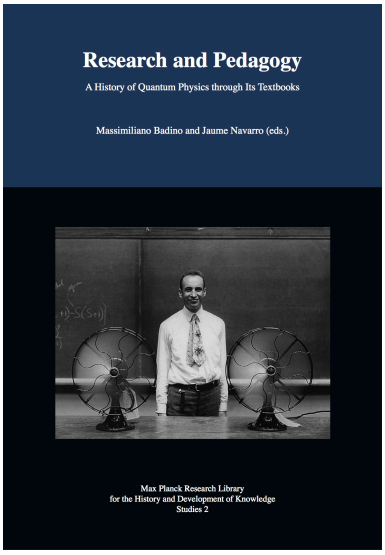
Max Planck Research Library for the History and Development of Knowledge

Studies 2

Michael Eckert:

Sommerfeld's *Atombau und Spektrallinien*



In: Massimiliano Badino and Jaume Navarro (eds.): *Research and Pedagogy : A History of Quantum Physics through Its Textbooks*
Online version at `http://edition-open-access.de/studies/2/`

ISBN 9783844258714
First published 2013 by Edition Open Access, Max Planck Institute for the History of Science under Creative Commons by-nc-sa 3.0 Germany Licence.
`http://creativecommons.org/licenses/by-nc-sa/3.0/de/`

Printed and distributed by:
Neopubli GmbH, Berlin
`http://www.epubli.de/shop/buch/30988`

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at `http://dnb.d-nb.de`

Chapter 6
Sommerfeld's *Atombau und Spektrallinien*

Michael Eckert

6.1 Introduction

A textbook is commonly perceived as a didactic tool dedicated to achieving the goals of curricula in teaching institutions. This definition may be regarded in an operational sense, with an eye to the actual uses in practical teaching, or with a focus on the author's intentions (Bertomeu-Sánchez, Garcia-Belmar, and Bensaude-Vincent 2005, 223). In neither regard did Arnold Sommerfeld's *Atombau and Spektrallinien* (1919) start out as a textbook. Its first edition was intended to popularize atomic physics for non-professionals. It was only in the course of its subsequent editions that it eventually transformed into one of the most renowned quantum textbooks in the twentieth century.

The story of *Atombau und Spektrallinien*, therefore, suggests a broader notion of a textbook. Rather than a singular *event* transforming past results of research into didactic lessons, a textbook may be a *process*—subject to change within its environment as much as the research for which it is accounting. *Atombau und Spektrallinien* entails an evolution of intentions, uses, and perceptions. Its author, Sommerfeld, was one of the architects of modern theoretical physics and a charismatic teacher who trained numerous quantum theorists (Eckert 1993; Seth 2010). He involved his talented students, among them prodigies like Wolfgang Pauli and Werner Heisenberg, not only in advanced quantum problems but also in the writing and proofreading of subsequent editions of *Atombau und Spektrallinien*. Thus it became a tool for teaching *and* research. Outside the Munich Sommerfeld school, it was perceived as an authoritative indicator of the current knowledge on atomic physics.

The first four editions of *Atombau und Spektrallinien* (Sommerfeld 1919; 1921; 1922; 1924) and a wave-mechanical supplementary volume (Sommerfeld 1929) mirror the transformation of quantum and atomic physics during this crucial decade after the First World War. In 1931 Sommerfeld published the fifth edition of what he now named volume 1 of *Atombau und Spektrallinien*. The wave-mechanical supplement became volume 2. Like the pre-quantum-mechanical editions of volume 1, the "wave-mechanical" part would be subject to revision, adaptation, and extension. Sommerfeld dedicated a good deal of his energies during the 1930s to this effort. When he finally published the second edition of volume 2 in 1939, its size had more than doubled from 352 to 819 pages. If we ignore the minor changes added in subsequent editions, the process that lay behind *Atombau und Spektrallinien* extended over more than two decades. The results of this process comprise a series of pre- and post-quantum-mechanical editions that stand out as unique within the physics textbook literature (see table 6.1).

Atombau und Spektrallinien		
1st edition	1919	550 pages
2nd edition	1921	583 pages
3rd edition	1922	764 pages
4th edition	1924	826 pages
Atombau und Spektrallinien I		
5th edition	1931	734 pages
6th edition	1944	734 pages
Atombau und Spektrallinien II		
Wellenmechanischer Ergänzungsband	1929	352 pages
2nd edition	1939	819 pages
3rd edition	1944	819 pages

Table 6.1: The chronology of editions of *Atombau und Spektrallinien* (1919–1944).

Despite this ongoing gestation, *Atombau und Spektrallinien* was already praised in 1923 as "the bible of the modern physicist."[1] These and other assessments of the early editions suggest that it was not the final result—the two–volume edition from the 1930s—but the entire process of its development, particularly on the eve of quantum mechanics during the early 1920s, which made *Atombau und Spektrallinien* a classic of modern textbook literature.

This chapter is concerned only with the first four editions of *Atombau und Spektrallinien*, published before the advent of quantum mechanics. The focus is on its conception, birth, growth, and reception, that is, the evolution that characterizes this textbook as the embodiment of a process extending from the First World War until the eve of quantum mechanics. The post-quantum-mechanical phase concerning the further transformation of the fourth into a fifth edition (1931) and the addition of a wave-mechanical supplementary volume (1929–1939) is left to a sequel.

6.2 Popular Lectures

We have to look at Sommerfeld's pedagogy to lay open the roots of *Atombau und Spektrallinien*. Although the later success of Sommerfeld's school tends to glorify its haphazard beginnings (Eckert 1999; Seth 2010, chap. 2), the list of his early disciples bears testimony to flourishing pedagogical activity. (Among these numbered Peter Debye, Paul Epstein, Paul Ewald, Max von Laue, Alfred Landé and Wilhelm Lenz, to list only those who would become famous for their accomplishments in atomic physics). Sommerfeld's advanced lectures covered, for example, quantum theory (summer 1914), the Zeeman effect and spectral lines (winter 1914/15), relativity theory (summer 1915) and quantum theory again (winter 1916/17). During the same period, Sommerfeld's main lecture course dealt with mechanics, continuum mechanics, electrodynamics, optics, thermodynamics, and partial differential equations for mathematical physics—already the same canonical sequence which he would forge into textbooks thirty years later.

[1] Born to Sommerfeld, 13 May 1922, DMA, HS 1977–28/A,34. Unless otherwise indicated, all English translations are by the author.

In addition to the lectures, students in the Munich "nursery of theoretical physics," as Sommerfeld used to call his institute, were trained for future careers in research and teaching through seminars and colloquia. The seminar was, at first, only a forum where students were presented with problems related to the theme of the main lecture.[2] Eventually, the seminar acquired the research orientation about which Sommerfeld's later students reported enthusiastically in their recollections (i.e., Bethe 2000). The pedagogical activity that offered the closest contact with current research themes, before the First World War, was the regular Munich Wednesday Colloquium.[3] Here Sommerfeld's advanced students could present results from their doctoral work and discuss them with advanced students from Wilhelm Röntgen's institute. Occasionally, the Munich theorists invited speakers from other universities to present their most recent papers in an informal environment. On 15 July 1914, for example, Niels Bohr personally introduced the Munich colloquium audience to "Bohr's atomic model, in particular the spectra of helium and hydrogen."[4]

In summer 1916, when Sommerfeld published his extension of Bohr's theory in the *Annalen der Physik*, he had been working for almost two years on what became known as the Bohr-Sommerfeld atomic theory (Eckert and Märker 2000, 431–445). Despite the outbreak of the First World War, Sommerfeld conducted his regular main lecture course four days a week in the morning for one hour, accompanied by a two-hour seminar each Tuesday afternoon; the advanced lectures were scheduled for one or two hours weekly; the colloquium took place on Wednesday evenings, or sometimes on another day of the week—but with few interruptions throughout the war. However, there were changes due to the absence of students who had been drafted for war service. In particular, the Munich professors offered lectures for non-professionals, addressed to colleagues from other faculties. "More recent experimental and theoretical advances in atomistics and electronics (popular, without mathematical developments), Monday, 6–7 pm," was how Sommerfeld announced his first popular lecture in the winter semester 1916/17. Henceforth the popular Monday evening lectures "for attendees from all faculties, without mathematical deduction" became almost routine. In the winter semester 1917/18, they were dedicated to "atomistics," and in the summer of 1918, to "atomic structure and spectral lines."[5]

How little Sommerfeld perceived these popular lectures as the seed for a textbook on theoretical physics is evident from the explicit emphasis on "without mathematical deduction." Although he must have already thought about publishing a book during the course of the first of these public lecture series, in the winter semester of 1916/17, he did not have physicists in mind as his readers. "This semester I held a popular lecture on atomic structure and spectral lines," he wrote to David Hilbert in March 1917.

> The audience was about 80 people, among them 12 colleagues, mainly chemists, medical scientists, and philosophers. I intend to publish it as a book. I had

[2] See the inventory of lectures of Munich University, http://epub.ub.uni-muenchen.de/view/subjects/vlverz_04.html, accessed 18 February 2012.

[3] Interview with Ewald by George Eugene Uhlenbeck and Thomas S. Kuhn, 29 March and 8 May 1962. AHQP, http://www.aip.org/history/ohilist/4523.html, accessed 18 February 2012. According to another recollection, its foundation is due to Peter Paul Koch, who was a *Privatdozent* in Wilhelm Röntgen's institute at that time. Koch to Sommerfeld, 6 August 1944, Nachlass Sommerfeld.

[4] Physikalisches Mittwoch-Colloquium, DMA, 1997–5115. Also in AHQP, P–2/20.

[5] See the inventory of lectures (n. 2), http://epub.ub.uni-muenchen.de/view/subjects/vlverz_04.html, accessed 18 February 2012.

> so much fun that I will try to lecture on relativity in the next semester also popularly, i.e., without mathematics, only conceptually presented.[6]

Sommerfeld also presented popular lectures for soldiers at the western front in January 1918. Unfortunately no records are preserved from these presentations; in a letter to his wife, Johanna (Höpfner) Sommerfeld, he merely revealed that he presented "four speeches about peace physics."[7] Three months later, he lectured before a Red Cross association about "The development of physics in Germany since Heinrich Hertz." Despite the title he also mentioned that "the young Dane physicist Bohr" considered the atom as "a planetary system in miniature" whose characteristics are inscribed in their spectra. "The explanation of the spectra, therefore, will be the acid test for our atomic model" (Sommerfeld 1918). The audience consisted of "about 1,000 people," as he reported home.[8] After this event, Sommerfeld traveled to Belgium for a sequence of popular lectures. "My presentation this morning was very nice and elicited total excitement with the rather small audience," he reported to his wife.[9] Sommerfeld's zeal for popularization was also expressed in other ways. "I am prepared to contribute to the display of the atomic structure with pleasure," he wrote in response to a request by Oskar von Miller, the founder of the Deutsches Museum in Munich. "I would like to do this in collaboration with my colleague Professor Fajans, the expert on radioactivity in our university."[10] Sommerfeld also mentioned the intended readership of his book when he wrote to Albert Einstein in the early summer 1918: "In the last 14 days I am writing a popular book on 'Atombau und Spektrallinien,' in its main part for chemists, in the appendices also for physicists."[11]

To address an audience of non-physicists may have been an exciting challenge when restricted to a few lectures, a museum exhibition, or a speech to soldiers about "peace physics"—but when it came to writing a book it also involved a sacrifice. Sommerfeld could not give as much space to his own recent achievements in atomic theory as he might have wished, had he envisaged theoretical physicists as his readership. Such advanced subjects as the fine structure theory were curtailed for the benefit of a broader exposition of subjects like radioactivity, X-rays, or the periodic system. He was well aware of this self-imposed limitation. "I am now writing a half-popular general presentation of the field and have repressed my own curiosity," he confided in December 1918 to a colleague with whom he otherwise exchanged his most recent results concerning the theory of X-ray spectra.[12]

But he did not entirely abstain from presenting research that had not yet had enough time to be generally accepted—all the more when it originated from his own institute. One recent accomplishment in which he took particular pride was the theoretical derivation of selection rules obtained without recourse to additional assumptions by Adalbert Rubinowicz just a few months earlier. Bohr had arrived at the same result, but by means of the correspondence principle. "The attitude of Rubinowicz is much more satisfying than Bohr's viewpoint in his recent paper," Sommerfeld wrote to a colleague in January 1919. "I will soon write chapter

[6] Sommerfeld to Hilbert, 13 March 1917, SUB, Cod. Ms. D. Hilbert 379A.
[7] Sommerfeld to his wife, Johanna (Höpfner) Sommerfeld, 9 January 1918, private collection, Munich. Also in (Eckert and Märker 2000, doc. 273).
[8] Sommerfeld to his wife, 14 April 1918, private collection, Munich.
[9] Sommerfeld to his wife, 17 April 1918, private collection, Munich.
[10] Von Miller to Sommerfeld, 28 January 1918; Sommerfeld to von Miller, 31 January 1918, DMA, VA 1271.
[11] Sommerfeld to Einstein, undated [June 1918], AEA. Also in (Eckert and Märker 2000, doc. 283).
[12] Sommerfeld to Richard Swinne, 25 December 1918, DMA, HS 1952–3.

VI of my book on atomic structure and spectral lines, where I will review Rubinowicz's ideas with particular fondness."[13] To Bohr he wrote a few days later that he regarded "your formal analogy principle between classical and quantum theory interesting and fruitful" but less satisfying than Rubinowicz's approach. In the same breath, he added that he was now writing "a book *Atombau und Spektrallinien* which should be also understandable for non-physicists."[14] Sommerfeld's pace of writing was quite rapid. Two weeks later, by the end of February 1919, he wrote to his former disciple, Landé, with regard to the interpretation of atomic spectra: "My book is ready except the last chapter."[15]

The writing of *Atombau und Spektrallinien*, therefore, lasted less than a year, from early summer 1918 to the spring of 1919. If we take the first mention of the book at the end of the winter semester 1916/17 as its inception, we may add a two-year stretch of popular lectures as a gestation. Neither the war nor the ensuing revolutionary turmoil seems to have had an impact on the transformation of the popular, wartime lectures into a semi-popular textbook. Sommerfeld, however, like most of his colleagues, was far from untouched by these events. Politically he may be characterized by and large as national-liberal.[16] His lectures at the front involved close contact with leading military officials and chauvinistic cultural propaganda. After his trip to Belgium in January 1918, Sommerfeld praised, in a newspaper article, the transformation of Ghent University into a German university as "the most effective and seminal trait of German politics in Belgium which tackled the problem at its root, the root of the common Germanic culture."[17] After the war, during the short-lived Soviet government in Munich in the spring of 1919 (to which the press often attached the epithet "Jewish"), Sommerfeld wrote in a moment of anger at the Munich revolutionary unrest to the right-wing Wilhelm Wien (who succeeded Röntgen a few months later as Sommerfeld's colleague in the chair for experimental physics) about the publishers he had envisaged for *Atombau und Spektrallinien*.

> It appears at Vieweg. I had also negotiated with Teubner and Springer. Teubner was not at all accommodating and seems to be in economic troubles. Springer was very tempting, but I did not trust his business practices and am becoming more and more anti-semitic in view of the Jewish-political mischief.[18]

Otherwise the turbulent times during which the book project was carried out left no traces. Up to the last moment, Sommerfeld continued to add recent results that seemed pertinent to the proofs.[19] In the preface, dated 2 September 1919, Sommerfeld emphasized once more that his book was an attempt to popularize its subject matter and its inception lay in popular lectures given during the war. That the last two of the six chapters, where he reviewed his fine-structure theory, Rubinowicz's selection rules and the like, might appear,

[13] Sommerfeld to Josef von Geitler, 14 January 1919, private collection, Warsaw. Printed in (Eckert and Märker 2004, doc. 1).
[14] Sommerfeld to Bohr, 5 February 1919, NBA. Printed in (Eckert and Märker 2004, doc. 2). For a comparison of the Sommerfeld-Rubinowicz and Bohr approach, see (Seth 2010, 228–233).
[15] Sommerfeld to Landé, 28 February 1919, Nachlass Landé 70 Sommerfeld.
[16] According to a questionnaire from July 1933, Sommerfeld was a member of the youth organization of the National Liberal Party (NLP) from 1903 to 1906, and for a short period after the war of the German Democratic Party (DDP), the left-wing successor of the NLP which dissolved in 1918, DMA, NL 89, 030, Mappe Hochschulangelegenheiten.
[17] München-Augsburger Abendzeitung, 26 February 1918.
[18] Sommerfeld to Wien, 27 March 1919, DMA, NL 56, 010.
[19] Sommerfeld to Landé, 2 July 1919, Nachlass Landé 70 Sommerfeld.

to a "mathematically untrained" reader, incompatible with this aim, Sommerfeld admitted, but the reader "should be convinced that the major difficulty of these parts is in the nature of things and does not result from the author's hobby" (Sommerfeld 1919, preface).

6.3 First Reactions

By the end of October 1919, the book was printed.[20] The very first reactions signaled that *Atombau und Spektrallinien* would be a success. Carl Runge, who was not only a noted mathematician but also an authority on spectroscopy, called it a "splendiferous book" which would serve "for many as an excellent introduction into the subject." As an expert, Runge particularly liked the final two chapters, which Sommerfeld had discerned to be rather difficult. "In the first chapters you appear to strike a more elementary tone, as if you had intended originally to write in a more popular manner and lost your way in the course of the writing."[21] Pieter Zeeman, the Dutch Nobel laureate, praised the "wonderfully clear, exhaustive, beautiful presentation of the subject" and Sommerfeld's skill as a writer: "Your book reads like a thriller." He considered it most fortunate that this book was authored by someone who had contributed so much of his own research to the field. "The victories of German science," Zeeman alluded to the political situation so shortly after the war, "will finally have to be acknowledged everywhere."[22]

This was not the only political allusion in the flood of positive, and often euphoric, reactions. Walter Kaufmann, for example, framed his praise as a congratulation—not to the author but to the reader of *Atombau und Spektrallinien*: "I commend German physics and all physicists who will have to deal with quantum theory and the like now and in the future to this opus."[23] Adding the attribute "German" reflected the embitterment toward the Entente's science policy, which, for a number of years, further deepened the wartime division of the international scientific community into hostile political camps (Schroeder-Gudehus 1966). Beyond its pedagogical use in teaching atomic physics, Sommerfeld's book served as ideological ammunition for those who considered science "Machtersatz"[24] (Forman 1973). Sommerfeld's renown as a prime authority in the nascent discipline of atomic physics shown forth from his book and decorated it like a glory. "Forsooth, in our science we do not yet notice any indications of the 'decline of the West,'" one admirer praised *Atombau und Spektrallinien* poingnantly—adding another ideological undertone by alluding to Ostwald Spengler's bestseller which had been published in the last year of the war.[25]

Thus the postwar political-ideological climate contributed to the transformation of Sommerfeld's book from a mere exposition of scientific facts into a classic of its time. Of course, there was also a true need for educating physicists on the recent developments in atomic physics. A whole generation of students was returning to the universities, hungry for mental as much as physical nourishment, and eager to absorb the new scientific knowledge

[20] Sommerfeld to Epstein, 26 October 1919, Epstein Papers.
[21] Runge to Sommerfeld, 12 January 1920, DMA, HS 1977–28/A,298.
[22] Zeeman to Sommerfeld, 16 January 1920, DMA, HS 1977–28/A,380. Also in (Eckert and Märker 2004, doc. 17).
[23] Kaufmann to Sommerfeld, 20 January 1920, DMA, HS 1977–28/A,161.
[24] "Machtersatz" literally translated, means replacement of power.
[25] Beggerow to Sommerfeld, 21 February 1920, DMA, NL 89, 022.

about atoms that had been developing so quickly while they were in the trenches.[26] *Atombau und Spektrallinien* offered this knowledge at the right time in a condensed and easily accessible manner. Within a few weeks, the need for a second edition became apparent. "Vieweg informs me today," Sommerfeld wrote to Zeeman by the end of January 1920, "that he has to envisage a new edition."[27] Max Planck found this news "among all the nice reviews the most impressive one."[28]

Given the euphoric response that Sommerfeld received in numerous letters, from his colleagues it is hardly astonishing that the public reception of *Atombau und Spektrallinien* was equally favorable. The reviewer in the *Physikalische Zeitschrift* recommended this "excellent opus" for every physicist interested in atomic physics simply as "indispensable" (Bergwitz 1920, 223–224). In the *Physikalische Berichte*, the review organ of the physics community, it was predicted that *Atombau und Spektrallinien* would exert "the deepest effect as a compendium, tool, and guide to further development" (Kossel 1920, 536–537). Another glowing review appeared in Springer's *Naturwissenschaften*. The book is

> [of] such a pervasive power that every reader with an interest in science must feel swept along and made a docile follower of the author into the new world which was opened up to a large extent by his scientific intuition and that of his disciples. (Franck 1920, 423–424)

The reviewer, James Franck, recommended the book most warmly to all scientists regardless of their specialty.

> Even though many will not follow the guide up to the highest peaks there are enough lookout points within effortless reach from which the sight is rewarding. In particular the first four chapters, which cover more than half of the book, may claim to be broadly understandable. Their reading will be particularly useful for the chemist. (Franck 1920, 423–424)

For the physicist, the book deserved "the greatest interest in all its parts," not the least because the author had the courage to present "here and there theoretical and experimental material which perhaps will not prove sustainable in the course of further research." In this manner he reached "to the farthest outposts of atomic research" (Franck 1920, 423–424).

The praise was not limited to private letters and book reviews. When Hilbert congratulated Sommerfeld for his "magnificent book," which he studied "with daily increasing pleasure," he revealed that "our faculty will offer you a little surprise for your book which will hopefully delight you."[29] The surprise arrived a few weeks later in the form of a check for over 10,000 German marks from the Otto Vahlbruch Foundation, a heritage fund at the disposal of the Philosophical Faculty of Göttingen University for bi-annually honoring "the author of a book written in German which represents the greatest progress in the sciences in these periods."[30]

[26] This view is based on dozens of letters written during the war in which Sommerfeld's students asked for reprints and other communications to learn about progress in their scientific fields. A box of such letters is preserved in DMA, NL 89, 059.

[27] Sommerfeld to Zeeman, 29 January 1920, RANH, Zeeman, inv.nr. 143. Also in (Eckert and Märker 2004, doc. 19).

[28] Planck to Sommerfeld, 15 February 1920, DMA, HS 1977–28/A,263.

[29] Hilbert to Sommerfeld, 21 January 1920, DMA, HS 1977–28/A,141.

[30] The check was dated 30 March 1920; Sommerfeld thanked on 15 April 1920, SUB, UAG II Ph 13i.

The favorable reception of *Atombau und Spektrallinien* was only occasionally accompanied with critical remarks. Max Born found, contrary to James Franck in *Naturwissenschaften*, that Sommerfeld presented:

> [S]ome things in such a way that the layperson must think that everything is in order; but that is often not the case, for example the molecular models of H_2 etc., furthermore the whole theory of X-ray spectra. Landé, at least, has told me recently that everything is in disorder here. Wouldn't it be good to emphasize the doubts a little more?[31]

He also blamed Sommerfeld for being too *lokalpatriotisch*, for example when he gave preference to Rubinowicz regarding the selection rules. "Isn't Bohr's formulation nice too?" But he belittled such criticism when he concluded with a hint to the second edition: "Do not change too much of your book, it is, as it is, wonderful!" Another critical response came from William Wilson, a lecturer at Kings College in London, who had earlier independently formulated the same quantization rule as Sommerfeld. "This should have been mentioned in your book," Wilson complained.[32] Sommerfeld responded that he already had acknowledged Wilson's priority in his publication in the *Annalen der Physik* in 1916, but omitted it in his book because Wilson had not drawn consequences for the theory of spectral lines, "the true subject of my book."[33] Because of "lack of time," as Sommerfeld wrote in September 1920 in the preface of the second edition, he refrained from a thorough revision. The changes concerned mainly the mathematical appendices. "Therefore many things were left (the molecular models, the calculation with co-planar rings of the X-ray spectra) which already appeared questionable to me in the first edition" (Sommerfeld 1921, preface).

6.4 The Second and Third Editions

The second edition was as short-lived as the first. A few months after its appearance, Sommerfeld wrote to Bohr: "I am in the uncomfortable situation that I again have to write a new edition of my book."[34] Bohr had thanked Sommerfeld only four months earlier for the second edition in a similar tone to Planck, arguing that "its fast re-appearance bears the best witness to the great interest that your book has elicited."[35] Within these four months, Bohr and Sommerfeld had exchanged more letters about recent progress in atomic physics. Bohr was at that time developing what was called his "second atomic theory," a concept about the structure of the electronic shells of successive elements in the periodic system. "Your remark," Sommerfeld responded to a letter from Landé in March 1921, "that Bohr has struck like a bomb, is also true for Munich. I received a copy of Bohr's letter to *Nature*. We have to relearn thoroughly."[36] Bohr planned to visit Göttingen that spring but had to cancel his journey because he fell ill. Sommerfeld attributed the illness to the "monstrous thought concentration" which Bohr had expended on his recent discoveries. "I would have visited you in

[31] Born to Sommerfeld, 5 March 1920, DMA, HS 1977–28/A,34.
[32] Wilson to Sommerfeld, 7 July 1920, DMA, HS 1977–28/A,371.
[33] Sommerfeld to Wilson, 14 July 1920. Draft, DMA, HS 1977–28/A,371. Sommerfeld added references to Wilson and Jun Ishiwara (another physicist who had formulated the same quantum rules) in the third edition.
[34] Sommerfeld to Bohr, 7 March 1921, NBA, Bohr. Also in (Eckert and Märker 2004, doc. 39).
[35] Bohr to Sommerfeld, 8 November 1920, NBA, Bohr. Also in (Eckert and Märker 2004, doc. 29).
[36] Sommerfeld to Landé, 3 March 1921, Nachlass Landé, Sommerfeld. Also in (Eckert and Märker 2004, doc. 38).

Göttingen and asked about your atomic constructions. Now I have to write my third edition without knowing more details about this decisive turn concerning the electronic orbits."[37]

After releasing the second edition with only minor changes, it was clear to Sommerfeld that he would have to make a considerable effort to adapt the third edition to the current state of atomic knowledge. Besides Bohr's second theory, this effort centered around a number of other specialties in which Sommerfeld saw fit to seek expert advice from colleagues. He asked Lise Meitner, for example, to update his paragraph on nuclear physics.[38] Sommerfeld's own research during the past year resulted in considerable changes with regard to the the spectra of atoms with more than one valence electron. In 1920 Sommerfeld had introduced the concept of an "inner quantum number" to account for certain regularities of these spectra. "You are brooding over the fundamental questions of light quanta," Sommerfeld wrote to Einstein in October 1921:

> I do not have the power to do this and am content with the details of the quantum magic in the spectra. Here there are the 'inner quantum numbers' which interest me. I have no idea what they mean but they unravel the composed triplets (and doublets).[39]

With the "inner quantum numbers" and other ad hoc concepts introduced to explain spectroscopic data, Sommerfeld's atomic theory became more empirical. The new approach seemed particularly appropriate in accounting for the anomalous Zeeman effect (Forman 1970; Seth 2008). "Your effect proves to be more and more an important guide through atomic physics," Sommerfeld wrote to Zeeman in the beginning of the winter semester 1921/22. In the preceding semester, he had dedicated his special lecture to "Magneto- and Electro-Optics," where he presented to his advanced students a "quantum-theoretical re-interpretation" of the classical model (conceived by Woldemar Voigt) of the anomalous Zeeman effect. After this trial run, he thought that the time had come to present "in the new edition of my book on spectral lines all these strange number laws which Landé has found recently and which Paschen has confirmed," he wrote to Zeeman. "Now a very talented disciple of mine even deduced these laws from a model based on simple assumptions."[40] In a letter to Einstein, he revealed that this prodigy student was Heisenberg, then in his third semester. "I have in the meantime convinced myself about wonderful number-laws of line combinations," he enthused about these recent results, "and I have presented them in the third edition of my book."[41]

By that point, in January 1922, he had finished the revisions for the third edition. The excitement about the most recent advances is also manifested in his preface to this edition:

> I attach particular importance to the introduction of the inner quantum numbers (chap. VI, § 5), and to the systematic arrangement of the anomalous Zeeman effects (chap. VI, § 7). The regularities that here obtain throughout are primarily of an empirical nature, but their integral character demands from the outset that

[37] Sommerfeld to Bohr, 25 April 1921, NBA, Bohr. Printed in (Eckert and Märker 2004, doc. 40).
[38] Sommerfeld to Meitner, 21 June 1921, Meitner Papers.
[39] Sommerfeld to Einstein, 17 October 1921, AEA.
[40] Sommerfeld to Zeeman, 2 October 1921, RANH, Zeeman, inv. nr. 910. Also in (Eckert and Märker 2004, doc. 46).
[41] Sommerfeld to Einstein, 11 January 1922, AEA. Printed in (Eckert and Märker 2004, doc. 50).

> they be clothed in the language of quanta. This mode of explanation, just like the regularities themselves, is fully established and is unique. Even at the present early stage it has shown itself in many respects to be fruitful and suggestive.[42]

Thus "Mr. stud. W. Heisenberg" and other Sommerfeld disciples (Adolf Kratzer, Wolfgang Pauli, Gregor Wentzel) found their names immortalized at a rather early stage in their career. Sommerfeld also acknowledged such contributions in doctoral reports.[43] "I have drudged a lot, particularly with the new edition of my book, and am ripe for a holiday now," he wrote to Einstein after the summer semester 1921. "I have made four PhDs (among them Pauli) and one Privatdozent (Kratzer)."[44] Furthermore, Sommerfeld paid tribute to the recent work of Alfred Landé who had turned from a devoted disciple into a rival (Forman 1970; 1968). Compared to a single reference in the second edition, Landé figures as a key player in several parts of the third edition of *Atombau und Spektrallinien*.

In terms of personalities, the indisputable main character of the book was Bohr. Sommerfeld had already praised his Copenhagen colleague in the preface to the first edition, "For all times the theory of the spectra will bear Bohr's name" (Sommerfeld 1919, preface). He had visited Bohr in autumn 1919 and privately compared him to Einstein.[45] With his "second atomic theory" about the build-up principle of the entire periodic system, Bohr's fame was growing further. Yet Bohr was not entirely happy with Sommerfeld's presentation of his ideas in the first and second editions of *Atombau und Spektrallinien*. In particular, Sommerfeld regarded the correspondence principle as merely useful—not as fundamental the way Bohr did. Although the third edition still left something to be desired in this regard, Bohr's response is telling. After expressing his congratulation and admiration, Bohr thanked Sommerfeld

> for the friendly attitude with which you regarded my work and that of my collaborators. During the last years I have often felt scientifically very lonely, under the impression that my tendencies to develop the principles of quantum theory systematically to the best of my ability have been received with very little understanding. For me this is not a matter of a didactic trifle but a sincere effort to obtain an inner connection such that one can hope to create a valid fundament for further construction. I understand very well how little things are yet resolved, and how clumsy I am with expressing my thoughts in an easily accessible manner. All the more I was pleased to see a change of your attitude in the new edition of your book.[46]

By and large, the third edition was praised as a new accomplishment—and a glimpse at a rapidly-evolving subject. "Everywhere one becomes aware about the progress," Planck wrote to Sommerfeld:

---

[42] The translation is taken from (Sommerfeld 1923; 1922, preface).
[43] Report to the faculty, 8 July 1921, UAM (OC-I-47p).
[44] Sommerfeld to Einstein, 10 August 1921, AEA.
[45] Sommerfeld to Margarethe Sommerfeld (his daughter), 24 September 1919, private collection, Munich.
[46] Bohr to Sommerfeld, 30 April 1922, DMA, HS 1977–28/ A, 28. Also in (Eckert and Märker 2004, doc. 55). See (Seth 2010, 233–237) for an excellent discussion about Bohr's and Sommerfeld's different perceptions of the correspondence principle.

> [A]nd at the same time the systematic rounding of the ideas developed by yourself. Admittedly even now one can not yet speak of an accomplishment of quantum theory as in classical theories. Even the immensely productive correspondence principle does not yet procure the complete connection to the classical theory.[47]

The mathematician Hermann Weyl admired Sommerfeld for his ability to orchestrate such a wealth of "recalcitrant empirical facts" into a well-ordered scheme: "You are in contact here as elsewhere with the reality that is accessible to our senses and sets the registers of your quantum organ. Your book is now my physical bible."[48] Even at technical universities the "bible" was studied. "We have now resolved to read your book together in the physics colloquium," Theodore von Kármán informed Sommerfeld from the Aachen Technical University.[49] At the same time, the third edition was translated into English and French. While these were in the making, however, physicists abroad used the German edition. Within less than a year, more than four thousand copies were sold.[50] However, its character as a "bible" evoked expectations of immortalization that were not always fulfilled to the satisfaction of Sommerfeld's colleagues. Paul Ehrenfest, for example, was "rather depressed," as Sommerfeld learned from Einstein, "because you denied him authorship of the adiabatic hypothesis."[51]

6.5 *Atombau und Spektrallinien* in the United States (1922/23)

In the summer of 1922, Sommerfeld received an invitation from the University of Wisconsin in Madison to lecture there as the Karl Schurz Professor for four months, from September 1922 to January 1923.[52] The invitation of a German so shortly after the war was an event that attracted great attention all over the United States. "German Scientist Coming," the *New York Times* reported the news on 6 August 1922. "The Karl Schurz Memorial Professorship was founded in 1910 as an exchange professorship with the German universities," the newspaper informed its readers. "The appointment of Professor Sommerfeld marks its resumption after the interruption caused by the war." But it was not only this political context—alluding to the pro- and anti-German attitudes taken in the course of US entry into the Great War in 1917—that made the invitation at the University of Wisconsin worth an article in the *New York Times*. The advances in physics achieved in Europe were being watched with great curiosity and had already resulted in invitations of professors from overseas to several American universities, including Einstein, Marie Curie, and Hendrik Antoon Lorentz, see (Sopka 1988, appendix II). "Professor Sommerfeld is expected to give a course on atomic structure, and a second course either on the analysis of wave propagation or in the general theory of relativity," the newspaper further reported.[53]

---

[47] Planck to Sommerfeld, 28 April 1922, DMA, HS 1977–28/A,263.
[48] Weyl to Sommerfeld, 19 May 1922, DMA, HS 1977–28/A,365. Also in (Eckert and Märker 2004, doc. 57).
[49] Von Kármán to Sommerfeld, 25 May 1922, Theodore von Kármán Papers.
[50] Vieweg to Sommerfeld, 12 January 1923, DMA, NL 89, 019, Mappe 4,1.
[51] Einstein to Sommerfeld, 16 September 1922, DMA, HS 1977–28/A,78. Also in (Eckert and Märker 2004, doc. 58).
[52] Birge to Sommerfeld, 5 July 1922, DMA, NL 89, 019, Mappe 4,1.
[53] *New York Times*, 6 August 1922.

At that time, in autumn 1922, there was still no English translation of *Atombau und Spektrallinien* available. Those attempting to learn about the recent advances in atomic physics used the third German edition, which had just appeared. But the fame of Sommerfeld's book preceded the English translation. The news of Sommerfeld's arrival spread among universities and research laboratories all over the United States, resulting in a flood of invitations to lecture on the subject of his book. "I will be very glad to visit your excellent laboratories at Schenectady and to deliver there a few lectures about Atomic Structure or Spectral Lines," Sommerfeld responded, for example, to an invitation from the Research Laboratory of General Electric.[54] He visibly enjoyed his role as harbinger of a new physics. "Crew is a spectroscopist," Sommerfeld explained in a letter to his wife about an invitation to the Northwestern University in Evanston, "my book was on his desk, I was an oracle for him."[55] At Berkeley his book was so much sought-after "that they cannot keep it," as he reported home. "It has been stolen from the institute's library and had to be purchased again."[56]

Altogether, Sommerfeld lectured at seventeen locations during his six-month sojourn in the United States. While he was based in Madison for his main stay, at the University of Wisconsin from September 1922 to January 1923, he visited Evanston, Milwaukee, Minneapolis, Ann Arbor, and Urbana. In January, he traveled to California, where Robert A. Millikan and Exum P. Lewis invited him to lecture for two weeks each at the California Institute of Technology in Pasadena and the University of California, Berkeley, respectively. On his way west, Sommerfeld included Kansas in his schedule, and on his return Denver and Ames for another couple of lectures. In March 1923, Sommerfeld's main base was at the National Bureau of Standards (NBS) in Washington, D.C., where he collaborated for ten days with the spectroscopy department, headed by William Frederick Meggers. He concluded his American sojourn with a circuit through the eastern states, lecturing in Schenectady, Cambridge (Massachusetts), Ithaca, and New York City.[57]

Although Sommerfeld was regarded by some of his American colleagues as "an oracle" with regard to atomic structure and spectral lines, the knowledge transfer accompanying Sommerfeld's lecture invitations worked both ways. Sommerfeld was particularly interested in "the astrophysical fairyworld of the Mt. Wilson and the first-rate research institution in Pasadena which the energy of Mr. Millikan has created," as he wrote some months before his visit to his former disciple Epstein, whom Millikan had called to Pasadena in 1921 as professor for theoretical physics.[58] His high expectations were not disappointed: "Apart from Millikan's institute the entire staff from Mt. Wilson is attending my lectures, all of them first-rate people," Sommerfeld wrote to his wife during his sojourn at Pasadena. "They offer me their enormous material most readily, including that which is unpublished."[59] Sommerfeld's visit at the NBS, too, brought him in close contact with a wealth of spectroscopic data. "Everyone is eager to present me his stuff," he wrote home.[60]

---

[54] Sommerfeld to Whitney, 10 October 1922, DMA, NL 89, 019, Mappe 4,1.
[55] Sommerfeld to his wife, 19 November 1922, private collection, Munich.
[56] Sommerfeld to his wife, 16 February 1923, private collection, Munich.
[57] This survey is primarily based on letters of invitation, preserved in Munich, NL 89, and Sommerfeld's correspondence with his wife, private collection, Munich.
[58] Sommerfeld to Epstein, 29 July 1922, Caltech Archives, Epstein 8.3.
[59] Sommerfeld to his wife, 1 February 1923, private collection, Munich.
[60] Sommerfeld to his wife, 9 March 1923, private collection, Munich.

The encounter with empirical spectroscopy in America left visible traces—in Sommerfeld's own research, in his pedagogical practice, and in the forthcoming fourth edition of *Atombau und Spektrallinien*. After his return to Munich, Sommerfeld continued to discuss spectroscopic details with his American colleagues. "May I ask you to send me the Fe-spectrum from Mt. Wilson," Sommerfeld wrote to Meggers in summer 1923. At that time, he was focusing his research on multiplets, families of regularly arranged spectral lines, which had first been identified in 1922 by Miguel Catalan in the spectrum of manganese. Such groups of lines were also observed when atoms were exposed to magnetic fields (Zeeman effect). This feature came to be represented mathematically in terms of different vectorial representations of angular momenta—but the interpretation of such constructions in terms of models remained dubious. "After Landé (*Zeitschrift für Physik*, Bd. 15, S. 189) has explained theoretically-empirically the Zeeman effects for arbitrary multiplets, we have discovered some multiplets in the spectrum of titanium and vanadium (from which we received the Zeeman effects from Pasadena)," Sommerfeld explained to Meggers. "Therefore, the comparison with Fe would be very interesting."[61] By "we" Sommerfeld meant himself and his advanced student Otto Laporte. A year later, Laporte wrote his dissertation on the spectrum of iron, a task which "was still a few years ago considered hopelessly complicated," as Sommerfeld argued in his report to the faculty.[62] In 1925, Laporte spent a one-year fellowship as a theoretical analyst in the spectroscopy department at the NBS; "we nicknamed him our Herr Geheimrat [Privy Councillor]," Meggers mused at the end of Laporte's term.[63]

Besides experimental spectroscopy, the "most interesting" scientific news which Sommerfeld encountered during his American sojourn was "a work by Compton in St. Louis." This was the manner in which he alluded, in a letter to Bohr in January 1923, to the discovery of the Compton effect, about which he had learned sometime after Christmas 1922. He reported no details (Compton's publication appeared in the *Physical Review* only in May 1923) but revealed that:

> it would have the consequence that the wave theory of X-rays has to be definitely abandoned. I am not yet totally convinced whether he is right, and I do not know whether I should already speak about his results. I only would like to point out that we may expect eventually a very fundamental new instruction.[64]

Within a few months, Compton's experimental result was transformed into the "Compton effect," reproduced in other laboratories and interpreted as a manifestation of the particle nature of X-rays (Stuewer 1975).

6.6 The Fourth Edition

Both the Compton effect and the new results about multiplets entered in the fourth edition of *Atombau und Spektrallinien*. Sommerfeld began the tedious effort of revisions and extensions as soon as he returned from America in the summer of 1923. "I am busy in preparing a new German edition in which I will also process my American experiences," he wrote to

[61] Sommerfeld to Meggers, 30 June 1923, Meggers Papers.
[62] Sommerfeld's doctoral report to the Faculty, 26 July 1924, UAM (OC-I-50p).
[63] Meggers to Sommerfeld, 8 July 1926, DMA, HS 1977–28/A,225. Also in (Eckert and Märker 2004, doc. 100).
[64] Sommerfeld to Bohr, 21 January 1923, NBA, Bohr. Also in (Eckert and Märker 2004, doc. 65).

the Madison physicist, Charles Elwood Mendenhall, at a time when the English translation *Atomic Structure and Spectral Lines*, made from the third edition, had just appeared in America.[65] In another letter to his former host at the University of Berkeley, Raymond Thayer Birge, he was more explicit. Besides news about molecular spectra, the fourth edition would cover:

> Bohr's theory of the periodic system, Compton's discovery, much more on inner quanta, magnetons and anomalous Zeeman effects than the third edition. Of course it will contain all we know until now about multiplets. I am glad that my sojourn in Washington bore good fruits in this regard.[66]

With regard to the Compton effect, Sommerfeld confessed that he had clung "as long as possible" to the view of light propagation as a wave phenomenon but that he was "impelled to adopt more and more the position of the extreme light quantum theory." Therefore, he ranked the Compton effect "among the fundamental empirical facts" to be reviewed in the first chapter. He presented the Compton effect as "the most important discovery which has been made in the present state of physics" (Sommerfeld 1924, preface, vii–viii).

The theory of complex spectra (i.e., the spectra of atoms with more than one valence electron) was a particular highlight of this edition. It forced Sommerfeld irrevocably to abstain from model interpretations of spectral lines. The demise of a visual interpretation in terms of electronic orbits seemed already unavoidable in light of the so-called doublet riddle (Forman 1968). Sommerfeld's fine structure theory from 1916 had persuasively shown that the doublets observed in X-ray spectra were caused by a relativistic effect, the same effect which caused the fine-structure split of hydrogen lines, but magnified by a factor proportional to the fourth power of the nuclear charge; on the other hand, the optical doublets, like the yellow sodium lines, were interpreted as a magnetic effect, resulting from different orientations of angular momenta. Thus, the doublets of the optical and X-ray spectra were interpreted in terms of different physical models. In April 1924, ultraviolet spectra measured in Millikan's laboratory in Pasadena indicated that both the optical and the X-ray doublets could be explained relativistically. As Sommerfeld wrote to his rival, Landé, about this news: "The relativity formula, far from being obsolete or refuted, extends its validity into the optical realm." But what reads like a victory of Sommerfeld's relativistic over Landé's magnetic doublet interpretation was not meant to suggest replacing one model by another—but rather the definitive abdication of all model-based explanations. "We have recently learned that arithmetical regularities reach farther than would be expected from models," Sommerfeld argued in view of the multiplets where these regularities were most conspicuous.[67] Sommerfeld also propagated this message in the new edition of *Atombau und Spektrallinien*. "Nowhere does the arithmetical character of quantum theory come to light in a more elementary and beautiful manner than in the complex structure of the series terms," he began the chapter on inner quantum numbers and multiplets, and followed it with the cautionary remark:

> Uncertain, however, is the interpretation in terms of a model […] Like with the X-ray spectra it is at present advisable to leave the model interpretation

[65] Sommerfeld to Mendenhall, 8 September 1923, DMA, NL 89, 003. Also in (Eckert and Märker 2004, doc. 67).
[66] Sommerfeld to Birge, 19 October 1923, Birge Papers, Box 26.
[67] Sommerfeld to Landé, 20 April 1924, Landé Papers, 70 Sommerfeld.

> more or less open and to limit oneself, in the main part, to ascertaining the facts quantum-theoretically. (Sommerfeld 1924, 575)

Apart from the wealth of new empirical material, it was this turn toward a model-free approach in atomic theory that rendered the fourth edition peculiar. Pauli, at least, perceived this message quite clearly, and he regarded as "particularly nice" that Sommerfeld had abstained in the new edition from all model-like explanations:

> The model conceptions are now in a fundamental crisis. I guess it will finally end in a further radical accentuation of the contradiction between classical and quantum theory. As becomes particularly clear from Millikan's and Landé's findings concerning the representation of the optical alkali doublets by relativistic formulae, it will hardly be possible to maintain the notion of definite distinct orbits of electrons in the atom. When we speak in terms of models we use a language that is not sufficiently adequate to the simplicity and beauty of the quantum world. For this reason I found it so nice that your presentation of the complex structure is entirely free of all model prejudices.[68]

Pauli argued from the perspective of a theorist who was primarily interested in the foundations of quantum theory, but experimental spectroscopists also had reasons to welcome the new edition. *Atombau und Spektrallinien* is "the bible of the practical spectroscopists," Friedrich Paschen wrote enthusiastically. "When I recall how I gradually learned about the quantum concepts, in the end it was always your work from which I received clarity." He praised Sommerfeld for offering, through his book, knowledge that "we practitioners could never have appropriated besides our work. I believe it is very similar with the Americans."[69] Exum Percival Lewis from the University of California in Berkeley confirmed this opinion: "The *Atombau* still remains our 'Bible' in its field," he wrote to Munich, "I shall always be very grateful to you for the copy of the last edition which you so kindly sent me."[70] The reaction from the NBS in Washington, D.C., was equally enthusiastic. Although the material "becomes more complex and detailed from the experimental side," Meggers remarked in response to the increase in size by another hundred pages "the beautiful developments in the theory" made it easier to digest. "The remarkable recent progress in the production and interpretation of spectra is tremendously stimulating."[71]

Others regarded the ever-growing empirical material in Sommerfeld's *Atombau* with mixed feelings—and added a dose of sober restraint to the praise. The reviewer in the *Physikalische Zeitschrift* (Georg Joos), for example, found it "regrettable, but apparently unavoidable" that since the appearance of the third edition "all hopes in model calculations were frustrated." But he acknowledged that the gain of "arithmetic laws in the complex structure of the spectra" compensated the abandonment of "atomic mechanical speculations" (Joos 1925, 424).

---

[68] Pauli to Sommerfeld, 6 December 1924, DMA, HS 1977–28/A,254. Also in (Eckert and Märker 2004, doc. 83). See also (Seth 2007; 2009).
[69] Paschen to Sommerfeld, 27 January 1925, DMA, Nl 89, 012.
[70] E. P. Lewis to Sommerfeld, 26 October 1925, DMA, NL 89, 010.
[71] Meggers to Sommerfeld, 15 December 1924, Meggers Papers.

6.7 Conclusion

Within only five years after the appearance of its first edition, *Atombau und Spektrallinien* experienced manifold transformations. The size increased considerably (from 550 to 862 pages). The popular character receded in favor of a growing exposition of expert knowledge. According to the review quoted above, it assumed "more and more the character of a handbook," although the reviewer considered it "still well readable for the scientifically educated non-professional."

For the professional quantum theorist, the transformations from the first to the fourth editions were even more striking: *Atombau und Spektrallinien* presented an evolving body of knowledge about quanta and atoms, which was used at the same time as an indicator of the forefront of research for those who contributed to this process. Numerous physicists recalled that they experienced their first encounter with quantum theory through *Atombau und Spektrallinien*.[72]

The fourth edition, which saw the explicit demise of "model prejudices," may be regarded as opening the door for Pauli's exclusion principle and the spin concept. Few other textbooks displayed to such an extent their own content as subject to change.

Quantum mechanics did not end this process of transformation. In 1929, Sommerfeld published the *Wellenmechanischer Ergänzungsband* which was subsequently labeled *Atombau und Spektrallinien II*. The story of this second volume is beyond the scope of this chapter, but it is worth mentioning here that it also underwent fundamental transformations. Unlike *Atombau und Spektrallinien I*, it was conceived from the very beginning as a physics textbook, without any aspirations to popularity among non-professionals. But this did not prevent an increase in size between the first and the second edition (published in 1939) from 351 to 820 pages. Furthermore, the second volume shared with the first volume the feature of having been a group effort: Sommerfeld explicitly thanked his disciples Karl Bechert, Walter Franz, Heinrich Welker, August Wilhelm Maue, and Ludwig Waldmann for their collaboration with parts of the book.

Over the years, other textbooks became available which dealt with one or another subfield of quantum physics in a more appropriate manner than the latest available edition of *Atombau und Spektrallinien*. For a physicist of the post-quantum-mechanical era, the historical legacy transmitted through the subsequent editions might appear more of a burden than a virtue. Nonetheless, a good deal of this material was regarded as worth knowing far beyond the initial publication of a new edition, so that later textbooks referred to *Atombau und Spektrallinien* as a basis from which one could embark in a new direction, and to which one could safely return whenever a detail demanded closer inspection. This longevity would be difficult to understand if *Atombau und Spektrallinien* had merely been a depository of settled knowledge from the pre-quantum-mechanical era.

[72] See the oral history interviews with Hans Bethe, Leon Brillouin, Gregor Wentzel and others in AHQP, available at http://www.aip.org/history/ohilist/, accessed 18 February 2012.

Abbreviations and Archives

AEA	Albert Einstein Archives, Hebrew University, Jerusalem
AHQP	Archive for History of Quantum Physics. American Philosophical Society, Philadelphia
AIP-NBL	American Institute of Physics, Niels Bohr Library, College Park, MD
Bancroft Library	University of California, Berkeley
Birge Papers	Bancroft Library
Caltech	Caltech Archives, California Institute of Technology, Pasadena
Churchill Archives Centre	Churchill College, Cambridge
DMA	Deutsches Museum, Archive, Munich
Epstein Papers	Caltech
Meggers Papers	AIP-NBL
Meitner Papers	Churchill Archives Centre
Nachlass Landé	SBPK
Nachlass Sommerfeld	UBM
NBA	Niels Bohr Archive, Copenhagen
NBS	National Bureau of Standards
NLP	National Liberal Party
Private collection, Munich	The owner of this collection wants to remain anonymous
Private collection, Warsaw	The owner of this collection wants to remain anonymous
RANH	Rijksarchief in Noord-Holland, Haarlem
SBPK	Staatsbibliothek Preußischer Kulturbesitz, Berlin
SUB	Staats- und Universitätsbibliothek, Göttingen
Theodore von Kármán Papers	Caltech
UAG	Universitätsarchiv, Göttingen
UAM	Universitätsarchiv, Munich
UBM	Universitätsbibliothek, Munich

References

Bergwitz, Karl (1920). Besprechungen: Prof. Dr. Arnold Sommerfeld: Atombau und Spektrallinien. *Physikalische Zeitschrift* 21: 223–224.

Bertomeu-Sánchez, José R., Antonio Garcia-Belmar, and Bernadette Bensaude-Vincent (2005). The Power of Didactic Writings: French Chemistry Textbooks of the Nineteenth Century. In: *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives*. Ed. David Kaiser. Cambridge, MA: The MIT Press. 219–251.

Bethe, Hans A. (2000). Sommerfeld's Seminar. *Physics in Perspective* 2: 3–5.

Eckert, Michael (1993). *Die Atomphysiker. Eine Geschichte der theoretischen Physik am Beispiel der Sommerfeldschule*. Braunschweig: Friedrich Vieweg und Sohn.

Eckert, Michael (1999). Mathematics, Experiments, and Theoretical Physics: The Early Days of the Sommerfeld School. *Physics in Perspective* 1: 238–252.

Eckert, Michael and Karl Märker, eds. (2000). *Arnold Sommerfeld. Wissenschaftlicher Briefwechsel, Band 1: 1892–1918*. München: Deutsches Museum and GNT–Verlag.

— eds. (2004). *Arnold Sommerfeld. Wissenschaftlicher Briefwechsel, Band 2: 1919–1951*. München: Deutsches Museum and GNT–Verlag.

Forman, Paul (1968). The Doublet Riddle and Atomic Physics circa 1924. *Isis* 59: 156–174.

— (1970). Alfred Landé and the Anomalous Zeeman Effect, 1919–1921. *Historical Studies in the Physical Sciences* 2: 153–261.

— (1973). Scientific Internationalism and the Weimar Physicists: The Ideology and Its Manipulation in Germany after World War I. *Isis* 64: 150–180.

Franck, James (1920). Besprechungen. Sommerfeld, Arnold, Atombau und Spektrallinien. *Die Naturwissenschaften* 8: 423–424.

Joos, Georg (1925). A. Sommerfeld, Atombau und Spektrallinien. *Physikalische Zeitschrift* 26: 424.

Kossel, Walter (1920). Arnold Sommerfeld. Atombau und Spektrallinien. *Physikalische Berichte* 1: 536–537.

Nisio, Sigeko (1973). The Formation of the Sommerfeld Quantum Theory of 1916. *Japanese Studies in the History of Science* 12: 39–78.

Schroeder-Gudehus, Brigitte (1966). *Deutsche Wissenschaft und internationale Zusammenarbeit 1914–1928. Ein Beitrag zum Studium kultureller Beziehungen in politischen Krisenzeiten*. Geneva: Dumaret and Golay.

Seth, Suman (2007). Crisis and the Construction of Modern Theoretical Physics. *British Journal for the History of Science* 40: 25–51.

— (2008). Crafting the Quantum: Arnold Sommerfeld and the Older Quantum Theory. *Studies in History and Philosophy of Science* 39: 335–348.

— (2009). Zweideutigkeit about "Zweideutigkeit": Sommerfeld, Pauli, and the Methodological Origins of Quantum Mechanics. *Studies in History and Philosophy of Modern Physics* 40: 303–315.

— (2010). *Crafting the Quantum: Arnold Sommerfeld and the Practice of Theory, 1890–1926*. Cambridge, MA: The MIT Press.

Sommerfeld, Arnold (1918). Die Entwicklung der Physik in Deutschland seit Heinrich Hertz. In: *Arnold Sommerfeld. Gesammelte Schriften*. Ed. Fritz Sauter. IV. Braunschweig: Friedrich Vieweg und Sohn. 520–530.

— (1919). *Atombau und Spektrallinien*. Braunschweig: Friedrich Vieweg und Sohn.

— (1921). *Atombau und Spektrallinien*. 2nd ed. Braunschweig: Friedrich Vieweg und Sohn.

— (1922). *Atombau und Spektrallinien*. 3rd ed. Braunschweig: Friedrich Vieweg und Sohn.

— (1923). *Atomic Structure and Spectral Lines*. London: Methuen. Translated by Henry L. Brose.

— (1924). *Atombau und Spektrallinien*. 4th ed. Braunschweig: Friedrich Vieweg und Sohn.

— (1929). *Atombau und Spektrallinien. Wellenmechanischer Ergänzungsband*. Braunschweig: Friedrich Vieweg und Sohn.

Sopka, Katherine R. (1988). *Quantum Physics in America*. New York: American Institute of Physics.

Stuewer, Roger H. (1975). *The Compton Effect: Turning Point in Physics*. New York: Science History Publications.