CHAPTER 1.4

# Bohr's genuine metaphor: On types, aims and uses of models in the history of quantum theory

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## Abstract

Modern physics is discussed often with concepts as "model," "analogy" or "metaphor," which apparently allow to bridge a gap that cannot be overcome by a straightforward application of mathematical formalism or experimental analysis alone. From drawings, the most common kind of these epistemological bridge objects, the scope extends to models of various kind and (material) quality, which can be found at a wide range of places from scientists' notebooks and workshops to university collections or public exhibitions. My discussion concerns the field of quantum physics and aims at putting Bohr's atomic model – in all its representational forms – into a wider context of drawings and artifacts related to quantum and atomic physics. The thesis is, that from a historical epistemological perspective Bohr's atomic model was a "genuine metaphor" (T. Kuhn), which made it a creative tool pushing forward theoretical research, rather than an illustration of established aspects of nature.

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## 1. Model, analogy, metaphor

Among the many attempts to grasp historically the quantum revolution as a rather longterm development that transformed mechanics from its classical foundation to quantum mechanics, three terms are often invoked: model, analogy and metaphor.[1] Their function apparently lies in their power to bridge a gap that cannot be overcome by a straightforward application of mathematical formalism or by improvements of deductions from experimental findings. Besides drawings (as actual inscriptions that historians can often find in letters and notebooks) the most concrete kind of these epistemological bridge objects are also models, often even material models, either improvised ones or ones carefully manufactured that eventually found their way into exhibitions or university collections.

I will thus ask: What is the role of such models in the history of quantum and atomic physics? Or, putting this question slightly differently: How can we embed these objects and graphical renderings or even suggestive descriptions into a long-term history of quantum and atomic physics? In order to answer this question I will consider various examples of models of different kinds, ranging from Max Planck's oscillators of 1900 and Jean Perrin's verbal description of a planetary atomic model in 1901, to Niels Bohr's early drawings of atoms and molecules, exhibition objects built according to the instructions of Arnold Sommerfeld in 1918 in Germany or according to the instructions of William Lawrence Bragg and Douglas Hartree in Britain some years later, or even to Harvey Elliott White's machine from 1931 that mechanically produced pictures of quantum mechanical electron orbitals in three dimensions. Within this broad range of models we may distinguish three classes with respect to how they relate to quantum concepts: one purely classical, one employing concepts of the old quantum theory and

1. Darrigol (1992), Petruccioli (1993), Schirrmacher (2009a).

one making reference to quantum mechanics. Before I go into more detail about such models, I shall first motivate why the analysis of models such as that proposed by Niels Bohr provides an important ingredient for the long-term history of quantum physics by turning to Thomas S. Kuhn as my main staunch ally.

In the late 1970s Richard Boyd and Thomas Kuhn engaged in a pointed exchange on the role of metaphors, analogies and the like in science which essentially shifted the discussion from hard-to-grasp metaphors to rather concrete models. Both authors agreed on the "interaction view" of metaphors that had been put forward by Max Black[2] as they shared the understanding that among the metaphors used in science many are merely decorative and could be eliminated by adequate non-metaphorical formulations while others are such that

> ... metaphorical expressions constitute, at least for a time, an irreplaceable part of the linguistic machinery of a scientific theory: cases in which there are metaphors which scientists use in expressing theoretical claims for which no adequate literal paraphrase is known. Such metaphors are *constitutive* of the theories they express, rather than merely exegetical.[3]

However, when it came to making this distinction for concrete examples controversy arose. For Boyd, Bohr's atom was just an example of the sort of metaphors that can be eliminated, since

> one can say exactly in what respect Bohr thought atoms were like solar systems without employing any metaphorical device, and this was true when Bohr's theory was proposed.[4]

For Kuhn, however, Bohr's atomic model was rather one of the "genuine metaphors" or "analogies". He thus proposed a more differentiated view:

2. Contributions by Boyd and Kuhn in Ortony (1979) and Black (1962). Cf. also Hesse (1963).
3. Boyd (1979), p. 360.
4. Boyd (1979), p. 359.

> Bohr and his contemporaries supplied a model in which electrons and nucleus were represented by tiny bits of charged matter interacting under the laws of mechanics and electromechanic theory. That model replaced the solar system metaphor but not, by doing so, a metaphor-like process.[5]

Although one might question the extent to which Bohr's atom was taken literally in the various stages of quantum theory – from J. J. Thomson who never accepted it to Peter Debye who actually made experiments to measure the electron orbits and their spatial relations[6] –, for Kuhn it appeared clear that

> ... even when that process of exploring potential similarities had gone as far as it could ... the model remained essential to the theory. Without its aid, one cannot even today write down the Schrödinger equation for a complex atom or molecule, for it is to the model, not directly to nature, that the various terms in that equation refer.[7]

Models like the Bohr atom provide in this way, according to Kuhn, an "interactive, similarity-creating process" that has an epistemological dimension. The typical reduction of models, however, to "historical" models (e.g., to avoid controversy)[8] and teaching aids or motivations that should eventually lead to more advanced and abstract theory well beyond pedagogical or heuristic uses,[9] is misleading according to Kuhn:

> Models are not, however, merely pedagogic or heuristic. They have been too much neglected in recent philosophy of science.[10]

Kuhn's call for more attention to models reminds us today of Ian Hacking's dictum on experiments. Thus the epistemological battle

5. Kuhn (1979), p. 414.
6. Cf. Schirrmacher (2007a).
7. Kuhn (1979), p. 415.
8. Eckert (2009).
9. Schirrmacher (2009b).
10. Kuhn (1979), p. 415.

cry "Models have a life of their own!" is at least one way to elucidate the nature of models in physics – as it was for experiments particularly with Hacking and Peter Galison.[11] Indeed, philosopher Margaret Morrison probably spelled out this approach best when she identified models as "autonomous agents". She explained that instead of looking at models of phenomena, models of data, models of theory, their representational character, their ontology, their implications for scientific realism, explanation and the possibilities for laws of nature etc.,[12] one may take a break and put aside all these philosophical discussions for a moment in order to concentrate on the epistemological role of models.

By looking particularly at the practices of science and analyzing knowledge creation or knowledge change, Morrison holds that one can arrive at two interesting claims: (1) that it is models rather than abstract theory that represent and explain the behavior of physical systems and (2) that they do so in a way that makes them autonomous agents in the production of scientific knowledge.[13] If it is true that in this way models "occupy a separate domain of scientific investigation" a history of the development of quantum physics has hence to look into models.[14]

A second way to bring models to the fore in the field of physics comes from the side of historical epistemology, as developed by historians of science who relate scientific models to mental models. A prominent example is the work of the Berlin Max Planck Institute for the History of Science on the basic interpretational framework for the analysis of Einstein's path to general relativity.[15] For the purpose of this essay it suffices to explain very generally how mental models relate to material models, and I will do this by simply citing three central tenets of the proponents of mental models on representation, transmission and longevity:

11. Hacking (1983), Galison (1987).

12. Cf. e.g., the similar discussions in Frigg and Hartmann (2006).

13. Morrison (1999), p. 39.

14. Morrison (1998), p. 85.

15. Cf. in general on the relation between models and mental models Büttner, Renn, and Schemmel (2003), Renn (2007) and Renn and Hyman (2012) pp. 20-29, on relativity Renn and Sauer (2007).

> Mental models can, as a rule, be externally represented by material models which also serve as the element of continuity in their transmission … .[16]

> The backbone of the long-term transmission of mental models is the transmission of their material counterparts.

> [Mental models are] characterized by a remarkable longevity across historical breaks as becomes clear when considering such examples as the mental model of an atom, of a balance, of the center of gravity or of positional weight.[17]

Among the models that played an important, if not crucial role in the genesis and development of quantum theory and have a long-term model history are in particular the virtual oscillator model and the planetary model of the atom. As the virtual oscillator has been treated already in a number of other works, I shall only recall some points, which turn out to be related to the planetary model; here I can follow largely along a path marked by John Heilbron.[18] With regard to the planetary model I shall focus on discussion of drawings and material models used for both research and dissemination. I shall ask when the models were introduced in writing, drawing or assemblages, what changes their status underwent and when, if at all, they were withdrawn from the scientific discourse. This analysis is based on the assumption that contrary to Hacking, who sees models only as mediators acting on some level between theory and phenomena, viz., as something that one has in one's brain rather than in one's hands,[19] I shall claim that models are around, that you can touch them, you can manipulate them, they can be constructed and they can also be destroyed. In short, models do have a life of their own – one that is real rather than a pipe dream.

16. Renn and Sauer (2007), p. 127.
17. Büttner, Renn, and Schemmel (2003), p. 43.
18. Heilbron (1994).
19. Hacking (1983), p. 216.

## 2. Key models in the history of quantum mechanics

In a long-term perspective the history of quantum mechanics starts at least with Planck's introduction of the quantum of action, which is closely related to the picture of oscillators describing radiation phenomena and extends well beyond the formulation of quantum and wave mechanics. The many problems related to treating quantum mechanical systems very quickly rehabilitated the picture that was so essential to the old quantum theory: particle trajectories. Although discarded by the new theory, they resurfaced in order to tackle more complicated systems, as mentioned by Kuhn above.

The concept of virtual oscillators predates quantum theory as basically any classical wave theory of light rests on an infinite number of virtual oscillators called the ether. However, only with the electron as an evident particle and in particular with the discussions of the Bohr atom and further on the route to quantum mechanics did virtual oscillators play a central role in solving problems. As John Heilbron has explained, it was the "humble resonator" that stood at the foundations of the theory of atomic structure. The Zeeman effect became the first means to analyze atomic structure when Lorentz identified – at least for radiation purposes – the atom with "a collection of oscillators each consisting of a charged particle bound elastically to a fixed point."[20]

For Drude, matter could be understood as a collection of virtual oscillators that had different charges and that displayed dispersion. Here an important interpretation can be found, which became crucial for both the Bohr atom and Heisenberg's route to quantum mechanics: Drude's theory accounts for resonant frequencies not by finding a single entity that corresponds to this frequency, but rather by identifying the frequency from parameters representing the whole collection of virtual oscillators.[21] Similarly, Heilbron has argued that also Ritz's combination principle for spectral frequencies hinges on sets of virtual oscillators.[22] Hence, Ritz's contribution to revealing the Rydberg

20. Heilbron (1994), p. 179.

21. Drude (1906)

22. Voigt (1911).

constant as a universal constant goes back to virtual oscillators. Clearly, Planck's resonator was also a virtual oscillator and while he thought that the energy of each individual oscillator could vary continuously and only the total energy had to obey the new quantum of action, Einstein made it clear that this must hold for each oscillator separately. In this way the quantized virtual oscillator was introduced. Again the question would arise whether the frequencies of spectral lines would coincide with those of mechanical motions in radiating atom – even when quantized.[23] Within the theory theory of solid bodies it was the treatment of specific heats developed by Einstein as well as by Max Born and Theodore von Karman where virtual oscillators played once more an important role, as they finally did in Richard Ladenburg's work on dispersion with his "Ersatz oscillators".

> Physicists replaced Bohr's original conception of an electron orbit by an infinite set of virtual oscillators 'conjugated' to each stationary state. Each of these Ersatz oscillators had the frequency of a spectral line that could be emitted or absorbed by an electron in the state conjugated with them.[24]

While the model of the virtual oscillator did not leave behind artistic rederings, the planetary model quickly extended much farther beyond verbal descriptions.

As a young lecturer of physical chemistry at the Sorbonne, Jean Perrin was the first to introduce the planetary model to an audience of students and friends of the university on 16 February 1901. It is instructive to look at the suggestive notions (below in italics) he had introduced to explain the workings of the microcosm:

> Chaque atome serait constitué, d'une part, par une ou plusieurs masses très fortement chargées d'électricité positive, sorte de *soleils positifs* dont la charge serait très supérieure a` celle d'un corpuscule, et d'autre part, par une multitude de corpuscules, sorte de *petites planètes négatives* … .

23. Heilbron (1994), p. 182.
24. Heilbron (1994), p. 184f.

> Si une force électrique suffisante agit sur un atome elle pourra détacher une des *petites planètes*, un corpuscule (formation de rayons cathodiques) … .
>
> Les *durées de gravitation* des différentes masses intérieures à l'atome correspondraient peut-être aux différentes longueurs d'onde des lumières que manifestent les raies du *spectre d'émission.*
>
> Un calcul simple donne une première indication dans ce sens … ; c'est-à-dire d'après les dimensions de cet atome, environ $10^{-7}$ centimètres; nous trouverons que la durée de cette gravitation (*l'année de cette planète*) est environ $10^{-15}$ secondes … .
>
> Si l'atome est très lourd, c'est-à-dire probablement très grand, le corpuscule le plus éloigné du centre, – le *Neptune* du système –, sera mal retenu dans sa course par l'attraction électrique du reste de l'atome …[25]

With this description of the atom as a small planetary system including "positive suns" and "negative planets," but also the translations of the concepts of "year" for the revolution time and "Nep-

25. Perrin (1901), p. 460, my italics. This twelve page article reproduces a special lecture for both students and friends of Paris university and appeared strictly speaking not in a scholarly journal but in the influential *Revue scientifique*, a journal of a very elevated interdisciplinary or even semi-popular level. For its role cf. Rollet (1996). In English (my italics):

> Each atom would consist, first, by one or more masses strongly charged with positive electricity, sort of *positive suns* whose charge is much higher than that of a corpuscle, and secondly, by a multitude of corpuscles, sort of *little negative planets* … .
> If a sufficient electric force acts on an atom it can detach one of the *little planets*, a corpuscle (formation of cathode rays) … .
> The *times of revolution* of the different internal masses of the atom may correspond to the different wavelength of the light which appear as the rays of the *spectrum of emission.*
> A simple calculation provides a first indication in this direction. …; that is to say according to the dimensions of this atom, about $10^{-7}$ centimeters, we find that the time of revolution (the *year of the planet*) is about $10^{-15}$ seconds … .
> If the atom is very heavy, that is to say, probably very large, the particle farthest from the center, the *Neptune* of the system, will be poorly retained in its course by the electrical attraction of the rest of the atom … .

tune" (Pluto was not yet discovered) for the outermost particle, Perrin saw explanations in reach for such problems in physical theory as the frequencies of spectral lines, or even radioactivity.

In 1904 in his contribution to the review journal *Naturwissenschaftliche Wochenschrift*, August Becker expanded on Philipp Lenard's 1903 *Annalen* paper, in which absorption experiments with cathode rays demonstrated the emptiness of the atomic scale. As the comparison with the universe of stars and planets is already in the *Annalen*, only a suggestive description of Lenard's ideas, including the need to adapt celestial mechanics for atomic physics, is communicated in the more popular review journal. In considering a case like the negative hydrogen ion Becker wrote:

> ... indeed each cathode ray particle contained within a force field [will] orbit rapidly around the positive point or describe paths, the knowledge thereof is to be expected from a yet-to-be-found solution to the three-body problem, which takes into consideration not only attracting forces but also repelling ones.[26]

The more one delves into reviews and popular scientific texts from the early years of the 20th century, the more often and more explicitly one can find the planetary model emerging as the picture of the microcosm. Further prominent examples can be found in articles written by astronomer Max Wilhelm Meyer (the "Urania-Meyer" who, together with Werner von Siemens and Wilhelm Förster, ran the Berlin Urania institution, a prominent forum for further education). He presented the planetary model in the two bestselling popular German science journals before the Great War, *Kosmos* and *Natur*, and he invoked the micro-macro analogy in descriptive as well as romanticizing ways when speaking of suns, planets, orbits and the like in the atomic realm.[27]

The first, however, to establish a connection of orbits within an atomic setting consisting of a central charge and revolving electrons with the quantum hypothesis was Johannes Stark. He tried to explain band spectra from a recombination of a detached valence elec-

26. Becker (1904), p. 532.

27. Meyer (1905), Meyer (1910), see Schirrmacher (2007b) for discussion.

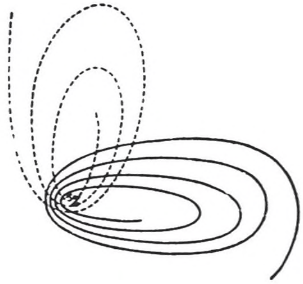


Figure 1: Drawing from Johannes Stark's three-volume work on *Atomdynamik* using the planetary model in combination with the quantum hypothesis for the discussion of band spectra. (Source: Stark (1911), p. 112).

tron to its ground state that involved elliptical revolutions of decreasing size giving raise to the whole band spectrum (Figure 1). Some scholars have even interpreted Bohr's atom as a mere adaptation of Stark's *Atomdynamik*, actually a three-volume work that Bohr had read just before writing his trilogy.[28]

It appears, however, that Stark's strong interest in using the quantum for solving problems of atomic physics did not turn out very fruitful for his own work – his results had rather limited success – but they ignited Sommerfeld's interest in the matter, which was crucial for the development of quantum theory, probably even more than the impact Stark's writing had on Bohr, although he found his way to atomic structure from the very same question of absorption of charged particles.[29]

Concerning Bohr and his use of the planetary model, it is interesting to note that he had employed it in many elaborate drawings in his 1912 Manchester memorandum even before he read Stark (Figure 2). The memorandum shows how Bohr's ideas on the hydrogen atom were embedded in a much more far-reaching theory of molecules and matter. It was seen to account for empirical facts

28. Stark (1908), Stark (1911), on Bohr's knowledge of Stark's work see Hermann (1969), p. 172f.

29. Cf. Heilbron and Kuhn (1969), pp. 237-255, Kuhn (1978), pp. 222–226, and Bohr (1981), pp. 103–134.

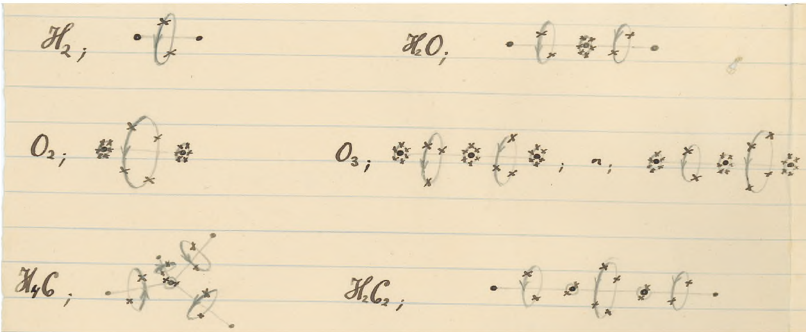


Figure 2: Drawings by Niels Bohr for the atomic structure of various simple molecules from his so-called Machester memorandum written in summer 1912. (Source: Bohr (1981), p. 138.)

about the periodicity of atomic volumes or the existence of hydrogen molecules in distinction to the non-existence of helium molecules among others.[30] We can thus argue that Bohr's revised 1913 theory of the atom actually emerged from thought and drawing processes that had involved a plethora of uses of the planetary model, which Bohr did not have to invent but just to use, as it had been part of the scientific and popular discourse for more than a decade.

The years after Bohr's trilogy were even more under the spell of the planetary model. Sommerfeld used it to extend and refine the theory, Peter Debye made very explicit use of the model.[31] It is, however, important to observe that Sommerfeld's later criticism towards modelling, which he expressed strongly, for example, in his 1924 *Naturwissenschaften* paper, only came after a rather long commitment to the planetary model.[32]

This commitment made him create the atomic symbol that eventually became the signet of an atomic age and he was also the first to craft a planetary exhibition model.[33] Hence, discussions of Sommerfeld's general engineering, crafting or even opportunistic attitudes towards models have to be analyzed with care, as he was the one who drew

30. Bohr (1981), p. 105.

31. See Sommerfeld (2013), pp. 52–55, and Jordi (2013).

32. Sommerfeld (1924).

33. Schirrmacher (2003).

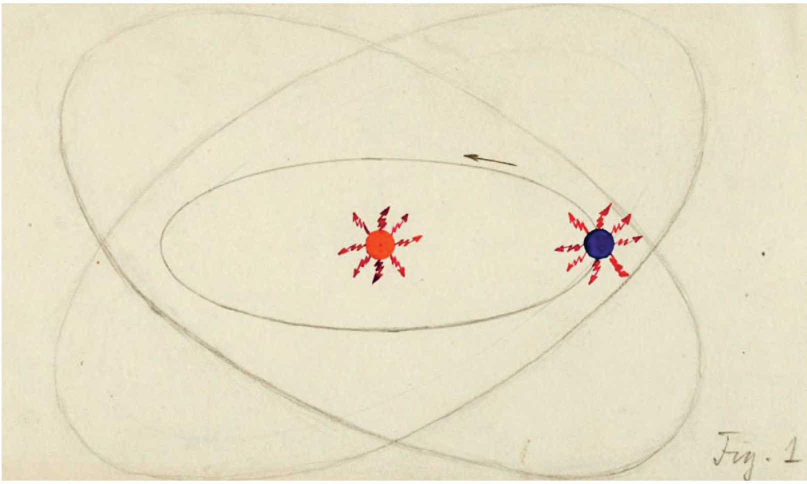



Figure 3: Drawings by Arnold Sommerfeld for the the construction of an atomic model for hydrogen made for the Deutsches Museum. From a letter by Sommerfeld to Armin Süssenguth, dated 4 December 1918. (Source: Deutsches Museum, Bildarchiv, BN 51885.)

the basic icon of the atomic age and displayed the first wood-and-wire model at one of the leading science museums (Figures 3 and 4).[34]

It was also Sommerfeld who gave Wolfgang Pauli his topic for his dissertation: the calculation of the orbits for the simplest molecule, the hydrogen molecule ion, which consists of two protons as atomic nuclei and a single electron. Pauli was particularly concerned with the problem of mechanical stability and worked hard to calculate and classify all orbits that were possible according to the old quantum theory. He tried to identify all stable orbits and hoped to produce the right experimental predictions as well as to find a route for going beyond the old quantum theory. Although Pauli was not really happy after concluding his study in 1922 – he realized that he had not fully solved the problem – an important finding resulted: instability renders simple, symmetric and circular orbits incapable to account for (mechanically) stable molecules. Only when the electron fills some shell-like surface with its path does a half-way

34. Cf. Seth (2010) for a recent discussion of Sommerfeld's technical or crafting approach and Eckert (2003) for its relation to mathematics and physics paradigms.

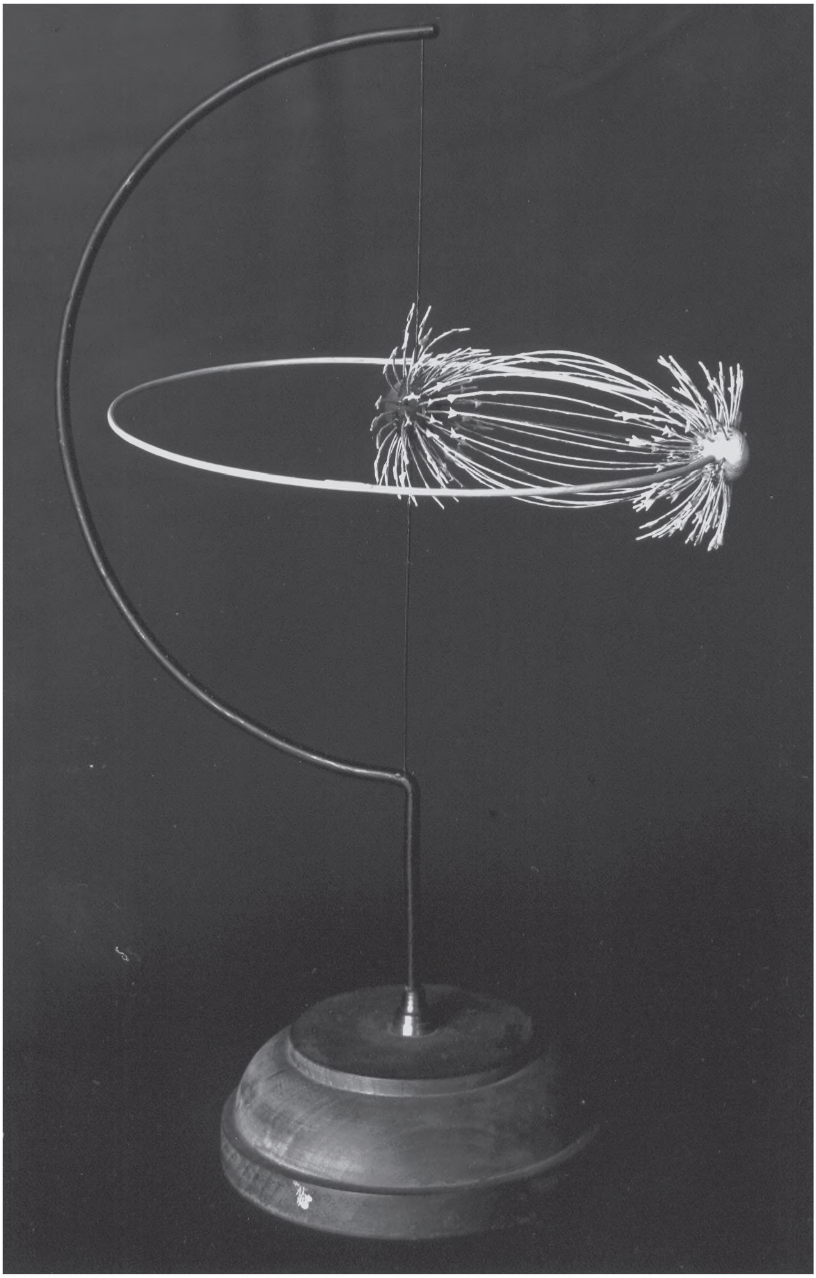


Figure 4: Model of hydrogen built according to Sommerfeld's instructions in 1918 and exhibited at the Deutsches Museum, Munich. (Source: Deutsches Museum, Bildarchiv, BN 2936.)

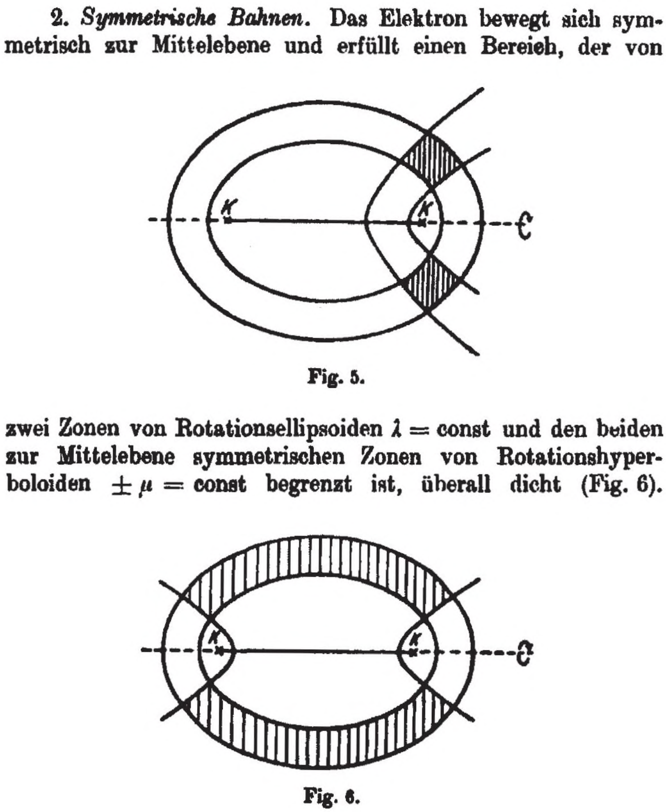

**2.** ***Symmetrische Bahnen.*** **Das Elektron bewegt sich symmetrisch zur Mittelebene und erfüllt einen Bereich, der von**



**Fig. 5.**

**zwei Zonen von Rotationsellipsoiden $\lambda = \text{const}$ und den beiden zur Mittelebene symmetrischen Zonen von Rotationshyperboloiden $\pm\,\mu = \text{const}$ begrenzt ist, überall dicht (Fig. 6).**



**Fig. 6.**

Figure 5: Drawings in Wolfgang Pauli's dissertation sketching the shape of a mechan- ically stable solution of the hydrogen ion molecule. (Source: Pauli (1922), p. 208.)

suitable, stable configuration emerge (Figure 5). Unfortunately, not much is known about the full story of Pauli's dissertation, which actually appeared in an improved version in the *Annalen*;[35] we do know that somebody – probably again Sommerfeld – thought Pauli's model was important enough for material modelling and for putting on display at the Deutsches Museum (Figure 6).

From the point of view of rationally reconstructing the history of quantum mechanics or typical conceptual histories of quantum the-

35. Cf. Enz (2002), pp. 63–70.

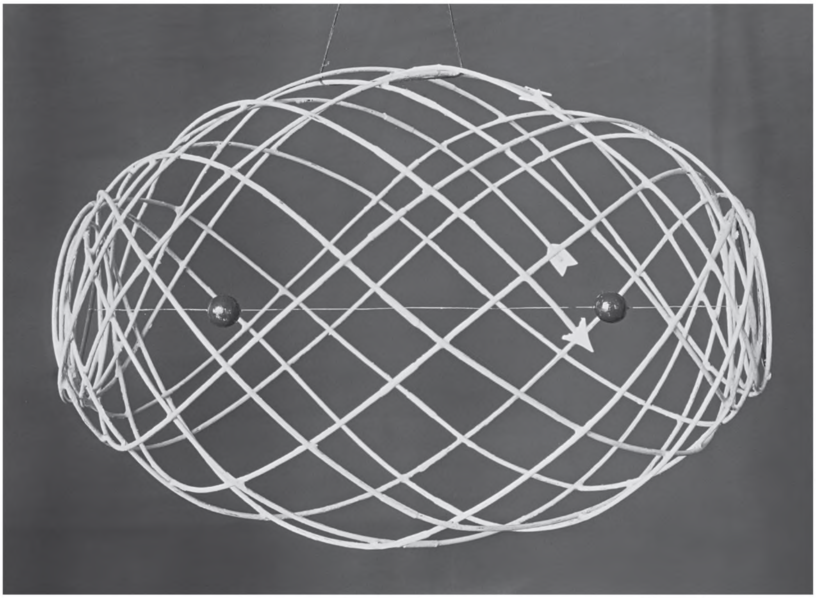


Figure 6: Model of hydrogen molecule ion built according to Pauli's calculations c. 1923 exhibited in the Deutsches Museum. (Source: Deutsches Museum, Bildarchiv, BN 2935.)

ory, Paulis's work has not yet been identified as important. From the point of view of basic models that guided physicist in the quantum revolution, the result that the simple planetary model gives rise to orbital surfaces already for very simple molecules exhibits a remarkable power of the old quantum theory to foreshadow typical models of quantum mechanical description, viz. electron clouds and quantum mechanical orbitals.

Similarly Bohr's second atomic theory helped much to understand the periodic table and the chemical properties of elements despite the fact that, under more careful scrutiny, it could not offer a lasting and convincing theory.[36] Figure 7, taken from Bohr's notes of 1920 shows nicely how the planetary model was put into relation with the periodic table. This was part of a major new conceptualization of atomic theory that Bohr developed between 1918 and 1922.

36. Cf. Kragh (1979).

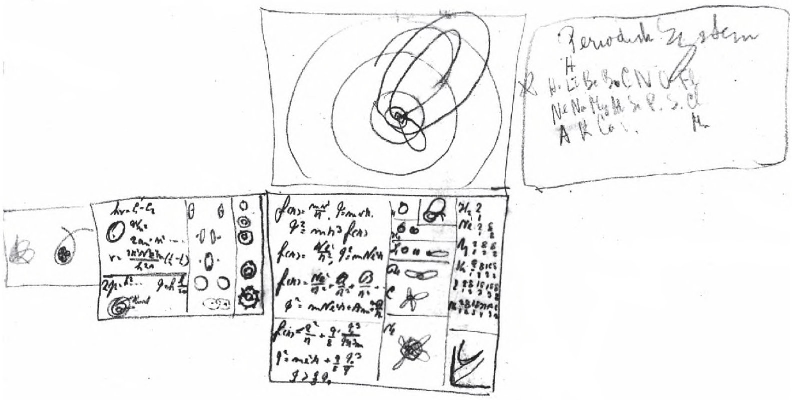


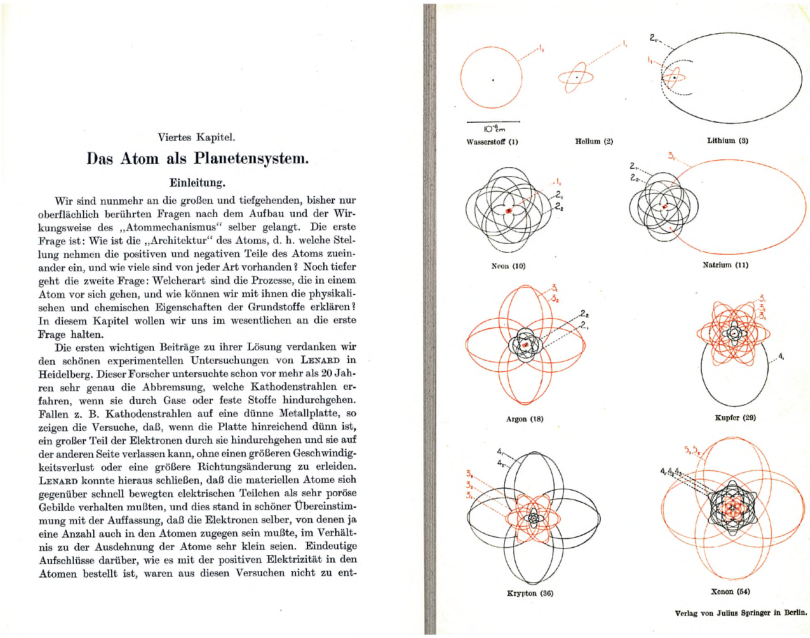
Figure 7: Drawing of electron orbits and considerations on the periodic table in notes of Niels Bohr. (Source: Kragh (1985), p. 55.)

It was actually this theory that was taken up most actively by German quantum physicists and probably had the greatest impact on the programme leading to quantum mechanics, as it has been usually related to the Göttingen 1922 Bohr *Festspiele*, when Heisenberg too entered the picture. Bohr made clear that electrons need not be arranged in concentric rings or in configurations of polyhedral symmetry as Sommerfeld, Landé and other had tried with limited success, instead it were rather penetrating orbits that establish couplings of inner and outer electrons. (These so-called "Tauchbahnen" had also been discussed by Schrödinger in 1921.)[37]

However, the greatest impact of the planetary model on the development of atomic theory, I would argue, lay in its role as an important conceptual tool for the correspondence principle. In his 1921 letter to *Nature* on "Atomic structure" Bohr wrote:

> ...; but the application of the correspondence principle seems to offer for the first time a rational theoretical basis for these conclusions and for the discussion or the arrangement of the orbits of the electrons bound after the first two.

37. Cf. Schrödinger (1921).



Viertes Kapitel.

Das Atom als Planetensystem.

Einleitung.

Wir sind nunmehr an die großen und tiefgehenden, bisher nur oberflächlich berührten Fragen nach dem Aufbau und der Wirkungsweise des „Atommechanismus“ selber gelangt. Die erste Frage ist: Wie ist die „Architektur“ des Atoms, d. h. welche Stellung nehmen die positiven und negativen Teile des Atoms zueinander ein, und wie viele sind von jeder Art vorhanden? Noch tiefer geht die zweite Frage: Welcherart sind die Prozesse, die in einem Atom vor sich gehen, und wie können wir mit ihnen die physikalischen und chemischen Eigenschaften der Grundstoffe erklären? In diesem Kapitel wollen wir uns im wesentlichen an die erste Frage halten.

Die ersten wichtigen Beiträge zu ihrer Lösung verdanken wir den schönen experimentellen Untersuchungen von Lenard in Heidelberg. Dieser Forscher untersuchte schon vor mehr als 20 Jahren sehr genau die Abbremsung, welche Kathodenstrahlen erfahren, wenn sie durch Gase oder feste Stoffe hindurchgehen. Fallen z. B. Kathodenstrahlen auf eine dünne Metallplatte, so zeigen die Versuche, daß, wenn die Platte hinreichend dünn ist, ein großer Teil der Elektronen durch sie hindurchgehen und sie auf der anderen Seite verlassen kann, ohne einen größeren Geschwindigkeitsverlust oder eine größere Richtungsänderung zu erleiden. Lenard konnte hieraus schließen, daß die materiellen Atome sich gegenüber schnell bewegten elektrischen Teilchen als sehr poröse Gebilde verhalten mußten, und dies stand in schöner Übereinstimmung mit der Auffassung, daß die Elektronen selber, von denen ja eine Anzahl auch in den Atomen zugegen sein mußte, im Verhältnis zu der Ausdehnung der Atome sehr klein seien. Eindeutige Aufschlüsse darüber, wie es mit der positiven Elektrizität in den Atomen bestellt ist, waren aus diesen Versuchen nicht zu ent-



Figure 8: The German version of the book of Kramers and Holst with unfolded plate of atomic drawings. (Source: Kramers and Holst (1925), p. 77 and plate.).

> ... this principle offers a simple argument for concluding that these electrons are arranged in groups in a way which reflects the periods exhibited by the chemical properties of the elements ... . [38]

The widest dissemination of the planetary model occurred through the two disciples of Bohr, namely Hendrik Kramers and Helge Holst. Their book *The atom and the Bohr Theory of its structure. An elementary presentation* appeared in English in 1923 with a foreword by Rutherford.[39] The Danish original is from 1922, the German edition from 1925, the Dutch from 1927 etc. The two-colour drawings (Figure. 8) were actually reproduced from larger plates Bohr had used in lectures. These drawings could soon be found in many scientific and popular science media including a German radio magazine or a

38. Bohr (1921), p. 105.

39. Kramers and Holst (1923), for discussion cf. Kragh and Nielsen (2012).

Spanish popular science journal.[40] Interestingly, there are subtle differences between the editions in different languages. While the Danish and German versions actually have a chapter heading using the term "planetary system" the English does not, here it reads "The nuclear atom." The drawings were put at the very end and were meant to be folded out so that they were visible throughout reading the whole book.

A number of different, yet no less impressive material models stem from the work of Lawrence Bragg. In 1920 he was still very critical of Bohr's model; however, this changed due to Douglas Hartree. Three years later Hartree would publish two papers that meticulously calculated the penetrating orbits and then demonstrated that from the dimensions of the orbits he could verify results of Bragg's X-ray spectra of certain crystal.[41] Hartree's combination of computational skill (which he had developed in war ballistics) now applied to more complicated arrangements of electron orbits, together with his talent for powerful approximation methods and his experimental understanding, which allowed him make contact with empirical data from X-ray scattering that Bragg's group had published, obviously motivated the latter to start a whole industry of model building. This included material models of at least hydrogen helium, lithium, sodium, magnesium, aluminum and even rock salt (Figure 9), which demonstrates to what great extent orbital models were taken to explain the structure of matter.[42]

At the same time as this British model crafting, Max Born was also intrigued by the planetary model and its variations. He grew however increasingly uneasy regarding the question of how far it could lead the physicist beyond the few manageable simple cases, as his strategy was to make perturbation theory reveal a new mechanics. In *Naturwissenschaften* he confessed:

> One of the strangest and at the same time most attractive results of Bohr's atomic theory is the conception that atoms are planetary sys-

40. Cf. Boscá (2009), p. 73, Schirrmacher (2008), p. 367.

41. Hartree (1923a), Hartree (1923b).

42. For more details see Schirrmacher (2009a) and Schirrmacher (2009c).

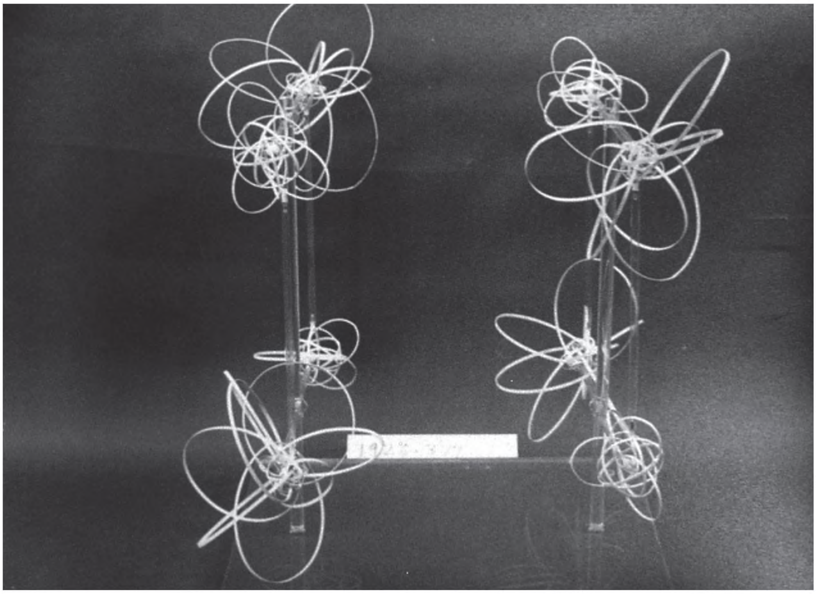


Figure 9: Lawrence Bragg's model for rock salt c. 1923, which was on display at the British Empire Exhibition at Wembley in 1924 and 1925. Photograph from the exhibit of the Science Museum, London. (Source: Science Museum, Documentation Centre, Paper Technical Files of Inv. 1926-371/377, here Inv. 1926-376.)

> tems in the small. ... In any case, we see that the similarity of atoms with planetary systems has its limitations.[43]

Even after quantum mechanics was established, the planetary picture still found application, at least for simple interpretations of wave mechanics. In the popular science journal *Kosmos* an interesting visualization of "Quantization as eigenvalue problem" was presented in an article by the prolific physics writer Paul Kirchberger (Figure 10), who also popularized quantum and atomic physics in German newspapers and wrote a number of (semi-)popular books.[44]

43. Born (1923), p. 537 and 542. Together with Heisenberg, Born also tried to make progress by classification of possible orbits of helium similar to Pauli's earlier approach, cf. Born and Heisenberg (1923).

44. Kirchberger (1928). Paul Kirchberger (1878–1945) obtained his doctorate in

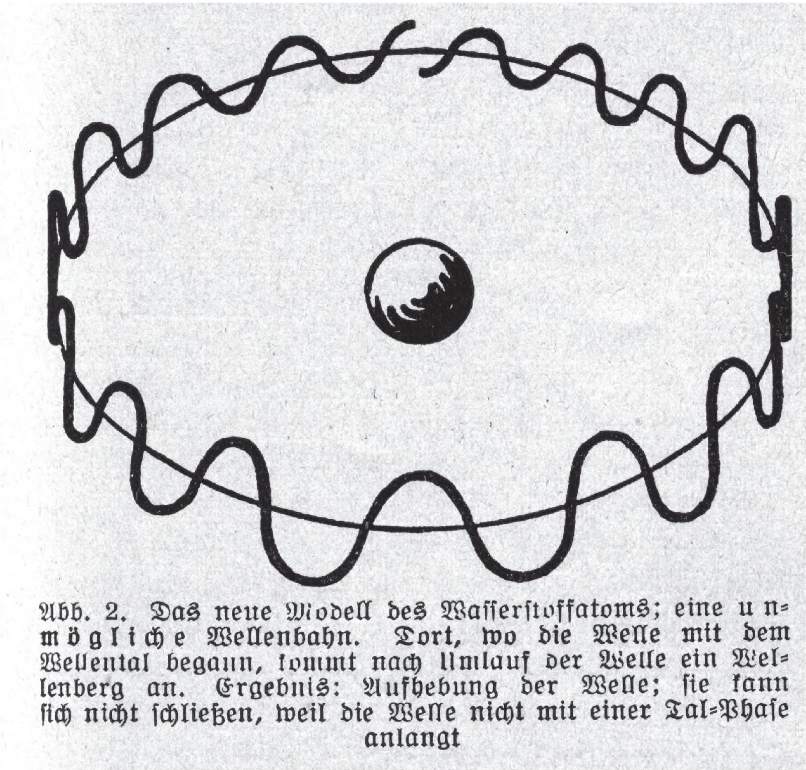



Figure 10: Drawing originally designed as a visualization of possible energy eigenstates in an article on quantum mechanics in *Kosmos*. (Source: Kirchberger (1928), p. 111.).

Interestingly, the planetary atom did not only survive in popular accounts but should still play a role in quantum mechanics as did the virtual oscillator.

mathematics in 1902 with David Hilbert and turned science writer in 1922 after a career as high-school teacher, see also Kirchberger (1922) revised 1929, and Kirchberger (1923).

## 3. Classical models and quantum mechanics

With this brief inspection of some examples of atomic models, which have materialized in drawings or as physical objects, my initial thesis that Bohr's atom should be regarded as a genuine metaphor, and as such as a creative tool, as Kuhn had already suggested, may have received some corroboration. Besides visualization as well as the visual and structural suggestions that come with each visualization and thereby produce epistemological power as seen in the cases from Perrin to Hartree, models also represent ways of approximation, computational strategy and descriptive vocabulary. This is what Kuhn hinted at in the debate with Boyd when arguing that the Bohr atom even in the quantum mechanical era remains indispensable for treating more complicated systems.

The more general question, which I cannot discuss here in sufficient detail, would address the extent to which quantum mechanical models are able to convey a form of atomic knowledge comparable the Bohr-Sommerfeld theory. One thing, however, seems clear concerning planetary models of the atom: they exert a certain spell that few people, even physicists, can evade. In Bohr's case we have the observation of Lawrence Bragg. He wrote to the director of the London Science Museum in 1946 that the material models of the early 1920s, which were still on display at the museum, were of much interest and he "even found Bohr himself gazing at them in a fascinated way when he visited us last summer."[45]

In 1931, *Physical Review* published a paper on "Pictorial Representations of the Electron Cloud for Hydrogen-like Atoms" which contained "photographs of the electron cloud for various states for the hydrogen-like atoms ..." which soon were to be found in many textbooks of physics and chemistry (Figure 11). While in *Physical Review* the above phrase continued "... as obtained from various models and the device shown in Fig. 5," (here Figure 12), the reprints of the "photographs" did not go into the details of the creation of the pictures.[46]

45. Lawrence Bragg to Herman Shaw, 13 December 1946, Science Museum, Documentation Centre, W.L. Bragg Files.
46. White (1931), for discussion see also Grosholz (2007), pp. 139–142.

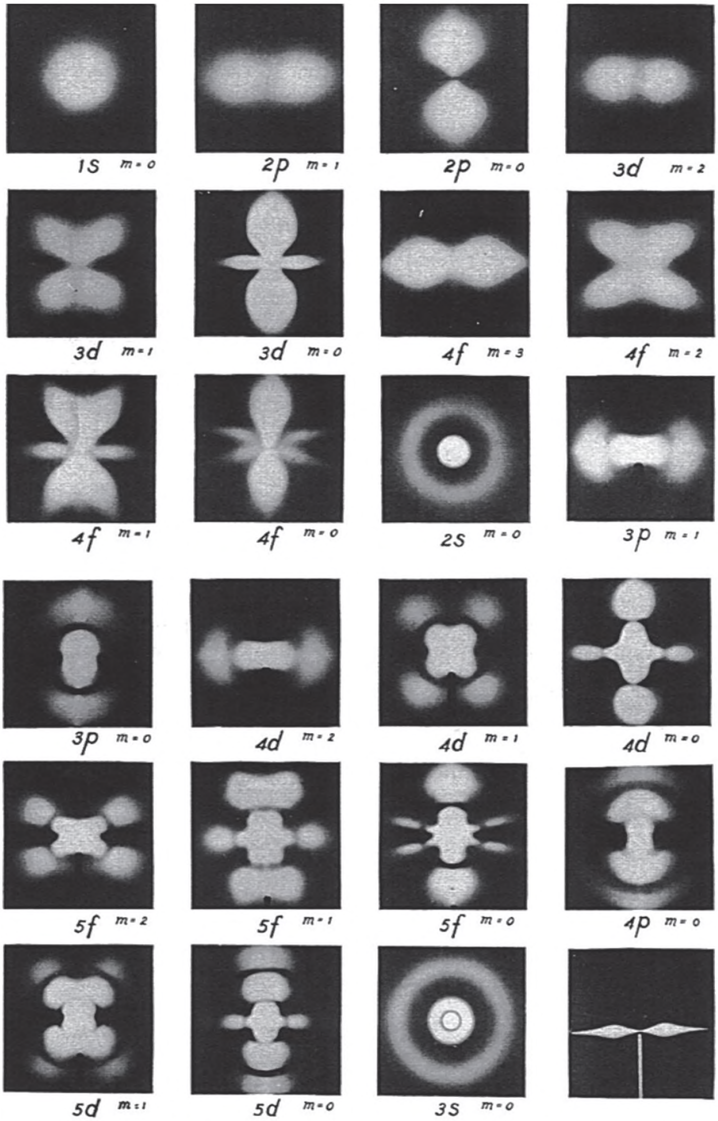
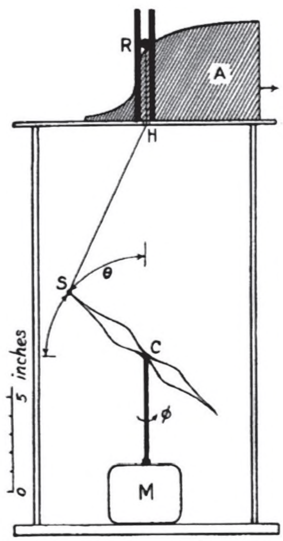



Fig. 6. Photographs of the electron cloud for various states of the hydrogen-like atoms as obtained from various models and the device shown in Fig. 5. The proability density $\Psi\Psi^*$ is symmetrical about the $\phi$ or magnetic axis which is vertical. The scale for each figure may be obtained from Fig. 4.

Figure 11: Plate with photographs of White's machine. (Source: White (1931), p. 1423.)

Figure 12: White's machine. (Source: White (1931), p. 1422.)




Before he returned to Berkeley, Harvey Elliott White, Cornell graduate and 1929/1930 Rockefeller fellow in Berlin under Friedrich Paschen, was the inventor of both the iconic "photographs" of electron clouds and a mechanical device which, when photographed with sufficiently long exposure time, produced the pictures. Thus a classical mechanical machine was used to simulate quantum mechanical results. Only when computer graphics evolved some 50 years later did these images begin to vanish. White's starting point, however, was a more intricate relation between classical and quantum mechanics, which became obvious from the fact that classical concepts of the old quantum theory had not been superseded when it came to concrete problems and to their understanding:

> With all the successes of the quantum mechanics one still hears on every hand, for want of an atomic model, the terms *electron orbits*, *penetrating orbits*, *non-penetrating orbits*, etc. This is of course due to the fact that in many cases one may think in terms of the simpler electron orbits and be led to a result which is the same or very nearly the same as that given by the quantum mechanics.[47]

47. White (1931), p. 1416.

White's observation of a desire for classical concepts and pictures made him try to fill the gap with his machine and the suggestive photographs. In the long run, however, a revival of semi-classical methods in quantum theory became a strong reason for the physicists to employ classical concepts in order to guide intuition, organize calculation and choose approximations, while the public never did get rid of the old pictures and models. White himself did not champion pure quantum mechanical imagery but eventually became a prominent educator in the US, presented physics programs on TV nationwide and later became director of the Lawrence Hall of Science in Berkeley.[48]

It has become clear that, in a decisive sense, models of atoms according to quantum mechanics lack the structural information one could get from old quantum theory. One could argue that even today physicists may agree that semi-classical approximations often carry more insight than straight-forward quantum mechanical approaches. A more detailed history of how the planetary model (but also the virtual oscillator) guided scientists during the various stages of quantum mechanics and quantum field theory until they acquired new prestige in the semi-classical research programs starting in the late 1950s and leading to new fields like quantum chaos, however, remains to be written.[49] Particularly effective approximation methods on the basis of Bohr's model have recently stirred physicists to reconsider orbital model building as well.[50]

The old quantum theory with its classical concepts of particle and trajectory, and thus the planetary model, was at least one rung of the ladder that was needed to climb up to quantum mechanics. If physicists, after the first successes of the new theory for simple systems, were quick to throw away the means that helped that ascension, they were just as quick to get back to it when it came to more intricate problems that demanded intuition and computabil-

48. See Seaborg (1989).

49. For an overview of literature see Gutzwiller (1990) and Gutzwiller (1998) for a pointed reinterpretation of the relation of old and new quantum theory.

50. Svidzinsky et al. (2005), see also Trabesinger (2005) and Herschbach, Scully and Svidzinsky (2013).

ity, probably more so in creative practices than in scholarly writing.

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