparent lack of foundation for Bohr's collection of postulates. And Bohr's approach could not easily be successfully extended to more complex atoms and to observations such as the response to an external magnetic field called the anomalous Zeeman effect. Understanding these would have to wait for the discovery of the full theories of quantum mechanics, Heisenberg's matrix mechanics in 1925 and Schrödinger's wave mechanics in 1926, which eventually became essential for a more complete understanding of atomic phenomena. However, several features of Bohr's insights were destined to become pervasive even with these developments: identification of the lowest-energy stationary state as the stable ground state which does not emit radiation; the attribution of spectra to radiation absorbed or emitted in transitions between stationary states; and the description of atoms in which an electron is in an excited state with very large quantum number n. Atoms existing in states given by high quantum numbers might indeed be quite large, with radii on the order of 0.01 mm. These large hydrogenic atoms were later called *Rydberg atoms* and were first observed in 1965 at the National Radio Astronomy Observatory when detected radiation from hydrogen atoms in interstellar space was found undergoing transitions between levels near $n = 100$ [545, p. 60]. These large atoms are well described by Bohr's picture and the full theory of quantum mechanics can actually justify the persistence of these several features of Bohr's early model. These aspects of the Bohr model have recently been demonstrated to be exact results of the Schrödinger equation examined in the limit of infinite dimensions where quantum mechanics morphs into classical mechanics [546], a remarkable testament to Bohr's deductive process.