1 Re-Examining the Crisis in Quantum Theory, Part 1: Spectroscopy

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One of the topics set for this workshop touches upon the transition from the old quantum theory to the new quantum mechanics—in particular, "how the physics community came to recognize the limitations" of the old quantum theory.[1]

Some of the answers to this question may be found in one of the most unsettled periods in the history of quantum physics. These were the years between the end of the First World War in 1918 and the breakthrough to quantum mechanics in 1925–27. It was a period of great difficulty and upheaval, but also remarkable creativity—both for quantum physics and for European society, Germany in particular.

Paul Forman and others have long recognized the remarkable simultaneity of events occurring at that time in the realms of physics and society. Equally remarkable is the appearance during this period of public expressions of a crisis situation within both realms. For example, while Oswald Spengler prophesied the *Untergang des Abendlandes*, a number of physicists, among them Einstein, lamented what he called "The present crisis of theoretical physics."[2] In both physics and society those years were indeed, to quote the title of another book by Spengler, *Jahre der Entscheidung*.[3]

What was going on here? What developments inside and outside the old quantum theory could lead a large number of quantum physicists to doubt the possibility of further progress using that theory? In what sense and to what extent could this be regarded as a "crisis" situation? Was there really any connection between the simultaneous events occurring within physics and society?

These are all very profound and far-reaching historical questions. But, of course, they are not new. This year marks not only the 60th aniversary of the passing of Max Planck in 1947, but also the 40th anniversary of the completion of the Archive for History of Quantum Physics and the publication of its catalogue in 1967.[4]

Greatly stimulated in part by the availability of this archive, during the past half century a large number of historical studies have been devoted to answering many of the fundamental questions about this fertile period of transition from the old to the new

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[1] MPIWG, "Conference on the history of quantum physics, 2–6 July 2007, Berlin."

[2] Oswald Spengler, *Der Untergang des Abendlandes*, 2 vols. (Munich: C. H. Beck, 1918); Albert Einstein, "Über die gegenwärtige Krise der theoretischen Physik," *Kaizo* (Tokyo), 4 (1922), 1–8, reprinted, Karl von Meyenn, ed., *Quantenmechanik und Weimarer Republik* (Braunschweig: Vieweg, 1994), 233–239, quote on 238–239. The talk of a crisis was not new in physics. It appeared before the war in, for instance, Paul Ehrenfest, *Zur Krise der Lichtäther-Hypothese* (Berlin: Springer, 1913). I thank Skúli Sigurdsson for bringing this to my attention.

[3] Oswald Spengler, *Jahre der Entscheidung*, erster Teil (Munich: C. H. Beck, 1933).

[4] Thomas S. Kuhn et al., eds., *Sources for history of quantum physics: An inventory and report* (Philadelphia: Am. Philosophical Society, 1967).

quantum physics.

Looking back over the past decades, two important historiographic works regarding the crisis in quantum theory immediately spring to mind.

Historiographic Works

1. Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 1962.

   For Kuhn, crises entail a rupture between two paradigms, caused mainly by internal developments within normal science. Kuhn described a crisis situation this way:

   > "Because it leads to large-scale paradigm destruction . . . the emergence of new theories is generally preceded by a period of pronounced professional insecurity. As one might expect, that insecurity is generated by the persistent failure of the puzzles of normal science to come out as they should."[5]

2. Paul Forman, "Weimar Culture, Causality, and Quantum Theory, 1918–1927," 1972, takes Kuhn one step further regarding the crisis in quantum theory:

   > "While it is undoubtedly true that the internal developments in atomic physics were important in precipitating this widespread sense of crisis ... nonetheless it now seems evident to me that these internal developments were not in themselves sufficient conditions. The *possibility* of the crisis of the old quantum theory was, I think, dependent upon the physicists' own craving for crises, arising from participation in, and adaptation to, the Weimar intellectual milieu."[6]

   Not until very recently has another work appeared offering a different perspective on the crisis situation in quantum theory.

3. Suman Seth, "Crisis and the construction of modern theoretical physics," March 2007.

   According to Seth, "Different subgroups within theoretical physics viewed the situation in dramatically different ways," depending upon their differing research agendas.

   - "Members of the Sommerfeld school in Munich, who saw the task of the physicist as lying in the solution of particular problems, neither saw a crisis nor acknowledged its resolution."
   - "Researchers associated with Bohr's institute in Copenhagen, who focused on the creation and adaptation of new principles, openly advocated a crisis even before decisive anomalies arose."[7]

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[5] Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962), pp. 67–68.

[6] Paul Forman, "Weimar Culture, Causality, and Quantum Theory, 1918–1927: Adaptation by German Physicists and Mathematicians to a Hostile Intellectual Environment," *Historical Studies in the Physical Sciences*, 3 (1972), 1–115, on 62; German translation in: von Meyenn, note 2, 61–179.

[7] Suman Seth, "Crisis and the construction of modern theoretical physics," *British Journal for History of Science*, 40 (March 2007), 25–51, on p. 25.

Historical Works

Historical studies of the crisis period over the past forty years display a similar pattern—an initial flurry of work on the origins and evolution of quantum physics, followed by a quantum gap as historians turned to other topics, ending with a revival of interest in recent years. Here are some examples:

M. Jammer. *The Conceptual Development of Quantum Mechanics*, 1966.
P. Forman. "The doublet riddle and atomic physics circa 1924," *Isis*, 59 (1968), 156–174.
P. Forman. "Alfred Landé and the anomalous Zeeman Effect," *HSPS*, 2 (1970), 153–261.
H. Small. *The Helium Atom in the Old Quantum Theory*, PhD diss., 1971.
R. Stuewer. *The Compton effect: Turning point in physics*, 1971.
D. Cassidy. *Werner Heisenberg and the Crisis in Quantum Theory*, 1920–1925. PhD diss., 1976.
D. Serwer. "Unmechanischer Zwang: Pauli, Heisenberg, and the Rejection of the mechanical atom, 1923–1925," *HSPS*, 8 (1977), 189–256.
J. Hendry. "Bohr-Kramers-Slater: A virtual theory of virtual oscillators," *Centaurus*, 25 (1981), 189–221.
—Gap—
O. Darrigol. *From c-numbers to q-numbers: The classical analogy in the history of quantum theory*, 1992. Chapter 8, "A Crisis".
H. Kragh. *Quantum generations: A history of physics in the 20th century*, 1999. Section: "Quantum anomalies".

In addition to these studies, the last few decades have brought us the publications of the Pauli correspondence, the Born-Einstein letters, the Sommerfeld-Nachlass, and the collected papers of nearly every major physicist of the era, along with many online resources.

With the availability of all of these pioneering works and interpretations, and a rich trove of primary source material, I think we may now be in a position to make the leap to a new quantum state—a re-examination of the quantum crisis at a much deeper level as both history and historiography, thereby achieving a much fuller understanding of what happened and why.

Origins of the Crisis

Re-examining the mounting problems arising within quantum theory during the early 1920s, we are soon lead back far earlier than 1918, all the way back to the introduction of the quantum itself by Planck and Einstein beginning in 1900, and to the Bohr-Sommerfeld theory of the atom in 1913–16.

While the nature of light and the quantum remained persistent problems, it was the Bohr atom of 1913 and its extensions by Sommerfeld that lay at the foundation of the later crisis situation in quantum atomic physics. It was a critical situation that reached an apex ironically with the celebration of the 10th anniversary of the Bohr atom in 1923. I would like to point out briefly several implications of this theory.

The Bohr Atom

- It provided an extraordinarily successful visualizable mechanical model of orbiting electrons in stationary states obeying classical mechanics but not electrodynamics. It accounted for stability, optical spectra, and ionization of hydrogen atoms.
- Despite this success, many statements appeared over the next decade on the fundamentally unsatisfactory nature of the theory, starting with Bohr himself in 1913. For instance, James Jeans declared: "The only justification at present put forward for these assumptions is the very weighty one of success . . . It would be futile to deny that there are difficulties, still unsurmounted, which appear to be enormous."[8]
- Yet the success of the Bohr atom (with extensions by Sommerfeld) set the standard for over a decade of a successful quantum theory of atomic phenomena.
- It became the definition, if you will, of normal quantum atomic science. In this science, what was frequently called "eine modellmäßige Deutung,"—"a modelbased interpretation/ explanation"—of atomic phenomena became the goal of a successful theory, what Heisenberg and Pauli later called a "physical explanation."

My Points

With the Bohr atom as a background, my argument regarding the crisis in quantum theory is composed of the following points:

- Beginning about 1918, new and more precise data and mechanical calculations resulted by the early 1920s in an increasing failure to achieve the ideal set by the Bohr atom. At the same time, new funding strategies during the post-war economic crisis in Germany provided a boast directly to atomic research.
- The failure of the theory magnified the sense of professional insecurity about the old quantum theory within the community of physicists and mathematicians.
- The insecurity reached such proportions by 1923 that it came close to what Kuhn described as a crisis situation. At the same time, as Seth has suggested, noticeable differences did appear among different groups. However,
- The old quantum theory did in fact work quite well for many other phenomena, such as molecular band spectra.[9]
- The Forman thesis and related issues regarding the quantum crisis are addressed in a separate paper.[10]

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[8] James Jeans, address to British Association, reported in *Nature*, 92 (1913), 304–309; quoted by Ulrich Hoyer, introduction to Niels Bohr, *Collected Works*, vol. 2 (Amsterdam: North-Holland, 1981), 124.

[9] For example, Edwin Kemble, "The application of the correspondence principle to degenerate systems and the relative intensities of band lines," *Physical Review*, 25 (1925), 1–22.

[10] D. Cassidy, "Heisenberg, Weimar culture, and the Forman thesis," paper delivered to conference on 35th anniversary of Forman's paper, Vancouver, March 2007.

Three Critical Problems, Three Groups, Three Places—Roughly Defined

In my rather internal re-examination of this period, I have identified three main problem areas, involving three main research groups in three different places, that caused increasing trouble.

1. *Problem*: Multiplet (complex) line spectra of atoms and their anomalous Zeeman effects. Research group: Sommerfeld school in Munich, including Tübingen spectroscopists Friedrich Paschen, Ernst Back with theorist Alfred Landé.

2. *Problem*: Simple 3-body atomic/molecular systems beyond hydrogen atom: H_2^+, normal He, and excited He. Research group: Born school in Göttingen, including Pauli and Heisenberg, also Sommerfeld, Kramers, Kemble, and Van Vleck. Both of these problem areas concerned atomic structure. The third problem area involved the nature of light.

3. *Problem*: Interaction of radiation and matter, including dispersion theory and the existence of light quanta. Research group: Bohr school in Copenhagen, including Pauli, Heisenberg, Kramers.

Sommerfeld and the Anomalous Zeeman Effect

As also discussed recently by Suman Seth and others, but with somewhat different interpretation, the problem of the Zeeman effect arose within quantum atomic theory as early as 1913, when Bohr sent a copy of his first paper on the Bohr atom to Sommerfeld. Sommerfeld replied immediately: "Will you also apply your atomic model to the Zeeman effect? I would like to concern myself with this."[11]

Sommerfeld did work on the problem, and in 1916 he published his fundamental paper "Zur Quantentheorie der Spektrallinien," which established the Bohr-Sommerfeld quantum theory of atomic structure.[12] I will list only briefly some of the important elements of this paper for our purposes:

- The Sommerfeld quantum conditions, involving only *integral numbers of quanta*

- a relativistic treatment of the Kepler orbits of the electrons in the Bohr model led to angular momentum as a degree of freedom, and ...

- two new quantum numbers for the orbital motion of an electron, giving 3 altogether: n the state number; k for azimuthal angular momentum; m for space quantization, if a z-axis is defined.

Sommerfeld intended to define the z-axis by a weak magnetic field and thus obtain the Zeeman effect. He did so in a follow-up paper that same year, as did Peter Debye. The

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[11] Sommerfeld to Bohr, 4 Sept. 1913, in Bohr, note 8, vol. 2, 603.

[12] Sommerfeld, "Zur Theorie der Spektrallinien," 3 parts, *Annalen der Physik*, 51 (1916), 1–94 and 125–167; reprinted in Arnold Sommerfeld, *Gesammelte Schriften*, vol. 3 (Braunschweig: Friedrich Vieweg & Sohn, 1968), 172–308.

result was the normal Zeeman effect of hydrogen and other singlet line spectra in a weak magnetic field defining the z-axis.[13]

$$E = E_0 + \frac{mh}{2\pi} \cdot \frac{eH}{2m_e c} = E_0 + mh\nu_L \qquad \text{where } \Delta m = \pm 1, 0$$

where E is the energy of a Zeeman term, E_0 is the energy of the unperturbed optical L term, and v_L is the Larmor frequency. This gives the splitting of a singlet line into 3 lines in a weak magnetic field, but the origin of the selection rule was unknown, and the theory could not account for the more prevalent anomalous Zeeman effect.

Anomalous Zeeman Effect

The effect was associated with the puzzling appearance of optical multiplet lines: the splitting of single lines into closely spaced doublets and triplets. The doublet sodium D-lines are a well known example. (As we know today, they arise from spin-orbit coupling within the atom.) Unlike singlets, which display the normal Zeeman effect, the multiplet lines split into more than 3 lines or into 3 lines that are not separated by the Larmor frequency. Furthermore, Paschen and Back had discovered by 1913 the so-called Paschen-Back effect, whereby the anomalous lines all coalesce continuously into the normal Zeeman triplet as the external magnetic field is increased.[14] In 1919 Sommerfeld listed this behavior and the appearance of the anomalous Zeeman effect among the "Schwebende Fragen der Atomphysik" (unsettled questions of atomic physics). Question number 1 entailed "eine modellmassige Deutung" of these phenomena, for which, he declared, "entirely new things" were required.[15]

Sommerfeld's Program

With new and more precise data pouring into his Munich institute from Tübingen, Sommerfeld set out to find the "entirely new things" in a program explained in paper published in 1920. But it entailed an obvious retreat for the author of the relativistic quantum model of the atom. For Sommerfeld the situation seemed similar to that in hydrogen spectroscopy before the Bohr atom. As Balmer had done decades earlier, Sommerfeld undertook analyses of the highly regular Zeeman data in search of empirical relationships and number harmonies that he hoped would provide clues to the underlying model interpretation of the data. As Seth has argued, Sommerfeld was solving problems not seeking new principles, but, like Balmer, he had little choice at this point.[16]

Sommerfeld soon found what he was looking for. In 1920 he published his famous *Zahlenmysterium*, number mystery. It consisted of a table of number harmonies in

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[13] A. Sommerfeld,"Zur Theorie des Zeeman-Effekts der Wasserstofflinien, mit einem Anhang über den Stark-Effekt," *Physikalische Zeitschrift*, 17 (1916), 491–507; reprinted Sommerfeld, note 12, 309–325; Peter Debye, "Quantenhypothese und Zeeman Effekte," *Phys. Zs.* , 17 (1916), 507–512.

[14] F. Paschen and E. Back, "Normale und anomale Zeemaneffekte," *Annalen der Physik*, 39 (1912), 897–932. For the phenomena of the Zeeman effect as observed at that time, see A. Sommerfeld, *Atombau und Spektrallinien* (Braunschweig: F. Vieweg & Sohn), 1st edition 1919, 3rd edition 1922, 4th edition 1924. The effect is also discussed in the literature cited earlier.

[15] A. Sommerfeld, "Schwebende Fragen der Atomphysik," *Phys. Zs.* , 21 (1920), 619–620; reprinted in Sommerfeld, note 12, vol. 3, 496–497.

[16] A. Sommerfeld, "Ein Zahlenmysterium in der Theorie des Zeemaneffktes," *Naturwiss.*, 8 (1920), 61–64 on 64; reprinted in Sommerfeld, note 12, vol. 3, 511–514.

which he had traced the observed multiplet lines to combinations of quantum states to which he assigned empirical “inner quantum numbers” j. In his scheme, each angular momentum state k split into two or three states with values of $j = k,\ k-1$ for doublets, $j = k,\ k-1,\ k-2$ for triplets. Thus, for example, the sodium D-lines arise from downward jumps from $k = 2$, $j = 2$ to $k = 1$, $j = 1$ (D_2) and $k = 2$, $j = 1$ to $k = 1$, $j = 1$ (D_1). Sommerfeld believed the inner quantum numbers referred to some unknown inner rotation and “hidden” mechanical quantum condition.

We must be clear about what Sommerfeld was doing. He was not really engaging in number mysticism. Rather, he was attempting to solve a mystery. He was taking the phenomenological approach because he has no other choice, and he is not happy about it. Wrote Sommerfeld, “The musical beauty of our number table will not hide the fact that it presently represents a number mystery. In fact I do not yet see any way to a model-based explanation either of the doublet-triplet data or of their magnetic influence.”[17]

There is none of the sense of desperation and distress expressed by some others at that time. But it does seem to me that Sommerfeld was already participating in what Kuhn called “a pronounced professional insecurity” about the ultimate success of his program. This became more acute following the work of theorists Landé and Heisenberg during the time they participated as collaborators in the Sommerfeld School.

Landé’s g-Factors

Alfred Landé managed to take Sommerfeld’s number mystery one step further. Very briefly, he associated each multiplet term, j, with a series of Zeeman terms, each characterized by the magnetic quantum number m and an empirical “gyromagnetic” factor g.[18] But his most controversial innovation was the introduction of half-integer values for the magnetic numbers m of the doublet states on purely empirical grounds. Half integers were required in order to achieve an even number of magnetic states for each value of j, as shown below.

Landé, 1921:

$$\begin{aligned} E &= E_0 + mh\nu_L && \text{normal Zeeman effect} \\ E &= E_i + gmh\nu_L && \text{anomalous Zeeman effect} \end{aligned}$$

$$\begin{aligned} g &= 1 && \text{singlets} \\ g &= 2j/(2k-1) && \text{doublets} \end{aligned}$$

$$g = \left\{ \begin{array}{l} 1 + 1/k \\ 1 - 1/(k+1)(k-1) \\ 1 - 1/(k-1) \end{array} \right\} \begin{array}{l} j = k \\ j = k-1 \\ j = k-2 \end{array} \qquad \text{triplets}$$

$$\begin{aligned} m &= 0, \pm 1, \pm 2, \ldots, \pm j && \text{triplets, } 2j+1 \text{ states, odd} \\ m &= \pm\tfrac{1}{2}, \pm\tfrac{3}{2}, \pm\tfrac{5}{2}, \ldots, \pm\left(j - \tfrac{1}{2}\right) && \text{doublets, } 2j \text{ states, even} \end{aligned}$$

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[17] Ibid., 64. The number table contained the so-called Runge fractions for the Zeeman terms.

[18] Alfred Landé, “Über den anomalen Zeemaneffekt (Teil I),” *Zs. f. Physik*, 5 (1921), 231–241. Discussed at length by Forman, “Alfred Landé and the anomalous Zeeman Effect,” *HSPS*, 2 (1970), 153–261.

Sommerfeld was ecstatic: “Bravo, you are able to work miracles!” he wrote Landé. “Your construction of the doublet Zeeman types is very beautiful.”[19] To Einstein he wrote, “Light, or better, dawn really is coming to spectroscopy.”[20]

But Sommerfeld and Landé also acknowledged the lack of a model interpretation of the empirical g-factors along with their continuing hope for a satisfactory model. A model interpretation did soon appear, but it made matters only worse. It showed that the g-factors and all of the empirical number harmonies could be reduced to a model only if the model was so radical as to force an explicit break with the Bohr-Sommerfeld ideal—in particular a violation of space quantization in a field, and the introduction of actual half-integer angular momenta.

The model was Heisenberg’s Rumpf or core model of the atom, submitted in 1921 as his first published paper while still only a 3 semester student.

Heisenberg’s Core Model

Heisenberg’s core model arose directly from Sommerfeld’s latest insight: a derivation of Landé’s g-factors from a “quantum-theoretical reinterpretation” of a classical harmonic oscillator model of the atom proposed earlier by Woldemar Voigt. In December 1921 Sommerfeld submitted a paper titled: “Quantentheoretische *Umdeutung* der Voigtschen Theorie des anomalen Zeemaneffektes vom D-Linientypus.”[21] I believe the title and the approach of this paper had a direct influence on Heisenberg’s *Umdeutung* paper four years later. Heisenberg’s core model paper was submitted 7 days after Sommerfeld’s *Umdeutung* and published immediately following it in *Zeitschrift für Physik.*[22]

In his paper, Sommerfeld had obtained an equation for the energy of a Zeeman term for doublet lines as a function of the external magnetic field. The equation, shown in the slide below, yields Landé’s doublet g-factors for small magnetic field, and it displays the Paschen-Back effect for the continuous transition to the normal Zeeman effect as magnetic field increases. (Today, this equation appears as the off-diagonal matrix elements for the energy operator in quantum mechanics.)

The Sommerfeld-Voigt equation for doublets (1921) reads

$$E = E + h\nu_L \left(m^* \pm \frac{1}{2}\sqrt{1 + (2m^*/k^*)\gamma + \gamma^2} \right) \quad ,$$

where E is the energy of the Zeeman term, E the average of the doublet energies and

$$\gamma = \frac{\Delta\nu}{\nu_L} \propto \frac{1}{H} \quad , \quad k^* = k - \frac{1}{2} \quad , \quad j^* = j - \frac{1}{2}$$

$$m = \pm\frac{1}{2}, \pm\frac{3}{2}, \ldots, \pm - k^* \quad , \quad |m^*| \leq j^* \quad .$$

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[19] Sommerfeld to Landé, 25 Feb. 1921, published in Forman, note 18, p. 249.

[20] Sommerfeld to Einstein, 17 Oct. 1921, published in Einstein and Sommerfeld, Briefwechsel, ed. Armin Hermann (Basel: Schwabe, 1968), p. 94.

[21] Sommerfeld, *Zs. f. Physik*, 8 (1922), 257–272; reprinted in Sommerfeld, note 12, vol. 3, 609–624.

[22] W. Heisenberg, “Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen,” *Zs. f. Physik*, 33 (1925), 879–893; idem, “Zur Quantentheorie der Linienstruktur und der anomalen Zeemaneffekte,” *Zs. f. Physik*, 8 (1922), 273–297.

Heisenberg managed to derive this equation for E from his core model, and to obtain the triplet g-factors as well. The following concerns only the doublet factors.[23]

1. Heisenberg noted that doublet atoms are single-valence, while triplet atoms are double valence. A single valence atom, such as sodium, contains a nobel-gas "core" of filled electron shells, with one valence electron in the outer shell.
2. The basic idea of Heisenberg's model is that the half-integer numbers arise from actual half-integer angular momenta. They are $\frac{1}{2}$ integral because the valence electron for some reason shares $\frac{1}{2}$ unit of angular momentum with the core, leaving the valence electron with $k - \frac{1}{2}$ units of momentum.
3. This reproduces what we now recognize as spin-orbit coupling. The valence electron sets up an internal magnetic field at the site of the core. The doublet term structure arises from the parallel or anti-parallel alignment of the core, resulting in a total angular momentum of j units, where

$$\begin{aligned} j = &\ \left(k - \tfrac{1}{2}\right) + \tfrac{1}{2} = &\ k \quad , \\ j = &\ \left(k - \tfrac{1}{2}\right) - \tfrac{1}{2} = &\ k - 1 \quad . \end{aligned}$$

4. When an external magnetic field is applied, the motion of the valence electron is space quantized, but the core is NOT. It simply aligns itself along the total field vector, changing direction continuously as the external field varies. This results in Sommerfeld's square-root factor with its continuous transition from the anomalous to the normal Zeeman effect.

Despite Landé's repeated objections in letters to Heisenberg at that time, Heisenberg held to these and other violations of quantum and classical principles, mainly because the model worked. When Pauli objected, too, Heisenberg responded with his now famous Machiavellian motto: "Der Erfolg heiligt die Mittel."—"Success sanctifies the means."[24]

The Response

And success it was, but at what a cost! Bohr, expressing his own agenda at that time, rejected the model for its violation of integral quantization of angular momenta. His newly successful building-up principle (*Aufbauprinzip*) of the periodic table required integers. Bohr complained to Landé in May 1922:

"My viewpoint is this: that the entire manner of quantization (half integer quantum numbers etc.) does not appear reconcilable with the basic principles of the quantum theory, especially not in the form in which these principles are used in my work on atomic structure."[25]

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[23] Further discussed in D. Cassidy, "Heisenberg's first core model of the atom: The formation of a professional style," *HSPS*, 10 (1979), 187–224; and Olivier Darrigol, *From c-numbers to q-numbers: The classical analogy in the history of quantum theory* (Berkeley: Univ. California Press, 1992), chapt. 8.

[24] Heisenberg letters to Landé (AHQP Mf 6, 2); Heisenberg to Pauli, 19 Nov. (1921), published in W. Pauli, *Wissenschaftlicher Briefwechsel*, ed. A. Hermann, K. v. Meyenn, V. F. Weisskopf, vol. 1 (Berlin: Springer, 1979), p. 44.

[25] Bohr to Landé, 15 May 1922 (Bohr Scientific Correspondence, Mf 4, 2).

Sommerfeld, on the other hand, once again expressed amazement and delight (and thus approved publication), but he was also perplexed. He wrote to Einstein on 11 January 1922, a now famous statement:

"I have in the meantime uncovered wonderful numerical laws for line combinations in connection with the Paschen measurements and presented them in the third edition of my book. A pupil of mine (Heisenberg, 3rd semester!) has even explained these laws and those of the anomalous Zeeman effect with a model (Z. f. Ph., in press). Everything works out but yet in the deepest sense remains unclear. I can pursue only the technique of the quanta, you must make your philosophy... Set yourself to it!"[26]

This was a remarkable statement for the co-author of the Bohr-Sommerfeld quantum atomic theory. As with the Bohr atom earlier, not only is he fully aware that something is wrong with quantum atomic theory "in the deepest sense," but also he has now given up the search for a model interpretation as too difficult and is pursuing instead the engineering of empirical data. Pauli and Heisenberg began referring to Sommerfeld's approach as one seeking formal connections as opposed to physical clarification.

The Bohr-Festspiel

The unsettled situation in the old quantum theory by 1922 became more unsettled following one of the most important events of the period in quantum theory—Bohr's series of lectures on atomic structure in Göttingen in June 1922, known as the Bohr-Festspiel.

The hostilities of the world war did not cease with the Armistice in 1918. Because many German scientists had openly supported the German cause during the war, French and British scientists attempted a boycott of German science after the war. While Einstein and Curie worked through the League of Nations to end the boycott, Bohr openly defied it by traveling to Germany on several occasions and inviting German scientists to Copenhagen. In 1922 he accepted an invitation to deliver the Wolfskehl Lectures in Göttingen. The Bohr festival became a turning point. It set the standard for success in quantum atomic theory and thereby rendered the failure to achieve that standard all the more obvious and unsettling.

Over a period of ten days in June 1922, Bohr presented seven lectures on "Die Theorie des Atombaus."[27] In these lectures he systematically developed what we now view as the old quantum theory of atomic structure. The audience consisted of nearly every major and minor German quantum theorist. Bohr's systematic approach in his lectures was so impressive that it immediately reenforced at least two research efforts that fall. The first of these, undertaken by Born and Heisenberg in Göttingen, entailed the second problem-area noted earlier: a rigorous and systematic application of celestial mechanics to quantum models of highly excited helium atoms. With the inner electron shielding the $+2$ charge of the nucleus, the outer electron should give the spectral lines and ionization potential of a perturbed hydrogen atom. The goal was to determine if, under rigorous mechanical calculation, the quantum atomic theory did or did not yield the observed

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[26] Sommerfeld to Einstein, 11 Jan. 1922, in Einstein and Sommerfeld, note 20, 96–97.

[27] Bohr, "Sieben Vorträge über die Theorie des Atombaus," 12–22 June 1922 (Bohr Manuscripts, MF 10); published in Bohr, note 8, vol. 4, 341–419.

results. In the end it did not, but I will leave that for another occasion.[28]

The second research program to arise from the Bohr-Festspiel was undertaken by Bohr and Pauli in Copenhagen. Bohr explained it to Landé in March 1923: "It was ... a desperate attempt to remain true to the integer quantum numbers, in which we hoped to see even in the paradoxes a hint for the way in which we might seek the solution of the anomalous Zeeman effect."[29] The attempt also proved to be a complete failure, and they never published the work. Faced with the inconsistent use of half integers by other theorists, Pauli had had enough. He complained to Bohr in February 1924 that physicists in Germany were using integer and half-integer quantum numbers as they pleased, depending on whether or not they could get the result to agree with experiment. "I myself have no taste for this kind of theoretical physics and retire from it to my heat conduction in solid bodies."[30]

In light of both of these failures, Max Born summed up the desperate situation for the public in his now famous statement in celebration of the 10th anniversary of the Bohr atom in a special issue of *Die Naturwissenschaften*, published in Bohr's honor (probably in gratitude for his support of German science) in July 1923: "It is becoming ever more probable that not only new assumptions in the usual sense of physical hypotheses will be necessary, but rather that the entire system of concepts of physics must be rebuilt from the ground out."[31]

Born and Heisenberg began the search for what Born was now calling a new "quantum mechanics."

Conclusion

Even though I have not yet discussed the other two problem-areas to any extent, it is already clear that by mid-1923 the crisis in quantum theory was in full swing. As Seth has suggested, different people and their collaborators reacted to the situation in different ways. While Pauli resigned, Sommerfeld and Landé continued analyzing the data for numerical harmonies, Bohr maintained his consistency, and Born and Heisenberg began the search for a new quantum mechanics. Whatever their response, all appeared to be experiencing, in Kuhn's words, a "pronounced professional insecurity ... generated by the persistent failure of the puzzles of normal science to come out as they should"—in other words, a crisis in quantum theory.

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[28] The failure is discussed in several of the works cited earlier in the text, especially those by Small, Darrigol, and Cassidy.

[29] Bohr to Landé, 3 March 1923 (AHQP Mf 4, 1).

[30] Pauli to Bohr, 21 Feb. 1924; published in Pauli, note 24, 147–148.

[31] M. Born, "Quantentheorie und Störungsrechnung," *Naturwiss.*, 11 (6 July 1923), Heft 27: "Die ersten zehn Jahre der Theorie von Niels Bohr über den Bau der Atome," pp. 537–542, on 542. See also, A. Landé, "Das Versagen der Mechanik in der Quantentheorie," *Naturwiss.*, 11 (24 Aug 1923), 725–726, letter dated 15 July 1923.