Forsinket referee report om *On the Constitution of Atoms and Molecules*

Af Tomas Bohr og Benny Lautrup

Da Niels Bohr indsendte sin historiske artikel til *Philosophical Magazine* i 1913 var det ikke almindeligt med anonyme bedømmelser ligesom i dag. Artiklens to forfattere har med 100 års forsinkelse læst artiklen grundigt og gennemgået Bohrs argumentation kritisk.

Niels Bohr skrev sin første artikel om kvantemekanikken i begyndelsen af 1913 med titlen "On the Constitution of Atoms and Molecules" [1]. Artiklen blev indsent den 5. april og trykt i juli-udgaven af *Philosophical Magazine*. Senere på året uddybede Bohr sin teori i yderligere to artikler med samme hovedtitel og undertitlerne "Systems containing only a Single Nucleus" og "Systems containing several Nuclei".

Anonyme bedømmelser af videnskabelige artikler (såkaldte *peer reviews*) var ikke almindelige i begyndelsen af det 20. århundrede, selv om princippet var foreslået langt tidligere. I stedet vurderede et tidsskrifts redaktør suverænt artiklens faglige indhold og accepterede eller afviste artiklen på dette grundlag. Et andet princip, der stadig anvendes nogen steder (fx i det amerikanske PNAS), er baseret på, at en artikel indsendes og anbefales af en tredje person. I Bohrs tilfælde var det Ernest Rutherford, der kommunikerede hans første artikler til *Philosophical Magazine*.

Efter opfordring fra Jens Ramskov ved *Ingeniøren* besluttede vi os i foråret til, at forsøge med et "peer review" af Bohrs første artikel af samme karakter, som nu anvendes af så godt som alle videnskabelige tidsskrifter. I bedømmelsen måtte vi naturligvis ikke eksplicit benytte viden, der er fremkommet senere end artiklen, selv om det i praksis kan være en smule svært at undgå. Vi forsøgte også at bruge et sprog og en lidt mere omstændelig stil, der mindede om den videnskabelige praksis omkring 1913, men da ingen af os er professionelle historikere, er det mål nok uopnåeligt.

Lige som de fleste andre fysikere havde vi faktisk aldrig læst artiklen rigtig grundigt, fordi hovedindholdet er blevet genfortalt i så mange senere artikler og lærebøger, hvor man har kunnet simplificere fremstillingen i lyset af den efterfølgende udvikling. Men det lønner sig faktisk at læse det hele. Det giver et stærkt billede af Niels Bohrs personlighed og den utrolige grundighed, hvormed han argumenterede sin sag, hvilket dog også indimellem gør teksten svær at følge. Artiklen giver også et slående indtryk af, hvor radikalt et brud med den herskende fysik han var klar til at tage. Han vidste fra sin doktordisputats, hvor store problemer der var med at få den klassiske elektrodynamik til at forklare stoffernes natur, for eksempel metallernes magnetiske egenskaber. Vi håber, at vores lille spøg kan inspirere til læsning af Niels Bohrs artikel i sin helhed, og vi inkluderer et link til den originale tekst [1], så man kan følge henvisningerne i denne noget forsinkede referee report. 100 år er vel i overkanten selv for travle referees!

Figur 1. Niels Bohr på vej hjem fra England i sommeren 1912. Med i bagagen havde han skitserne i baggrunden, som viser at brintatomet ifølge den klassiske elektrodynamik er voldsomt ustabilt. Fotografik baseret på fotos fra Niels Bohr Arkivet, København.

Litteratur

[1] N. Bohr, On the Constitution of Atoms and Molecules, *Philosophical Magazine*, July 1913. Særtryk. http://www.nba.nbi.dk/pdffiles/trilogypart1.pdf

[2] Jens Ramskov, Sønnesøn Bohr siger god for kritisk bedømmelse af Niels Bohrs artikel om atommodellen, *Ingeniøren* den 14. juni 2013, http://ing.dk/artikel/soennesoen-bohr-siger-god-kritisk-bedoemmelse-af-niels-bohrs-artikel-om-atommodellen-159655 (Kopier linket)

Referee report [anonymous]

Author: N. Bohr
Title: Dr. phil.
Affiliation: Copenhagen, Denmark
Manuscript: On the Constitution of Atoms and Molecules
Submitted: April 5, 1913

The structure of the atom has in recent years been the subject of considerable interest. In the theoretical model proposed by J. J. Thomson [*Phil. Mag.* vii, p. 237 (1904)], the atom is seen as rings of circulating negatively charged electrons situated inside a uniformly distributed positively charged sphere. In the present article, the author introduces a Keplerian planetary model of the atom in which the negatively charged electrons circle around a positively charged *nucleus*. This model is inspired by the recent discoveries by Rutherford and collaborators on scattering of α-particles through large angles, which demonstrate that matter must contain extremely small and dense electrically charged objects.

As Larmor showed in 1897, an accelerated electrically charged particle will always emit electromagnetic radiation. In the planetary model, the energy of this radiation can only be taken from the electron, which therefore continuously spirals inwards until it merges with the nucleus. The conclusion is that the planetary atom must be unstable from the outset.

But instead of rejecting this model, the author daringly postulates that the undisturbed electron can remain in a set of discrete orbits, called stationary states, without emission of electromagnetic radiation, and that a transition of the electron between two such orbits is accompanied by emission of a single Planck energy quantum carrying the difference in the electron's binding energies in these orbits. A large part of the paper presents arguments for the basic assumption that the frequencies of the spectral lines are determined, not by corresponding mechanical frequencies of the system, but by *differences* in energies between the stationary states. This assumption is in stark contrast to ordinary electrodynamics, but the author shows that it can account for the discrete spectral lines of the substances and that it does not contradict ordinary electrodynamics in cases where that is known to work, such as the treatment of atoms in highly excited states or free electrons.

The crucial result in favour of the present atomic model is the derivation of a mathematical relation for the transitions between the discrete non-radiating atomic electron orbits and the precisely known discrete line spectra of the elements, in particular for hydrogen. The author thus establishes a relation between the Balmer-Rydberg constant and the fundamental natural constants, i.e., the charge e and mass m of the electron, and the "quantum of action" h introduced by Planck. In addition, he predicts several new spectral lines in hydrogen and, most importantly, that the lines observed by Pickering in the spectrum of the star ζ Puppis, and ascribed to hydrogen, do *not* derive from hydrogen but from ionized helium. This seems somewhat unlikely in the light of the existing experimental evidence since these lines have so far not been seen in the helium spectrum. It is, however, an issue that can be settled by experiment, and it must be expected that the publication of the present paper will soon lead to such experiments.

The new postulates put forward by the author introduce discrete (i.e. integer) numbers into otherwise continuous mechanical systems in a quite unexpected way. The author uses this "qualitative" feature of the theory to argue (p. 14, bottom) that one might expect "an absolute agreement between the values calculated ... and not only an approximate agreement". This is a strong claim with far-reaching consequences related to the exact identity of two systems in the same stationary state, such as two hydrogen atoms in the permanent state, which is completely foreign to ordinary mechanics.

The assumptions made by the author are very radical and it is hard at present to judge their validity. The author does not try to conceal this fact, but writes explicitly (p. 15, top) that "there obviously can be no question of a mechanical foundation of the calculations given in this paper" and further (p. 15, a few lines below) uses the word "symbol" about the angular momentum to emphasize that its meaning might not be fully in agreement with our present dynamics.

In spite of the radical views presented here - postulating a breakdown of Newton's mechanics and relating it to Planck's modification of Maxwell's electromagnetism - it is recommended that this paper should be published, because of its concrete numeric results and its carefully reasoned theoretical analysis. Although the validity of the theoretical foundations is hard to assess at present, the paper contains a number of precise predictions, which can be tested by experiment and may quickly determine, whether the path chosen by the author is a fruitful one.

Before publication the author is, however, asked to consider the following comments, which might lead to some revisions in the paper.

Questions and comments to the author

p. 1 (top) The author claims that the atom consists of a "positively charged nucleus surrounded by a system of electrons kept together by attractive forces from the nucleus", citing E. Rutherford [*Phil. Mag.* xxi, p.669 (1911)]. In this article Rutherford explicitly emphasises that his experiment does not determine the sign of the central charge. Neither does he use the word "nucleus" to denote the object carrying the central charge. In the recent article by Geiger and Marsden (1913), also cited by the author, it is likewise explicitly stated that the sign of the central charge has not been determined. The model presented in the present paper appears to reflect the author's own views on the structure of the atom.

p. 4 (bottom) To arrive at the stationary states, the author writes: "Let us now assume that, during the binding of the electron a homogeneous radiation is emitted of a frequency ν, equal to half the frequency of revolution of the electron in its final orbit". This is a very abrupt introduction of a very specific, and seemingly arbitrary, assumption of great consequence. It is slightly confusing since one of the author's key points is that the frequency of the emitted radiation is *not* given by a dynamical frequency in the system. The author elaborates on this issue several times later, and should consider introducing some of the material from §3 already at this place, thereby motivating the postulated form of Eq. (2) better.

p. 5 (middle) It is claimed that the non-radiating atomic states are "stationary as long as the system is not disturbed from outside". If this were rigorously true for even the most distant electron orbits, it would not be possible to establish a complete correspondence between the radiation emitted from such states and the observed Larmor radiation from accelerated charged particles, which is known to occur without external disturbances. Could it be that the stationary states are actually quasi-stationary and eventually and spontaneously must emit radiation and decay to deeper states until the lowest, truly non-radiating permanent state, is reached?

p. 7 (postulate (2)) Can the author give some indication of the process by which an electron jumps from one stationary state to another. How long time does this take? How can the radiation emitted be *homogeneous*, i.e. of a single frequency? Would this not require an infinite time for the electron to make the jump?

p. 9 (middle) One of the key results of the paper is the theoretical derivation of the Balmer-Rydberg spectrum for hydrogen. In fact, as shown in the high resolution experiments by Michelson and Morley [*American Journal of Science* **38**, 181 (1889)], the red H_α line is actually a closely spaced doublet. How can this be understood within the proposed model?

p. 11 (top) As mentioned above, the author predicts that the Pickering lines observed in mixtures of hydrogen and helium but not, so far, in pure helium, are actually due to helium and not, as believed up to now, to hydrogen. This requires that the helium in question is ionized by the loss of one of its two electrons. The author argues that "Hydrogen atoms can acquire a negative charge; therefore the presence of hydrogen in the experiments of Fowler may effect that more electrons are removed from some of the helium atoms than would be the case if only helium was present". It seems unlikely that hydrogen atoms in the hydrogen-helium mixtures will be able to capture an electron from the helium atoms. By the arguments used by the author, the outer electron of helium should be bound by an energy comparable with or larger than that of the permanent state of hydrogen, whereas the outer electron in negatively charged hydrogen should be extremely weakly bound.

p. 13 By introducing the more general relation $W = f(\tau)h\omega$, the author shows that the assumption Eq. (2) made earlier can be obtained from the correspondence between the theory proposed by the author and classical electrodynamics, which should remain valid, when the atom becomes very large, i.e., when the integer τ that describes the level of excitation of the level becomes large. This is done by showing that for a linear $f(\tau) = c\tau$, this correspondence fixes the value of the constant c to 1/2, precisely as postulated in Eq. (2). The *linearity* of $f(\tau)$ is, however, inferred from the observed spectra, i.e., the Balmer spectrum. Can a more basic theoretical explanation be given?

p. 16 (middle) In the section on *absorption* of radiation, the author writes "From the circumstance that certain substances in a non-luminous state, as, for instance, sodium vapour, absorb radiation corresponding to the lines in the line-spectra of the substances, we may, on the other hand, conclude that the lines in question are emitted during the passing of the system between two states, one of which is the permanent state." It is not clear what "the lines in question" represent?

p. 17 (middle) The author writes "$E = h\nu$, where E is the difference between the total energy of the system in the two states". The use of the symbol E for energy is unfortunate since the author has already used it for the charge of the nucleus.

p. 19 (below middle) The author writes that "the bound electron by the collision could not acquire a less amount of energy..." and similarly "lose a less amount". Here the word "less" could perhaps better be replaced by "smaller".

p. 20-23 In §5 the author discusses atoms with more than one electron and in particular introduces a model of n electrons rotating in a ring similarly to the models used by Thomson [loc. cit.]. This seems a somewhat arbitrary choice, since one might expect models with nearly spherical electron distributions to be at least as relevant (as noted by Thomson). For such cases the separation of the stability problem into those in the plane "that cannot be treated on the basis of ordinary dynamics" and thus "secured by the universal constancy of the angular momentum" (p. 23), and those out of the plane, which *can* be treated by ordinary dynamics, becomes untenable. All in all, the author is advised to defer the discussion of these more complicated atoms to Part II, which is announced on p. 21.

p. 21 (middle) The author writes: "corresponding to the motion of an electron in an elliptical orbit round the nucleus, there will be a motion of the n electrons in which each rotates in an elliptical orbit with the nucleus in the focus, and the n electrons at any moment are situated at equal angular intervals on a circle with the nucleus as the centre." Does this mean that the circular ring is "breathing", i.e. time dependent? If so, what is the consequence of introducing explicit time-dependence into the "stationary states"?

p. 23 (bottom) – 24 (top) Could the author explain more clearly why the assumption that the radiation is only scattered and not fully absorbed, means that one gets agreement with Nicholson, i.e., that the radiation lines correspond to dynamical frequencies in the system? In particular, the sentence "If the above assumption is correct, we immediately understand the entirely different form for the laws connecting the lines discussed by Nicholson and those connecting the ordinary line-spectra considered in this paper", is not clear to this referee.

General Compared to the atomic model of J. J. Thomson [loc. cit.], the planetary atom described here appears to endow the electrons with velocities that are much larger, about one 137th of the speed of light for the permanent state of hydrogen. Can the author indicate a possible way to determine these velocities by experiment?

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