"My courage is ablaze so wildly" Niels Bohr *en route* to his quantum atom

*J.L. Heilbron**

SCI.DAN.M. I · ONE HUNDRED YEARS OF THE BOHR ATOM: PROCEEDINGS FROM A CONFERENCE
THE ROYAL DANISH ACADEMY OF SCIENCES AND LETTERS · 2015

Abstract

The paper first describes the revolutionary sacrifices contained in or implied by Bohr's first paper on the "constitution of atoms and molecules," and the background in physics from which Bohr put his quantum atom together. It goes on to delineate the intellectual and psychological furnishings of the mind that could forge a compelling synthesis from such disparate ingredients. The delineation makes use of some hitherto unavailable family correspondence that suggests the sources and course of Bohr's scientific creativity. A key factor in the account is a concept of partial truth, which can be traced backwards to roots as deep in Danish culture as Kierkegaard's *Stages on life's way* and forwards to the four conflicting foundations that Bohr offered for his quantum postulate in his revolutionary paper of 1913.

Key words: Niels Bohr; Harald Høffding; Søren Kierkegaard; Bohr atom; scientific creativity

* April House, Shilton, Burford OX18 4AB, UK. E-mail: johnheilbron@berkeley.edu.

The text that follows is a slightly revised version of the talk given at the opening session of the Conference; I am obliged to the editor for allowing me to retain its conversational tone. Footnotes are given only for direct quotations.

1. Introduction

The quotation in my title comes from a letter from Niels Bohr to his fiancée Margrethe Nørlund. It dates from February 1912, just before Niels caught a train from Cambridge to Manchester. He was on his way to arrange a transition – it turned out to be a quantum jump – between the domain of Sir Joseph John Thomson, whom Bohr ranked as a pioneering genius, to the laboratory of Thomson's former student, Sir Ernest Rutherford, evidently the coming man in English physics. It was a special moment for Bohr, as he had not made a perfect success at Cambridge, and hoped for a better outcome at Manchester. The prospect of a new start, and a chance of showing himself to be the man of genius his family and friends took him for, might seem to explain sufficiently the rhetoric with which he described his frame of mind to Margrethe. "My courage is ablaze so wildly."[1]

In fact, his correspondence with Margrethe is full of references to his blazing courage and boiling blood. He had arrived in England, to begin work with Thomson, "with all my stupid wild courage." His blood boiled at the sight of the chapel of King's College Cambridge, a pillar in St Giles Cathedral in Edinburgh, the Forth Bridge – not from irritation, but because great human achievements fired up his spirit of emulation. When he glimpsed some progress in his physics, his blood could get "feverish," or so he wrote to Margrethe, with apologies for his "silliness" in growing incandescent over so little.[2]

Many other stimulants could provoke this ebullience: the great works of Goethe, Shakespeare, Ibsen, and Kierkegaard; grand scientific syntheses, like Hendrik Lorentz's *Theory of electrons* and Joseph Larmor's *Aether and matter*; an opera, a friend, a sense of well-being. After attending an opera with a colleague one fine November afternoon, he wrote semi-poetically to Margrethe, "my courage these days is ablaze competing with the autumn sky and with all those things that by turn run through my silly head."[3]

1. Aaserud and Heilbron (2013), p. 66.

2. Aaserud and Heilbron (2013), pp. 74-75.

3. 25 November 1912, Aaserud and Heilbron (2013), p. 37.

Figure 1. "My courage is ablaze so wildly, so wildly." Niels Bohr *en route* to his atom, photographed during his return from England for his wedding in Denmark.

The transition to Manchester started Bohr on the path to his quantum atom, brought him the success that had eluded him in Cambridge, and resulted in a revolution in physicists' approach to the microworld. I will try to specify the revolutionary sacrifices demanded by this approach as contained in or implied by Bohr's first paper on the "constitution of atoms and molecules," which was published in July 1913, almost a year to the day after he switched his research field from the electron theory of metals to the theory of atomic structure.

After identifying these sacrifices with the authoritative help of Rutherford and Einstein, I'll sketch the background in physics from which Bohr put his quantum atom together. In the foreground of this background were Planck's ideas about quanta, Thomson's program in atomic physics, Rutherford's nuclear atom, Nicholson's model of radiation, and Balmer's formula for the spectrum of hydrogen.

The rest of my talk is an attempt to delineate the intellectual and psychological furnishings of the mind that could forge a compelling synthesis from these ill-assorted ingredients. In this attempt – and it is only a trial – I'll make use of some hitherto unavailable family correspondence that Finn Aaserud and I have been permitted to excerpt. We all owe thanks to the Bohr family for allowing study of this unusual documentation of the sources and course of scientific creativity. A key factor in my account is a concept of partial truth, which can be traced backwards to roots as deep in Danish culture as Kierkegaard's *Stages on life's way* and forwards to the four conflicting foundations that Bohr offered for his quantum postulate in his revolutionary paper of 1913.

I've divided the talk into four parts: 1, Bohr's revolutionary sacrifices; 2, Their background in physics; 3, Bohr's partial truths; 4, Their payoff.

2. Revolutionary sacrifices

To say what we all know, Bohr's quantum model of the hydrogen atom allows its single electron to occupy a series of discrete stationary states, in any of which it can rotate around the atomic center without radiating or losing energy by collisions, but otherwise following the rules of ordinary physics. Radiation occurs when it jumps from one state to another of lower energy; and, what is singular, this radiation occurs at one and only one frequency or color determined solely by the electron's loss of energy, or, less insipidly expressed, by the number of stationary states it jumps over.

This way of picturing radiation seemed a fatal flaw to the first physicist to read about it. This was Rutherford, to whom Bohr sent a draft of the revolutionary paper. Rutherford wrote:

> Your ideas about the mode of origin of [the] spectrum of hydrogen are very ingenious ... . There appears to me one grave difficulty in you hypothesis, [however,] which I have no doubt you fully realize, namely, how does an electron decide what frequency it is going to vibrate at when it passes from one stationary state to the other. It would seem to me that the electron knows beforehand where it is going to stop.[4]

For Rutherford, whose strength as a theorist lay in picturable models and robust common sense, an electron that knew its future was as inconceivable as a frequency without a vibration. Here then is the first revolutionary sacrifice: renunciation of an understanding of the radiation process if understanding requires a physical picture of events.

As Einstein observed, the situation was even worse, or, as he put it, Bohr's "achievement" was even greater. We have this information from a letter from the chemist George Hevesy, whom Bohr met in Manchester and who much later became an ornament of Bohr's Institute here in Copenhagen. When Hevesy told Einstein that spectroscopists had confirmed Bohr's attribution to helium of certain lines they had awarded to hydrogen, then, according to Hevesy,

> [Einstein] was extremely astonished and told me: "Than the frequency of the light does not depand at all on the frequency of the electron ... . [T]his is an enormous achiewement. The theory of Bohr must then be wright.[5]

4. Rutherford to Bohr, 20 March 1913, Bohr (1981), pp. 583–584.
5. Hevesy to Bohr, 23 September 1913, Bohr (1981), p. 532.

Einstein had pinpointed the peculiarity of Bohr's theory in its disconnection of the frequency of the emitted light from the orbital frequency of the electron supposed to emit it. And indeed, since the jump involves two stationary states, two different orbital frequencies intervene, and the single color given off by the leaping electron obviously could not be equal to both. (To avoid confusion, I'll speak of the color of radiation and reserve frequency for the periodic motions of orbiting electrons.) The relationship between the frequencies of the participating orbits and the color associated with the electron passing between them is distant and opaque. For example, in the case of a line in the Balmer series, of which more later, the color of the *n*th line, associated with an electron jumping from the *n*th to the 2nd stationary state, is the orbital frequency of the second state minus one half of *n* times the orbital frequency of the *n*th state. There was not much purchase for a mechanical picture there!

When describing this disconnection as an enormous achievement Einstein may have had in mind the liberation of radiation from the usual picture, implicit in Rutherford's reaction to Bohr's theory, that a radiating electron directly stimulated a vibration whose color was that of the electron's frequency. The dissolution of this bond consequently deprived physicists of the conceptual tools with which they had handled the extensive domain of radiation phenomena. That was agreeable to Einstein, whose light quanta did not involve vibrations in the medium through which the radiation traveled.

To Bohr also the disconnection of the color of the radiation from the frequencies of the electrons in the participating stationary states was the most revealing and distinctive feature of his atom. Disagreeable as it was, nature compelled physicists to shelve the tools of their trade when tinkering in the microworld. "We have been forced to assume that a system of electrons will [emit and] absorb radiation of a frequency different from the frequency of vibration of the electrons calculated in the ordinary way."[6]

To most readers then and now, the most striking and persuasive result of Bohr's three-part paper of 1913 was and is the calculation

6. Bohr (1913). p. 16. Bohr (1981), p. 176.

in the first installment of an obtrusive number that recurs in formulas for the colors of spectral lines. This number, called the Rydberg constant or, more familiarly, "the Rydberg," after a Swedish spectroscopist, appeared to be "universal," that is, it had the same value irrespective of the element giving rise to the spectrum. Evidently, it concealed something fundamental. Bohr's calculation expressed the Rydberg in terms of the charge and mass of the electron and Planck's quantum of energy, all supposed to be fundamental constants, or building blocks of matter. When Bohr took into account that ordinary mechanics required the nucleus to move around the center of mass of the atom, his calculation agreed with measurement to five significant figures in the case of hydrogen and ionized helium. So good indeed was the agreement that Bohr suggested that his expression for the Rydberg constant could be used to refine the accepted values of the fundamental constants it contained.[7]

3. Their background

In proposing that his quantum atom might bring an improvement in the values of the electronic mass and charge, Bohr was echoing Planck, who had recommended his radiation formula primarily because his theory of it gave privileged access to the dimensions of the microworld. His colleagues agreed and proposed to award the Nobel Prize in Physics to him in 1908 for his way of calculating the electronic charge. The prize for chemistry would add further emphasis, for it was to go to Rutherford for getting a similar result by counting the accumulated charges carried by a known number of alpha particles. This symmetry broke, however, when the Swedish Academy of Sciences learned that the theory underlying Planck's calculation was out of tune with sound physics. The Academy dropped him and changed the motivation for the prize to Rutherford.

The sticking point in Planck's theory was its covert consequence, which not even Planck had noticed, that every exchange of energy between radiation and matter must occur in certain fixed amounts.

7. Bohr (1913), p. 14. Bohr (1981), p. 174.

He had modeled material radiators as electrons attached to perfect springs of different frequencies. His energy condition, introduced to bring theory into line with experiment, required that the energy element equal the oscillator's frequency multiplied by a fixed number that by Bohr's time was known as Planck's constant or Planck's *h*. The requirement is bizarre from the standpoint of ordinary physics. For it comes down to saying that a very large amount of energy is required to budge a very stiff micro-spring by even a nanometer.

When a Planck oscillator emits radiation it must do so in multiples of its basic energy quantum. In most presentations of his theory around 1913, this emission took place one quantum at a time; but in the form then preferred by Planck himself, an oscillator of frequency ν could deliver itself of a single quantum of frequency-color $n\nu$ or n simultaneous quanta of frequency ν. Bohr would use all these conflicting versions, also simultaneously, when working Planck's *h* into Rutherford's nuclear model.

Although it had been in existence for over a year when Bohr took it up, the nuclear model had not aroused much interest among physicists. Their disinterest had two main causes. For one, Rutherford had introduced the model to explain why thin metal foils sometimes reflected alpha particles that fell upon them, a most improbable feat unless atoms contained tiny, highly charged kernels. This geometry challenged the arrangement in the model Thomson had devised and applied with some success to a wide variety of physical and chemical phenomena. In Thomson's model the electrons circulate in concentric rings within a resistanceless space that acts as if positively charged. Since alpha particles could pass through or by these spaces, and were seldom deflected much by the relatively flimsy electrons, they could not receive a smart enough blow to be knocked backwards in traversing thin foils. But although Thomson could not explain alpha scattering plausibly, he could account for much else, for example, the periodic properties of the elements, for which Rutherford could not offer a competitive explanation.

This brings me to the second set of reasons for the initial indifference to the nuclear atom. Thomson's explanation of chemical periodicity rested on calculations of the stability of different arrangements of the orbiting electrons against small disturbing forces.

Only stable configurations could represent chemical atoms and Thomson showed analogies between some of the acceptable ones and the rows and columns of the table of the elements. The nuclear atom is not mechanically stable for any configuration involving more than one electron, and did not lend itself to an analysis of Thomson's type.

There is one exception to this generalization. An electron ring in a nuclear atom oscillating perpendicularly to its plane can be stable; it is the oscillations in the plane that tear the atom apart. In 1912 a Cambridge mathematician named John William Nicholson calculated the frequencies of the stable small perpendicular oscillations of rings containing a few electrons. He managed to match closely the frequencies of a dozen or more unattributed lines in the spectra of the sun's corona and of certain nebulae; and by this astonishing performance succeeded in extending the purview of the nuclear atom well beyond the original application of Rutherford's model and, in respect of spectra, well beyond the confines of Thomson's program. Moreover, Nicholson was able to connect his models with Planck's *h* by drawing on the latest deliberations on the subject.

These were the proceedings of the Council that assembled in Brussels in 1911 at the invitation of an enthusiastic architect of world systems, Ernest Solvay, who on the side ran and owned the largest chemical conglomerate in the world. The Solvay Council considered problems in radiation theory and the puzzle of Planck's *h*. Many of Solvay's councilors, notably Planck and Einstein, believed that the phenomena to which *h* had been applied, like radiation, specific heats of solids, and the photo-effect, were not tractable by ordinary, or, to use their new term, classical physics. Others, among whom Rutherford probably should be placed, thought that with moderate changes classical physics could account for the awkward phenomena. And several of the councilors, including Planck and Arnold Sommerfeld, agitated the questions whether the proper category of Planck's *h* was energy, action, or angular momentum, and whether the theoretically significant value of Planck's constant was h, $h/2$, or $h/2\pi$.

Nicholson must have been one of the first attentive readers of the

Council's proceedings, which came out in 1912. He promptly answered the questions about the category and quantity of Planck's constant: it measured angular momentum and its proper measure was $h/2\pi$. By working backwards from his association of the nebular and coronal lines with his nuclear ring atoms, he could calculate the angular momentum of their electrons; and this, in every case, came out to be a small multiple of $h/2\pi$.

Nicholson's excursion into spectroscopy did not include an elucidation of the Balmer formula for a series of lines in the spectrum of hydrogen. This simple formula, which relates the lines' colors to two integers and the Rydberg constant, was purely empirical and arithmetic, even numerological; its simplicity had enticed a few bold physicists to attempt derivations from physical models, but in the quarter century since Johann Jakob Balmer enunciated it, no one had proposed anything plausible or useful. The quantitative relation that would provide the test of Bohr's quantum atom was well removed from the concerns of atom builders in 1912.

4. Partial truths

It took courage and confidence to cook up an atom from the ingredients available in 1912 and more of both to dish out the needed sacrifices to the skeptical community of physicists. Einstein regarded Bohr's performance as extraordinarily bold, and Einstein was not a timid physicist. Where did Bohr's intellectual courage, not to say recklessness, and his self-confidence come from? The new material, especially the letters to Margrethe, opens approaches to an answer. Bohr's reaction to her gift to him of Thomas Carlyle's bombastic book *On heroes and hero worship* is a good place to begin.

Carlyle's heroes include the Norse god-man Odin and lesser mortals like Mohammed, Luther, Cromwell, and Shakespeare. Margrethe apparently saw some resemblance between these over-achievers and her Niels. He liked the first chapter, on Odin, because, as he put it lukewarmly, everything about the old North made his blood boil. But he soon grew tired of Carlyle's noise and nonsense, and said so. Margrethe must have been affronted, since her hero felt obliged to apologize. Here is what he wrote:

> You ask what I meant by what I wrote about Carlyle … . By comparing [his style] with a sermon I just mean that one does not demand from a sermon that everything in it should be true, in the same way as from a great work of literature. There exist so many different truths … . With the sermon the main purpose is to show your sympathies and make others enthusiastic about them; and that can of course be just as important as trying to create something which one calls greater – that is, more universally human – and the truth of which will be of a somewhat different kind, coming closer to the so-called scientific truths, which again are of a somewhat different kind. This is so stupidly and badly put, but … it is something I feel very strongly about; I can almost call it my religion, that I think that everything that is of any value is true.[8]

Although Niels did not state the source of this religion, it is easy to spot parallels to its sparse dogma in the teachings of his professor of philosophy, Harald Høffding, and Høffding's friend and admirer William James. Parallels and connections of this kind have been proposed before, to provide a background for Bohr's later philosophy of complementarity; but they lacked hard evidence and hard-headed physicists and historians have tended to downplay or reject them. As the excerpt I've just given suggests, the hitherto unavailable early letters provide much firmer ground for these parallels and connections and, as will appear, for tracing even deeper roots of Bohr's thought in Danish culture.

Before proceeding to a second example, I should point to texts of Høffding and James that resemble Bohr's belief that whatever has value is true. We read in Høffding's *Problems of philosophy*, a short presentation of his approach to the great problems in life, that truth is a word for a successful analogy between "things in being and in human thought;" truth does not signify a reproduction or mirror of reality, but, rather, a utility, whose value lies in "mak[ing] intelligible experience possible."[9] James says similar things more succinctly in his lectures on Pragmatism given in 1906. "The true is the name of whatever proves itself to be good [that is, useful and thus valua-

8. Aaserud and Heilbron (2013), pp. 51-52, 155-156.

9. Høffding (1905), pp. 82-83.

ble] in the way of belief." This definition allows for, indeed, requires, many truths. "The whole notion of the truth is an abstraction from the fact of truths in the plural."[10] The notion is also confused. We must "overhaul the very idea of truth, for at present we have no definite idea of what the word may mean."[11] Bohr took up the challenge. We know from a letter to Margrethe that he was confident enough in his answer to expose it to the criticism of mathematicians at a lunch party in Cambridge. None of them, he reported, had ever heard the like before. Apparently they had not read Høffding or James.

My second example concerns real religion, organized religion, which Niels repudiated when a teenager. Although his mother was a non-practicing Jew and his father, who bore the name Christian, was an atheist, they brought Niels up in the Danish state church in order, as he later supposed, that he not feel different from other boys. Niels took to religion more readily than his parents may have liked. He tried very hard, so he wrote Margrethe, to believe in the Lutheran faith and the salvation of his soul, to understand what salvation might mean, and to divine why it depended on acceptance of improbable stories. But, as James wrote, "[God's] animal spirits are too high, his practical jokes too monstrous," for rational reconstruction.[12] The task overcame even Niels' power to reconcile contradictions.

In an instant, suddenly, completely, discontinuously, Niels perceived that Christian dogma could not be true in any of the many senses of truth he could admit. When he confessed this leap into non-faith to his father, whom he idolized, he received a sage smile in reply. He recalled the episode for Margrethe: "That smile, my little one, taught [me] a lot." "[M]y courage roared so wildly, so wildly, for [I thought] then that [I] too could think."[13] The approving smile of the man he most admired in the world taught him that he belonged among the few who could reason their way free from the

10. James (1907), pp. 30, 92.

11. James (1907), p. 74.

12. James (1907), p. 55.

13. Aaserud and Heilbron (2013), p. 47.

standard beliefs of their class and culture, place and time. He would repeat the performance when recognizing that ordinary mechanics represented the truth of the microworld only a little better than conventional religious beliefs accorded with the meaning of life.

Bohr's rejection of conventional religion brought as much distress to Margrethe's devout parents as his quantum atom would to classical physicists. True to himself and to the memory of his father, who had died in 1911, Bohr refused to be married in church. In a beautiful reply to an unhappy letter from his future mother-in-law, he touched again on his theory of knowledge:

> There was a time when I completely believed every single word, or perhaps more correctly fought hard and victoriously with my doubts .... [S]uddenly I understood that all of it was not true; understood it in a way that to me was beyond any doubt .... But you must not think that I do not believe in anything at all; I believe that there is meaning in the world, a meaning that human beings cannot understand, but can only sense. And that does not make life poorer for me, on the contrary it would be so infinitely trivial if I thought I could understand it. I further understand quite logically that there must be something a human being does not understand.[14]

The striking statement that a logical demonstration exists that proves the limitation of human understanding sends us again to the sources. Høffding put it this way: "all understanding is conditioned by the relation between continuity and discontinuity," by which he meant between rational connection and arrangement, on the one hand, and resistance to analysis, even impenetrability, on the other. The rational and continuous cannot completely render our experiences. There will always be something discontinuous, "an irrational relation between the principles which may compose our consciousness and the Being itself from which our experiences are drawn." Or, as James summarized Høffding's position, facts are abstractions, completion an ideal. "Neither is given in experience, nor can either be adequately supplied by our reason; so that, above and be-

14. Aaserud and Heilbron (2013), p. 77.

low, thought fails to continue, and terminates against an 'irrational'."[15]

Kierkegaard says the same thing even better, as Bohr could have read in Høffding's succinct summary of the philosophy of "the greatest of our thinkers." According to Kierkegaard, it is logically impossible for us to create a complete account of Being because our knowledge and experience grow and change; and as we are part of the Being we are trying to capture in thought, we are attempting to grasp something unformed or continually forming. We live forwardly, understand retrospectively. Only the dead, for whom Existence does not change, can devise a complete system, and, as far as we know, they are not in a condition to do so. And even this dour assessment is over-optimistic, for the dead are no more able than the living to explain how we can understand retrospectively the necessity of what was open-ended prospectively.[16]

Kierkegaard regarded his main task as criticism, as raising difficulties about accepted beliefs. Among his preferred targets was the assumption that we can make "a smooth and continuous connection [among the parts of] our knowledge." That was wrong both intellectually and morally. "It is only reprehensible laziness or impatience to believe that there must be something complete and closed."[17] Kierkegaard's claim to the role of universal critic added to his attraction for Bohr. For if there was anything at which both excelled it was slicing to the bottom of things. Bohr: "[Kierkegaard's] honesty and willingness to think the problems thorough to their very limit is what is great [about him]."[18]

The centerpiece of Høffding's précis of Kierkegaard is the notion of distinctive and even discontinuous stages or types of civilized life. Bohr extolled one of Kierkegaard's presentations of this theme, a lively book entitled *Stages on life's way.* Here we are on unusually solid ground because in 1909 Niels sent his copy of the book to Harald as a birthday present with a commendation that reads as

15. Høffding (1905), pp. 60, 84-85. James, in ibid., p. xi.

16. Høffding (1896), pp. 2 (quotation), 63, 66.

17. Høffding, (1896), pp. 57, 63.

18. Bohr, as quoted by Rud Nielsen (1963), p. 27.

follows: "It is the only thing I have to send; nevertheless, I don't think I could easily find anything better … . I think absolutely that it is about the most beautiful thing that I have ever read."[19]

Harald returned the book in which one of Niels' grandsons, Tomas Bohr, recently found some manuscript notes. Although they are not in Niels' hand, they may yet be the critical remarks that, notwithstanding his admiration of *Stages*, he told Harald that he had written about it. In another letter he refers self-deprecatingly to himself as "Skraep," which I take to be a further reference to his ability and proclivity to criticize; for Skraep was the old Norse sword so sharp that it could cut through the toughest knot and the hardest steel without blunting its edge.[20] Here is part of what Skraep wrote (or may have written) about Kierkegaard:

> From my point of view I must condemn his life and behavior while respecting his struggle and his work, whose fruit is among the most beautiful writing in the world … . I, who do not feel in any way united with, even less, bound to a God, and therefore am much poorer [than Kierkegaard] would say that the good [is] the overall lofty goal … . But, oh God, Kierkegaard, how rich a person you are.[21]

I'll return directly to what might have been meant by Kierkegaard's riches. First, however, I must say a word about Bohr's circumstances when at the age of 24 he expressed himself so ecstatically about *Stages on life's way*. He sent the book to Harald from a parsonage to which he had withdrawn from the bustle of Copenhagen to prepare for his master's thesis and examination. It was just the place for a romantic intellectual. "I walk here in solitude [he wrote Harald] and think about so many things." He thought about physics, of course, and mathematics and logic, but also about the problem of cognition, the stages of life, the nature of the good. I assume that the document Tomas Bohr found is either a copy of the original

19. Niels Bohr to Harald Bohr, 20 April 1909, Bohr (1972), p. 501.
20. "Skraep," in Niels Bohr to Harald Bohr, 26 June 1910, Bohr (1972), p. 513; on proclivity to criticism, same to same, 1 August 1909, ibid., p. 107.
21. Aaserud and Heilbron (2013), pp. 56-57.

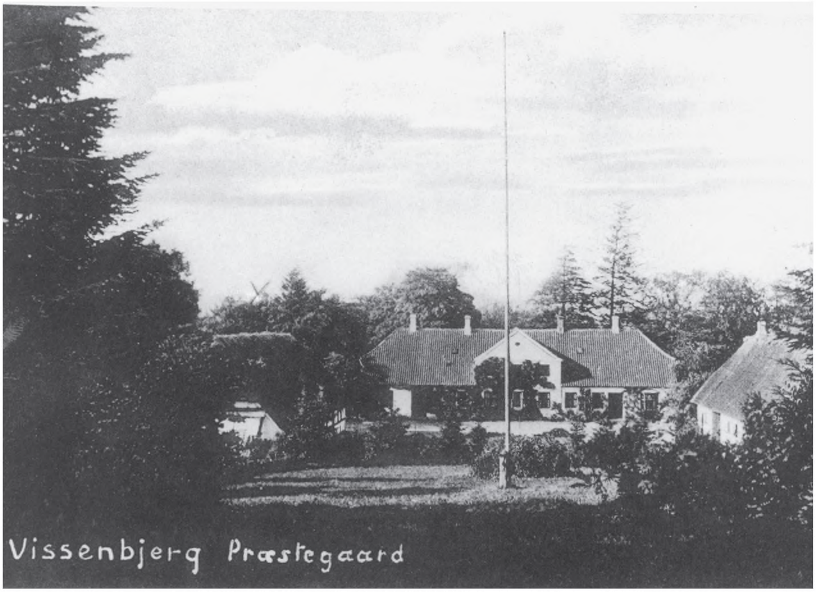

Figure 2. "The parsonage where Bohr walked alone."

written at the parsonage or notes taken there to Bohr's dictation, a method of working characteristic of him.[22]

The reference in the notes to Kierkegaard's riches returns us to the problem of truth. His insight into the human condition was so deep that he had to divide himself into a dozen different personae to do justice to it. These personae appear in his books as characters and on his title pages as pseudonyms. He needed six of them to convey the truths in *Stages*. The earliest stage, the aesthetic, which for some people lasts a lifetime, is a period of carefree experimentation, of flitting from one experience or idea to another. Kierkegaard depicts it through speeches given by four of his avatars at a symposium on love, life, and the universe. Each says something true, though his statement conflicts with what the others say. Another avatar, a self-satisfied judge, sets forth the merits of a good mar-

22. Niels Bohr to Harald Bohr, 20 April 1909, Bohr (1972), p. 501 (solitude); 17 and 27 March 1909, ibid., p. 499 (logic); 26 Apr 1909, p. 503 (notes); 26 June 1910, p. 513 (cognition); 9 June 1909, p. 505 (mother as amanuensis).

riage, the essence of the second or ethical stage. The judge's wife was patient, understanding, supportive, protective, enabling him to reach the highest level his talents and training permitted; neither he nor she could achieve as much apart as they did by pooling their complementary qualities; each contributed an equal share to the truths of married life. Bohr needed such a partner more than most men. As for the third and final stage, the religious, it can be reached only by a leap of faith, which, as we know, was a quantum jump that Bohr made in the opposite direction.

Another of Kierkegaard's personae made a perfect model for a romantic young critic walking in solitude around a country personage. This was young Johannes Climacus, who had a passion for thinking so intense that he could not think about girls. Instead he worried about the meaning of the key of philosophy, the slogan *de omnibus dubitandum est*. Having a "romantic soul which always looked for difficulties," that is, being a consummate critic, Climacus managed to prove that the foundational principle, "modern philosophy begins with doubt," did not mean anything at all.[23] And if it did mean anything, it would exterminate the race of philosophers, since every student would be obliged to doubt the words of his teacher, and each generation would slay its predecessor. And so poor Climacus never advanced even to the threshold of received philosophy. "He became more and more retiring, fearing that thinkers of distinction might smile at him when they heard that he too wanted to think."[24]

I would guess that the multiplicity of points of view in *Stages*, all of which have some value and hence some truth, and Kierkegaard's invincible *amor intellectualis*, as represented by Johannes Climacus, were among the great attractions of Kierkegaard's aesthetic writings for Bohr. Bohr's mental furniture certainly contained some principal items from the workshops of Kierkegaard and Høffding and, perhaps, also of William James. This does not mean that Bohr was a thorough student of philosophy; like Climacus, he never crossed the threshold of the profession. Nonetheless, he had a

23. Kierkegaard (1958), pp. 103, 116 (1st quotation), 126, 140 (2nd quotation).
24. Ibid., pp. 138, 115 (quotation).

strong interest in a few philosophical problems as posed and answered by Høffding, who, in turn, had a high regard for Bohr's philosophical acumen. Could it be that the "young friend" from whom Høffding expected "much in philosophical respects" and who, around 1902, offered a criticism of his *Philosophy of religion*, was Niels Bohr?[25] Though only 17 in 1902, Niels had been present at informal meetings in his home at which his father discussed general philosophical and scientific questions with Høffding and two of their colleagues; and, not much later, Niels corrected a passage in one of Høffding's textbooks.

I fear that I may have created a monster in harping on the philosophical ideas that Bohr picked up during his adolescence and while studying at the University of Copenhagen. The letters to Margrethe document a lighter side, though perhaps overly intellectual for some tastes. They quote poetry to one another, Goethe, Ibsen, Shakespeare, and sometimes descend to Dickens novels. Bohr loved adventure stories, and as a boy was addicted to the tales of James Fennimore Cooper. The ridiculous feats of Cooper's Indians and marksmen in the great American forests perhaps reminded him of the exaggerations of the Icelandic sagas, for which he also had a taste.

And, of course, there was Margrethe. Departing here from Johannes Climacus, Niels came to think almost as obsessively about her as Quidam in *Stages*, the Seducer in *Either/Or*, or Kierkegaard himself in real life did about their girlfriends. But, as Margrethe understood perfectly, she would have to share Niels with his work. In reply to a question put to her in several ways in their letters, she acquiesced in this ménage à trois and professed, in so many words, to love his work as she loved him. She bore the test cheerfully when spending her honeymoon in Manchester helping Niels finish a paper on the life history of alpha particles. Before her marriage Margrethe worried that she might not know enough, or be able to learn enough, to be a companion to a compulsive thinker and his thoughts. Her future mother-in-law assured her that she need not know anything except the value of intellectual work.

25. Høffding to Ferdinand Tönnies, 27 March 1902 in Bickel and Fechner, eds. (1989), p. 90.

Figure 3. Margrethe and Niels in their engagement photograph.

> You are so genuinely good, and also wise precisely because your soul is so sensitive to everything really good and wise. Wisdom is not the amount of knowledge but the understanding of and love for the value of intellectual work, which is so rarely valued because so few know what it requires of strength, diligence and unselfish striving … . [You know] what a rare treasure Niels is.[26]

5. Their payoff

In the interest of time and clarity, I will conclude with a caricature of the way Bohr's special mind set could have assimilated and transformed the conflicting ingredients of his quantum atom. A caricature is not an untruth but an exaggeration designed to bring out some features at the expense of others. A good caricature is a memorable expression of a partial truth – and, although I certainly do not claim that mine is memorable, I can say that it is fitting. For what, after all, was Bohr's quantum atom but a caricature contrived to bring out certain aspects of the microworld?

Convinced that human beings can never arrive at a coherent theory of everything, Bohr did not worry, but rather expected, that classical physics had its limits. One of the advantages of the nuclear atom was that it exposed the limits: it represented several features of the microworld simply and cleanly, but could not be a mechanical structure. To proceed further Bohr needed a quantitative discrimination or definition of quantum concepts. For this he adapted Planck's mysterious relation between the energy and frequency of an oscillator. An electron ring rotating around a nucleus is not much like a Planck oscillator. Nonetheless, Bohr made the assimilation work at first by confining his attention to the atom in its ground state, in which it does not radiate at all; and so, evidently, would be useless as a model for the theory of radiation from which Bohr took Planck's famous, and famously obscure precept, $E = h\nu$.

In Planck's theory the same symbol, ν, stood for the color of the radiation and the frequency of the oscillator, which are identical on his model. At first, when he confined himself to the ground state,

26. Aaserud and Heilbron (2013), p. 18.

Bohr did not have any reason to distinguish between them. So he took the frequency of the orbit in the ground state as the quantity required in Planck's precept. For the corresponding energy, Bohr took the amount lost by the electron during its binding by the nucleus, which, in a nuclear atom, is just equal to the electron's orbital kinetic energy. Thus obscuring or disguising the ambiguity between color and frequency, he had a model with which to pursue Thomson's program to elucidate the periodic table. This program remained his purpose throughout the trilogy. Even in its first part, after delivering his theory of the hydrogen spectrum, he specified that his subject was the behavior of atoms in their ground state.[27]

The interaction with Nicholson, which turned Bohr's attention to spectra, provoked him to a compromise in which Nicholson's atom described the radiation process and Bohr's the ground-state behavior. There had to be some truth in Nicholson's model! It had value: it agreed well with experiment and married quantum theory to ordinary physics. Even after Bohr had invented his own account of radiation and had discarded Nicholson's, he did not reject it altogether, and reinstated it to scatter light.

Absorption of Nicholson's papers increased the ambiguity of Bohr's model atom by introducing higher stationary states, in each of which an electron had an orbital frequency proportional to its kinetic energy. As long as he left radiation to Nicholson, the increased ambiguity could be papered over: for the frequencies of the small oscillation of the electrons perpendicular to their ring, to which Nicholson ascribed radiation, were the colors of the light emitted, as in Planck's theory.

A glance at the Balmer formula written in the suggestive form $\nu_n = R(1/2^2 - 1/n^2)$ revolutionized the subject in Bohr's prepared mind. He multiplied the formula by h and read it as a Planck precept, or energy equation; since $h\nu_n$ would equal a change in energy, the equation immediately suggested hR/n^2 as the kinetic energy of a hydrogen atom in its nth stationary state. It appeared that the radiation process was the locus of the quantum difficulty: radiation did not take place by oscillation around stable orbits but by abrupt

27. Bohr (1913), p. 20. Bohr (1981), p. 222.

transitions or jumps between them. And, since the frequencies of the participating orbits differed, the color of the light emitted could not be equal to both of them and, in fact, was equal to neither. Bohr then had a crisp dichotomy between stationary states, in which electrons behaved as if Newton had designed the atom, and quantum jumps, in which not even a Newton could follow them.

With what satisfaction a student of Høffding's would have contemplated this outcome! The master had taught that the world consisted of the continuous, describable, and rationally explicable, and the discontinuous, irrational, and novel. Here, in a simple case, Bohr had found one of those closed doors at which continuity must stop; or, to adopt the words Niels used to reconcile his future mother-in-law to her daughter's marriage outside the church, a place where we confront the demonstrable truth that there are things human beings cannot understand. What struck Rutherford and Einstein as spectacularly bold conclusions were for Bohr only what was to be expected. That physicists had to renounce their ambition to give rational accounts of all physical phenomena was in the nature of things as viewed from Copenhagen.

The identification of the Balmer terms as energies of stationary states was one of two components that made possible Bohr's theoretical derivation of the Rydberg constant. The other was the postulate that the ratio of kinetic energy to orbital frequency in the *n*th stationary state equals *n* times Planck's constant divided by 2 ($T_n = nh\omega_n/2$). Bohr was too responsible a physicist to want to rest his derivation on so obscure a postulate. So he offered a more basic foundation, or foundations; in all, he gave no fewer than four such groundings or partial truths. Two of these truths are analogies to Planck's radiation theory, one based on each of its chief formulations in 1913. The third partial truth brings the radiated color into asymptotic agreement with the frequencies of the participating orbits by requiring that at great distances from the nucleus, where the electron is almost free and the energies in nearest neighboring orbits almost equal, the color as calculated by jump equals, almost, the approximately equal orbital frequencies. The fourth partial truth or grounding appears to be a mathematical reworking of the basic postulate $T_n = nh\omega_n/2$ into the familiar condition on the angular momentum of an electron in a stationary state, the only one of the four partial truths now remembered.

The grounding via analogy to Planck's precept $E = h\nu$ contains whatever truth there is in Planck's radiation theory. As we know, the analogy does not fit the nuclear atom very well and Bohr soon gave it up as "misleading." He came to prefer the asymptotic grounding. This he later generalized into the Correspondence Principle, which required that at some limit classical and quantum calculations should agree. It contains the partial truth, or vague requirement, that where the domains of validity of contradictory theories overlap, the quantitative descriptions they give should coincide. The Correspondence Principle may appear to plug the breech between the micro- and the macroworld. It does not. For although the calculations may agree, the physical pictures underlying them do not.

The fourth grounding is not a mere reworking of the postulate. It is conceptually quite different from the other three. They mix together quantities pertaining to the radiation emitted, and to the motions of the electrons somehow responsible for it, whereas the condition on the angular momentum relates only to the orbit. But it too is only a partial truth, as, indeed, are the electron orbits themselves. As Bohr puts it in a typically oracular phrase,

> While there obviously can be no question of a mechanical foundation of the calculations given in this paper, it is, however, possible to give a very simple representation of the calculation ... by [the] help of symbols taken from the ordinary mechanics.[28]

This foundation that is not a foundation is the condition on the angular momentum.

As we all know, Bohr's quantum atom initiated a development that, within a decade (taking time out for World War I), produced quantum mechanics and revealed to Bohr the philosophy of Complementarity. It rested on the perception that partial truths come in pairs, not trios or quartets. Each pair has the property, characteristic of Bohr's thought, of being formally inconsistent and even contra-

28. Bohr (1913), p. 15. Bohr (1981), p. 175.

dictory, and yet necessary for a complete representation of experience. Thus wave and particle, space-time and causality, as applied to the microworld, and free will and determinism, mechanism and vitalism, as applied to wider human concerns. These last extrapolations were not evidences of a turn to philosophy by a decaying physicist, but of a return to the broad questions that Bohr had encountered through Høffding in the old days when he discovered that he too could think.

BIBLIOGRAPHY

Aaserud, Finn, and John L. Heilbron (2013). *Love, Literature, and the Quantum Atom: Niels Bohr's 1913 Trilogy Revisited.* Oxford: Oxford University Press.

Bohr, Niels (1972). *Niels Bohr Collected Works, Vol. 1: Early Work (1905–1911).* J. Rud Nielsen, ed. Amsterdam: North-Holland.

Bohr, Niels (1981). *Niels Bohr Collected Works, Vol. 2: Work on Atomic Physics (1912–1917).* Ulrich Hoyer, ed. Amsterdam: North Holland.

Bickel, Cornelius, and Rolf Fechner, eds. (1989). *Ferdinand Tönnies, Harald Høffding Briefwechsel.* Berlin: Duncker and Humblot.

Bohr, Niels (1913). "On the constitution of atoms and molecules." *Philosophical Magazine* 26, 1-25.

Høffding, Harald (1896). *Søren Kierkegaard als Philosoph.* Stuttgart: F. Frommann.

Høffding, Harald (1905). *The Problems of Philosophy.* New York: Macmillan.

James, William (1907). *Pragmatism: A New Name for Old Ways of Thinking.* New York: Dover, 1995.

Kierkegaard, Søren (1958). *Johannes Climacus, or, De omnibus dubitandum est, and A Sermon.* Translated by T. H. Croxall. Stanford: Stanford University Press.

Rud Nielsen, J. (1963). "Memories of Niels Bohr." *Physics Today* 16: 10, 22-30.