How to Conceive the Atom: Imagery vs. Formalism

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Abstract Given the belief in the universality of Newtonian mechanics, it is hardly surprising that atomic structure was compared to that of a planetary system, taken as a model for it. However, Heisenberg eliminated all pictures and models from his new theory. While Sommerfeld, the theoretical physicist, stressed the didactic importance of the defunct theory, Reichenbach, the philosopher of science, argued that a researcher cannot do without visualization, although this visualization is the "outer clothing" of the theory and does not represent its conceptual "skeleton". The problem underlying Reichenbach's statement may stem from what Born considered the naive assumption that the laws governing the macrocosm and the microcosm are the same. But even Born continued to present the defunct theory as a preliminary step for understanding quantum mechanics, not as a theory of historical interest. The force of the model and its accompanied imagery were apparently too strong to resist.

Resumo Dada a crença na universalidade da mecânica newtoniana, não surpreende que a estrutura atómica tenha sido comparada à de um sistema planetário, tomada como seu modelo. Contudo, Heisenberg eliminou qualquer imagem ou modelo da sua nova teoria. Ao passo que Sommerfeld, o físico teórico, salientou a importância didáctica da defunta teoria, Reichenbach, o filósofo da ciência, argumentou que um investigador não pode trabalhar sem visualização, apesar de esta visualização ser a "roupagem" da teoria e não representar o seu "esqueleto" conceptual. O problema subjacente à posição de Reichenbach pode provir do que Born considerava como a suposição ingénua de que as leis que governam o macrocosmo e o microcosmo são as mesmas. Mas mesmo Born continuou a apresentar a defunta teoria como um passo preliminar para compreender a mecânica quântica, e não como uma teoria com interesse histórico. A força do modelo e a imagética associada eram aparentemente irresistíveis.

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> When one contemplates what has really been done [in atomic physics], one sees clearly that [mechanical] model conceptions [*Modellvorstellungen*] have no real meaning. The orbits [*Bahnen*] are not real, neither with respect to frequency nor energy.
>
> W. Heisenberg to A. Sommerfeld, December 8, 1923.[1]

> We should not want to clap the atoms into the chains of our preconceptions [*Vorurteile*] (to which in my opinion belongs the assumption of the existence of electron orbits [*Elektronenbahnen*] in the sense of the usual kinematics), but we must on the contrary adjust our ideas [*Begriffe*] to experience [*Erfahrung*].
>
> W. Pauli to N. Bohr, December 12, 1924.[2]

I. Background

Given the belief in the universality of Newtonian mechanics, it is hardly surprising that the structure of the atom was compared to that of a planetary system. Nevertheless, in the early stages of the development of atomic physics it was clearly perceived and explicitly noted that the atom exhibits a categorically different kind of stability from that of a mechanical scheme. For example, Niels Bohr (1885-1962) spelled out this limitation in his Nobel lecture of 1922. To be sure, the analogy between the planetary system and the structure of the atom "provide[s] us with an explanation," but it has its limitations:

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[1] Eckert and Märker, 2004, 157. Translated in Kragh, 2012, 322. By *Modellvorstellungen* Heisenberg means mechanical modeling (as he says earlier in this letter); he refers explicitly to orbits, that is, to the frequency and the energy which the material particle possesses in its motion around a core at the center of its trajectory. We are grateful to Michael Eckert for supplying us with a copy of the original German manuscript of this letter as well as a transcription of it.

[2] Quoted and translated by Serwer, 1977, 243 n. 167; Hermann et al., 1979, 189.

> As soon as we try to trace a more intimate connexion between the properties of the elements and atomic structure, we encounter profound difficulties, in that essential differences between an atom and a planetary system show themselves here in spite of the analogy we have mentioned.
>
> The motions of the bodies in a planetary system, even though they obey the general law of gravitation, will not be completely determined by this law alone, but will depend largely on the previous history of the system. Thus the length of the year is not determined by the masses of the sun and the earth alone, but depends also on the conditions that existed during the formation of the solar system, of which we have very little knowledge.... The definite and unchangeable properties of the elements demand that the state of an atom cannot undergo permanent changes due to external actions.[3]

And Bohr surmised:

> On the basis of our picture of the constitution of the atom it is thus impossible, so long as we restrict ourselves to the ordinary mechanical laws, to account for the characteristic atomic stability which is required for an explanation of the properties of elements.[4]

We may formulate the difference in this way: mechanical stability has "memory", it records mechanical disturbances and retains their influence. Atomic stability, by contrast, can undergo all sorts of interactions, but the atom of some element will always remain the same with the same physical properties, unless it is transmuted into another element. Notice that Bohr spoke of a picture of the constitution of the atom, a picture which, given his analysis, cannot be retained.

To be sure, the planetary system is probably the most stable mechanical system known to man, but as a contingency it cannot – in principle – be related to the inherent necessity of the stability of atoms, the building blocks of matter. However, confidence in the planetary model was greatly enhanced by its success in explaining and predicting phenomena of simple atomic structures. For example, Karl

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[3] Bohr, [1922] 1965, 10–11.
[4] Bohr, [1922] 1965, 11.

Schwarzschild (1873–1916) and Paul Sophus Epstein (1883–1966) applied theories and techniques of celestial mechanics to the mechanics of the atom; their theoretical success in explaining the Stark effect consolidated Sommerfeld's approach and persuaded Bohr that the planetary model was worthy of elaboration (see Figure 1).[5]

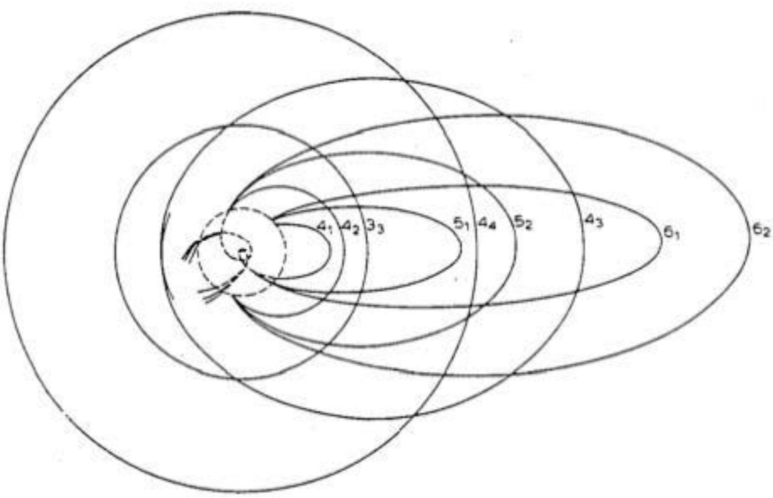

Fig. 1. Bohr, [1922] 1965, p. 32, Fig. 8.

Arnold Sommerfeld (1868–1951) conceived the atom as "a closed mechanical system in which only internal forces act."[6] At stake was the dynamics of this mechanical system.

> The question arises: how can the electrons of the atom maintain themselves in opposition to the attractive action of the nuclear charge? Will this action not cause them to fall into the nucleus? The answer – a

[5] Schwarzschild, 1916; Epstein, 1916. For a discussion, see Jammer, 1966, 103.
[6] Sommerfeld, [1919/1922] 1923, 264.

> possible one which is particularly simple and satisfactory – is furnished by the conditions of the solar system.[7]

Sommerfeld transferred the problem of stability from the atom to the solar system, that is, the stability of the atom is likened to the stability of the planetary system:

> The earth fails to fall into the sun for the reason that it develops centrifugal forces owing to its motion in its own orbit [*Umlauf*], and these forces are in equilibrium with the sun's attraction. If we transpose these ideas to our atomic model we arrive at the following view. **The atom is a planetary system in which the planets are electrons. They circulate about the central body, the nucleus**. The atom of which the atomic number is Z is composed of Z planets each charged with a single negative charge, and of a sun charged with Z positive units. The *gravitational attraction*, as expressed in Newton's law, is represented by the *electrical attraction* as given by Coulomb's law; these laws are alike in form.[8]

The imagery is quite extraordinary (see Fig. 2). Sommerfeld, in so many words, identified the atom as a planetary system: the stability of the atom is due to the same conditions that maintain the stability of the solar system, so his argument went. Moreover, for Sommerfeld it was not merely an analogy, for he stated an identity: "the atom *is* a planetary system." This is, of course, an exaggeration, expressing enthusiasm (surely a sign of his confidence in the model) rather than objective analysis. And Sommerfeld retreated immediately to the analogy: the gravitational force is "represented" by the Coulomb force, the two laws being alike in form. Sommerfeld was aware of the differences too. Although the laws are formally similar,

> There is a difference in that the planets repel one another in our atomic microcosm – likewise according to Coulomb's law – whereas, in the case

[7] Sommerfeld, [1919/1922] 1923, 65.
[8] Sommerfeld, [1919/1922] 1923, 65, boldface and italics in the original; for the German, see Sommerfeld, [1919] 1922, 79.

of the solar macrocosm they undergo attraction not only from the sun but also from themselves.[9]

Still, the claim that the dynamical laws hold in the "atomic microcosm" exactly as in the "solar macrocosm" runs like a thread in Sommerfeld's study. Confidence in the correctness of the Bohr-Sommerfeld approach had reached its height in 1922. This success made it seem likely that a fully satisfactory theory of this kind would be found in the near future, although later on it became clear that this initial optimism was ill-founded.

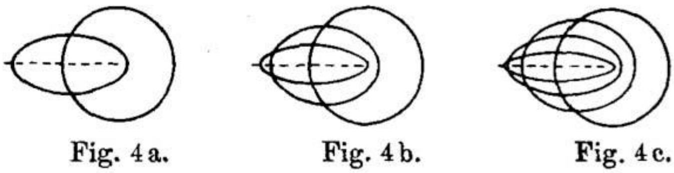

Fig. 2. Sommerfeld, 1916, p. 23.

II. Confidence vs. Confirmation

We distinguish between "confidence" and "confirmation"; the latter is the subject of a vast literature in philosophy of science. It concerns the relation between evidence and theory: in what ways and to what extent does the evidence support the theory (or hypothesis)? One may identify three conceptions: qualitative, comparative, and quantitative. The first simply states that evidence *e* confirms hypothesis *H*; the second claims that *e* confirms *H* more than *H′*, and the third conception calculates the degree to which *e* confirms *H* in probabilistic

[9] Sommerfeld, [1919/1922] 1923, 65.

terms.[10] If a theory has been confirmed, there may no longer be reasons to doubt it, whereas confidence in a theory will vary according to the individual scientist who weighs the evidence idiosyncratically, given certain predispositions which are not always conducive to probabilistic measure. This is akin to scientists ignoring "anomalies", that is, confidence in the theory is not shaken by anomalies.[11] We are not engaged here with the formal analysis of the probabilistic relation between evidence and theory. Rather, we characterize the attitudes which scientists take vis-à-vis a theory under scrutiny. This is the conception of confidence. It is not surprising that close agreement between experimental data and consequences of a theory leads to confidence in the theory. We thus invoke "confidence" as an epistemic disposition which, however, is not related to "degree of belief". Confidence is what keeps a scientist focused on improving a theory so that the theory, as modified, can be confirmed by future experiments. It therefore expresses expectation: Is it worth investing time, effort, and material resources in the theory, or not? Confidence then refers to the expected future state of the theory.

In the case under discussion one was confident that, with some relatively minor adjustments, the quantum theory, complete with the imagery of a planetary system, will work over the entire domain of atomic physics, whereas at its height it had only been shown to work for a nucleus surrounded by one electron. To be sure, the results were excellent and so expectations were running high. This confidence was based on an analogy with Newtonian mechanics; Newton first described a two body problem (and solved it); later it was shown that the same technique with relatively minor modifications yields a very close approximation to the solution of the three-body problem (even

[10] See, e.g., Achinstein, 2001.

[11] This is related to what we have called "snapshot" (as distinct from "baseline"): see Hon and Goldstein, 2009.

though an exact solution could not be found). There was an expectation that the three-body problem could be solved or, at least, one could make progress towards its solution, without casting doubt on any of the fundamental assumptions of Newtonian mechanics. A long series of theoretical physicists and mathematicians made the effort to work towards that solution.[12] This was seen as a useful precedent for confidence in solving the N-body problem at the atomic level, without challenging any of the basic tenets of the theory.

Early in December 1925, in an article that appeared in *Nature*, Bohr offered a brief survey of the development of the quantum theory up to that time, including an acknowledgment that in July 1925 a new phase was ushered by the theoretical work of Werner Heisenberg (1901–1976).[13] In this paper, "Atomic Theory and Mechanics," Bohr noted that "perhaps the greatest successes of mechanics lie in the domain of astronomy".[14] He then elaborated Planck's contribution and the discovery of the quantum of action, which rendered classical theories inadequate when applied to atomic structure.[15] According to Bohr, Rutherford's conception of the atom, that "around the nucleus there move a number of light negative electrons" made "the problem of atomic structure [take] on a great similarity to the problem of celestial mechanics." Still, Bohr pointed out the well-established fact that "there exists a fundamental difference between an atom and a planetary system."[16]

It is, however, important to note that Bohr relaxed the strong contrast between mechanical and atomic stability that he himself identified, and followed a methodology that allows continuous

[12] See, e.g., Barrow-Green, 1997, espec. 7–27. Poincaré, 1893, served as the base for these studies.
[13] Rüdinger and Stolzenburg, 1984.
[14] Bohr, 1925, 845.
[15] Bohr, 1925, 846.
[16] Bohr, 1925, 847.

analysis. This point is critical. In 1925, when quantum mechanics had just arrived on the scene, Bohr – in his reflection on the methodology of his own contribution – remarked:

> Nevertheless, it has been possible to construct mechanical pictures of the stationary states which rest on the concept of the nuclear atom and have been essential in interpreting the specific properties of the elements. In the simplest case of an atom with only one electron, such as the neutral hydrogen atom, the orbit of the electron would be in classical mechanics a closed ellipse, obeying Kepler's laws, according to which the major axis and frequency of revolution are connected in a simple way with the work necessary for a complete separation of the atomic particles.[17]

Bohr's references to "pictures", and "mechanical pictures" at that, should not escape the notice of the reader. Indeed, Bohr added that, as Sommerfeld had shown, the small deviations from Keplerian motion for the electron are consistent with the theory of relativity and offer an explanation for the fine structure of the lines of hydrogen in the spectrum.[18] These considerations made the planetary model attractive and instilled confidence in it; yet Bohr concluded his paper by insisting on the inadequacy of mechanical pictures.[19] In fact, Bohr acknowledged the contribution of Heisenberg who, in a revolutionary move, replaced quantum theory with a new theory, quantum mechanics, in which "the difficulties attached to the use of mechanical pictures may ... be avoided.... In contrast to ordinary mechanics, the new quantum mechanics does not deal with a space-time description of the motion of atomic particles."[20] Indeed, Heisenberg eliminated all pictures and models from his new theory (pictures are static and

[17] Bohr, 1925, 848.
[18] Bohr, 1925, 849.
[19] Bohr, 1925, 850.
[20] Bohr, 1925, 852; see also 845.

models in this case are dynamic).[21] To put it strongly, it is surprising that Bohr did not draw the logical consequences from his own analysis of the physics of the atom, for he continued to seek a mechanical picture of the constitution of the atom.

The three leading physicists who played key roles in developing the quantum theory may be singled out. In brief, Bohr was the originator of the theory with an implicit appeal to the planetary model; Sommerfeld consolidated a full-fledged, indeed Keplerian, planetary scheme, and Max Born (1882–1970) contributed to its demise. In spite of the fact that all three knew very well that the theory could not account for phenomena of complex atomic structures, they continued to appeal to the quantum theory in its planetary presentation. The two Nobel Laureates in physics, Bohr and Born, and the influential teacher of theoretical physics, Sommerfeld, all expressed attitudes which can be characterized as "schizophrenic": the quantum theory failed to capture atomic phenomena and was indeed at some point formally discarded; yet, all three physicists continued to present this theory in one way or another after its demise. What was the attraction of the model? And why was it so popular among powerful thinkers who clearly recognized its limitations? In other words, what was the source of confidence in the quantum theory?

III. The Path of an Electron in Motion

What is the geometrical form of the path of an electron in motion? Or, better, how should one picture the path of a free electron? Obviously, no one asked this question before the discovery of the

[21] In his revolutionary paper Heisenberg (1925) referred neither to a picture nor to a model of the atom. The thrust of the paper is abstract mathematics with which Heisenberg manipulated observable magnitudes.

electron at the end of the nineteenth century. But, even after its discovery and the development of the theory of electron which addressed many sophisticated issues of the physics of the electron, no one recognized any particular difficulty in characterizing the path of an electron in motion. For instance, Max Abraham (1875–1922) in his paper on the dynamics of the electron, and Einstein in his theory of special relativity, talked of a *Bahn*, a path, without saying anything more specific.[22] For another example, Augusto Righi (1850–1920) invoked the expression "la trajectoire d'un électron" in a study of interactions among electrons, ions, atoms, and molecules, again assuming the concept of trajectory without any discussion.[23] The geometrical form of the path of a free electron as it moves in empty space was not considered problematic at that time. The issue, however, had to be addressed once a bound electron, confined to the atom, became the object of study. Given that the atom is a stable and electrically neutral system, and that the electron – a charged component of this system – is not stationary, what is the geometrical form of the path of the electron in motion within the atom such that the atom can radiate and still remain stable and electrically neutral? This is certainly a fundamental problem, one which had no immediate solution. The obvious methodological move, when something new has to be confronted, is to appeal to analogy – "an explanation of the

[22] Abraham, 1902, 27; Einstein, 1905, 921. At Heisenberg's first meeting with Einstein in 1926, Einstein "pointed out to me that in my mathematical description the notion of 'electron path' did not occur at all, but that in a cloud-chamber the track of the electron can of course be observed directly. It seemed to [Einstein] absurd to claim that there was indeed an electron path in the cloud-chamber, but none in the interior of the atom. The notion of a path could not be dependent, after all, on the size of the space in which the electron's movements were occurring" (Heisenberg, [1974] 1989, 113). We may surmise that for Einstein an electron did have a path, a trajectory, both in free space and when bound within the atom. For analyses of observed trajectories in the cloud chamber by Heisenberg and Born, see Figari and Teta, 2013.

[23] Righi, 1908, 602.

unfamiliar by the more or less completely familiar."[24] The mechanical model for the atom, that is, the planetary model, is one such case.

Probably the most stable, well-studied, mechanical system with constituent moving elements is the planetary system. The term *orbit* had been used in astronomy since it was introduced by Johannes Kepler (1571–1630) in the early years of the seventeenth century and, without much discussion, it came to be applied to the path of the electron within the atom.[25] For example, in his paper on magnetism and the theory of electron, the French physicist, Paul Langevin (1872–1946), began his paper of 1905 with the following assumption:

> Let us suppose some electrons in motion in the interior of the molecule, following closed orbits [*suivant des orbites fermées*], that can be considered similar to closed currents circulating along these orbits [*ces orbites*] from the point of view of the magnetic field produced at a distance.[26]

It is of paramount importance to realize that a fundamental assumption is made here. The bound electron, as distinct from the free electron, is assumed to be moving in a closed orbit. No argument is offered to support this claim and, equally, no reference to a planetary system is made, although before the discovery of the electron the term *orbit* in physics had always been associated with a planetary system.[27] In other words, Langevin set up the discussion "silently" within a mechanical context whose paradigm is a planetary system. This theoretical framework seems to have influenced Bohr in the development of the quantum theory.[28] The idea was that the atom resembles a planetary system, that is, a central nucleus corresponding to the Sun with electrons rotating around the nucleus in orbits like

[24] North, 1981, 129.
[25] Goldstein and Hon, 2005.
[26] Langevin, 1905, 73.
[27] Comets, moons, etc. are included in "planetary system"; in particular, comets and moons have "orbits" in classical mechanics.
[28] See Heilbron and Kuhn, 1969, 219–223.

planets around the Sun, such that almost all of the atom is empty space.

Although the development of quantum mechanics, beginning in 1925, rendered the planetary conception obsolete, the model took on a life of its own and continued to flourish. In fact, the planetary model is not even good at representing the theory as it had developed prior to 1925. Yet, this model has continued to be invoked in textbooks of modern physics and now serves as an icon for atomic energy even though it is no longer scientifically meaningful.[29] It is puzzling that the defunct quantum theory continued to play a role in introducing students to the physics of the atom. Why did the planetary model complete with imagery persist?

IV. The Attractiveness of the Planetary Model

The heyday of the quantum theory based on explicit planetary modeling only lasted some seven years, from Sommerfeld's explicit introduction of Keplerian orbits in 1915 to the celebratory presentation of the full-fledged theory in Bohr's Nobel lecture in 1922.[30] Enthusiasm, an expression of great confidence in the theory, was then at its peak. The model offers an attractive metaphysics: the macrocosmos has a complementary microcosmos; physics has a "picture" conducive to understanding and, above all, mathematical techniques of one domain are applicable in the other. However, the decline was rapid: the period of dissatisfaction during 1923 and 1924 along with groping for a new conceptualization of the phenomena came to an abrupt end in the summer of 1925, when Heisenberg

[29] See, e.g., Born, 1933. For the history of the image that turned into the icon of atomic physics, see Goldstein and Hon, 2015.
[30] Sommerfeld, 1915; Bohr, [1922] 1965.

offered a new foundation, replacing quantum theory with quantum mechanics.[31] During these seven years research in quantum theory, such as the impressive achievements of Schwarzschild and Epstein, yielded a theory complete with a visual model which showed great promise.[32] However, after 1925 it was no longer at the cutting edge of research in atomic physics. In fact, the theory and its model had to be discarded; it proved to be wrong. Yet, the planetary model, together with its mechanical imagery, has persisted in a great many contexts (see, e.g., Fig. 3).[33]


THE AGENCY'S EMBLEM AND SEAL

The design of the Agency's emblem and seal, as adopted by the Board of Governors on 1 April 1960, is reproduced below for the information of all Members of the Agency.

Fig. 3. The emblem of the International Atomic Energy Agency (IAEA), adopted in 1960 and still in use.

[31] Heisenberg, 1925.
[32] Schwarzschild, 1916; Epstein, 1916. See n. 5, above.
[33] This figure appears in Wellerstein, 2013.

V. Enter the Philosopher Hans Reichenbach (1891–1953)

A contemporary leading philosopher of science, Reichenbach provided a perspective on this episode by a well-informed non-physicist. Once again, the tension between the defunct quantum theory and quantum mechanics is striking. In his *Atom and Cosmos*, in the section, "The Laws of Atomic Mechanism", Reichenbach described in detail what he called Bohr's model:

> Much more was achieved ... than an explanation of the atom's physical effect; even the chemical properties of the atom could be cleared up by the aid of Bohr's model. The fundamental idea ... is that chemical combination is regarded as the union of planetary systems of the atoms [*Vereinigung der atomaren Planetensysteme*] in more comprehensive systems.[34]

And Reichenbach added figures that illustrate the Keplerian planetary structure (*Ellipsenbahn*) of the various atoms. Chemistry, according to Reichenbach, had thus become a branch of physics.[35]

Reichenbach was well versed in the developments of recent physics. In the next chapter, "The Wave Character of Matter", Reichenbach presented Schrödinger's wave mechanics, informing the reader that Bohr's model finally fell victim to the contradictions inherent in his model of the atom. However, success came at a high price, namely, the new theory lacked a visual model. This was a radical break from the past:

> More clearly than ever does that reciprocal relation here stand out, which exists between mathematical formulae and visual images in modern physics; the kernel of a theory, its conceptual skeleton, is given by the mathematical formulae, whereas the images are only outer clothing [*während die Bilder nur eine dem Wechsel unterworfene*

[34] Reichenbach, 1930, 252; Reichenbach [1930] 1932, 237–238.

[35] Reichenbach, 1930, 257; Reichenbach [1930] 1932, 243. On the teaching of chemistry in light of the Bohr-Sommerfeld theory in the United States, see Martinette, 1940.

> *Umkleidung bedeuten*], subject to change, which have no immediate value for real knowledge. In spite of that, they are of practical worth, for the investigator in search of new paths cannot do without them.[36]

While Sommerfeld, the theoretical physicist, stressed – as we will see – the didactic importance of the defunct Bohr-Sommerfeld theory, Reichenbach, the philosopher of science, took this claim a step further. In his view the researcher cannot do without visualization, although this visualization is the “outer clothing” of the theory and does not represent its conceptual “skeleton”.[37] Indeed, Reichenbach went on to explain, as he understood it, the revolutionary approach that Heisenberg had taken:

> Heisenberg’s considerations are of a very radical nature; for they rest on a criticism of the very problem of a model. Heisenberg proposed the question whether there is any meaning in representing an atom, in the Rutherford-Bohr manner, by a model. For it is quite impossible for us to conceive of the atom’s planetary system, with its tiny dimensions, according to its correct size; what we do is to picture a highly magnified model [*wir malen uns da ein stark vergrößertes Modell aus*], in which the electron is about as large as a pinhead, and circles around a still larger nucleus at an appropriate distance. Is it permissible to think of what really happens as resembling this model? Heisenberg denies it. He objects that we can never really observe the atom in its minute dimensions, and so demands that we remove the model from our thought. We can say only so much about the micromechanism as we can justify by observations.[38]

It is not clear whether Reichenbach fully appreciated that the planetary model has no place in quantum mechanics for, after all, it is not simply a matter of the atomic dimensions that, in principle, makes the simultaneous measurement of an electron’s position and momentum impossible. The problem underlying Reichenbach’s statement may stem from what Born considered the naive assumption that the laws governing the macrocosm and the microcosm are the

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[36] Reichenbach, 1930, 274; Reichenbach, [1930] 1932, 257–258.
[37] This imagery of skeleton and clothing can be traced back to Hertz, 1892, 31.
[38] Reichenbach, 1930, 276; Reichenbach, [1930] 1932, 259.

same.[39] But even Born continued to present the Bohr-Sommerfeld theory as a preliminary step for understanding quantum mechanics, not as a theory of historical interest. The force of the model and its accompanied imagery were apparently too strong to resist.

VI. Born's Appeal to Mechanical Imagery

In 1933, eight years after the introduction of quantum mechanics Born, who was one of the principal architects of quantum mechanics, published a series of lectures on atomic physics, matter, and radiation. Born's *Moderne Physik* is also available in English translation with the title, *Atomic Physics*.[40] When the fourth English edition was published in 1948, Born was 66 years old and quantum mechanics celebrated its 23rd anniversary. One would have expected that the Bohr-Sommerfeld theory was by then a relic of the past – this, however, is not the case.

In fact, Born followed closely Bohr's original argument:

> It seems now a natural suggestion that we should regard the quantization condition for the angular momentum as an essential feature of the new mechanics. We therefore postulate that it is universally valid. At the same time, we must show by means of examples that the postulate leads to reasonable results. Although from the standpoint of Bohr's theory the underlying reason for this quantization rule remains entirely obscure, nevertheless, in the further development of the theory it has justified itself by results.[41]

Born was aware that Bohr's reason for postulating quantization was obscure, and he justifies the appeal to the incomplete theory for its successful results. When it comes to illustrate these results, Born offers the case of the hydrogen atom, whose complete quantization was carried out by Sommerfeld: "By Kepler's laws the orbit of the

[39] Born, 1923, 537–538.
[40] Born, 1933; Born, [1933/1935] 1948.
[41] Born, [1933/1935] 1948, 106–107.

electron round the nucleus is an ellipse; it is therefore simply periodic."[42] And Born directs the reader to the Appendix of his book, where he gives the quantization of "the Kepler ellipse", which in turn leads to the correct energy levels of the Balmer terms.

Again, we note that the year is 1948 and the context is physics, not history of physics. Moreover, Born reproduced Sommerfeld's drawings in the German edition of 1933 and, perhaps not surprisingly, they still appear in the English edition of 1948, except that in the English edition the drawings are no longer acknowledged as Sommerfeld's.[43] We find it puzzling that a defunct theory continued to play a role in introducing students to the physics of the atom. Why did the model persist?

We need not dwell on the many editions of Sommerfeld's textbook, *Atombau und Spektrallinien*;[44] suffice it to note that it was reprinted as late as 1978, and its English translation was reprinted in 1934, nine years after the introduction of quantum mechanics. The fifth German edition came out in 1931; it presented the by now defunct quantum theory. Sommerfeld had already published in 1929 a supplementary volume on wave mechanics. In his Preface to the 1931 German edition Sommerfeld offered an explanation why an invalid theory should be presented, albeit in abbreviated form:

> It has become clear that it is possible to understand the new theory only by building it up from the old theory. For this purpose the present volume necessarily treats not only the basic experimental facts, but also of the orbital ideas [*Bahnvorstellungen*] so far as they are required for introducing the quantum numbers, and for serving as a model [*Vorbild*] for the wave mechanical calculations. The final results are always given in the form in which they are presented by the new theory. Consequently, it has been necessary to refer frequently to the

[42] Born, [1933/1935] 1948, 114; Born, 1933, 81.
[43] Born, 1933, 78–81, and Born, [1933/1935] 1948, 111–114, respectively.
[44] First edition, 1919; cf. van der Waerden, 1969.

> supplementary volume and to leave occasional gaps [*Lücken*] in the proofs.[45]

In a somewhat apologetic tone, Sommerfeld says that a "wrong" theory from the past is beneficial to students in the process of learning and understanding the current theory, namely, wave mechanics (Schrödinger's representation of quantum mechanics). This appears to be the rationale for maintaining the planetary model, but it should be noted that there is no continuous transition from the quantum theory to quantum mechanics.

VII. Conclusion

Did quantum theory, with its underlying planetary model, become a theory of historical interest only? Apparently not. A clear example is Messiah's textbook, *Quantum Mechanics*.[46] This book is based on a series of lectures given in the early 1950s. After a general introduction entitled, "The End of the Classical Period", under the heading "Inadequacy of classical corpuscular theory", Messiah states that "*the evolution in time of a quantized quantity is impossible to describe in strictly classical terms*.... One must give up imagining an exact evolution of the energy as a function of time."[47] Thus the planetary model was dealt a death blow right at the outset of this textbook. Still, Messiah acknowledges the historical and heuristic importance of the Bohr-Sommerfeld theory:

> In spite of the difficulties of principle, and the limitations of [the] Old Quantum Theory, it is useful to know its main features in order to

[45] Sommerfeld, 1931, iv (author's Preface to the fifth German edition), translated by H. L. Brose, in Sommerfeld, [1919/1931] 1935 (slightly modified).
[46] Messiah, [1961] 1972.
[47] Messiah, [1961] 1972, 27–28, italics in the original.

> properly appreciate the later development of the theory. Furthermore, this older theory represents a first example of the application of a heuristic principle which played an essential role in the development of Quantum Mechanics: the correspondence principle.[48]

So, while physicists did see some merit in teaching the defunct theory, Messiah reminds us that:

> The quantization rules are purely formal restrictions imposed upon the solutions of the classical equations of motion; they were determined in an entirely empirical manner. The profound justification of this quantization of classical trajectories is completely absent. In fact, the very notion of trajectory is hard to reconcile with the quantization phenomenon. It implies that the particle possesses at each instant a well-defined position and momentum, and that these quantities vary in a continuous manner in the course of time.... To postulate this quantization amounts to giving up the (classical) idea of a precise trajectory of the electron and, quite logically, the idea of trajectory in general.[49]

For Messiah the old theory "represented a great step forward" and "played a large clarifying role in the history of contemporary physics. But this rather haphazard mixture of classical mechanics and ad hoc prescriptions can in no way be considered as a definitive theory."[50] According to Messiah, the concept of "electronic orbit" exemplifies all that had gone wrong with the quantum theory. It is a concept without experimental foundation. It is perhaps fitting to end on the very note with which we have begun – the orbit:

> Since no experiment allows us to assert that the electron actually describes a precise orbit in the hydrogen atom, nothing prevents us from abandoning the very notion of an orbit; in other words, the fact that the atom is in a well-defined energy state does not necessarily imply that the electron has at each instant a well-defined position and momentum.[51]

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[48] Messiah, [1961] 1972, 28.
[49] Messiah, [1961] 1972, 40–41.
[50] Messiah, [1961] 1972, 41.
[51] Messiah, [1961] 1972, 46.

In fact, postulating quantization requires dropping the notion of trajectory. Quantum mechanics begins when the concept of orbit – together with the planetary scheme complete with mechanical imagery – is discarded. What remains is the “skeleton” – the formalism.

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