Statistical M

B

Quantum Mechanics

Light Quantum
Hypothesis

Photoelectric
Effect

Bohr-Einstein Atom

Wave-Particle Duality

Bose-

Bohr-Einstein Atom

Born-Einstein Statistical

Chance

Nonlocality

Irreversibility

Nonseparab

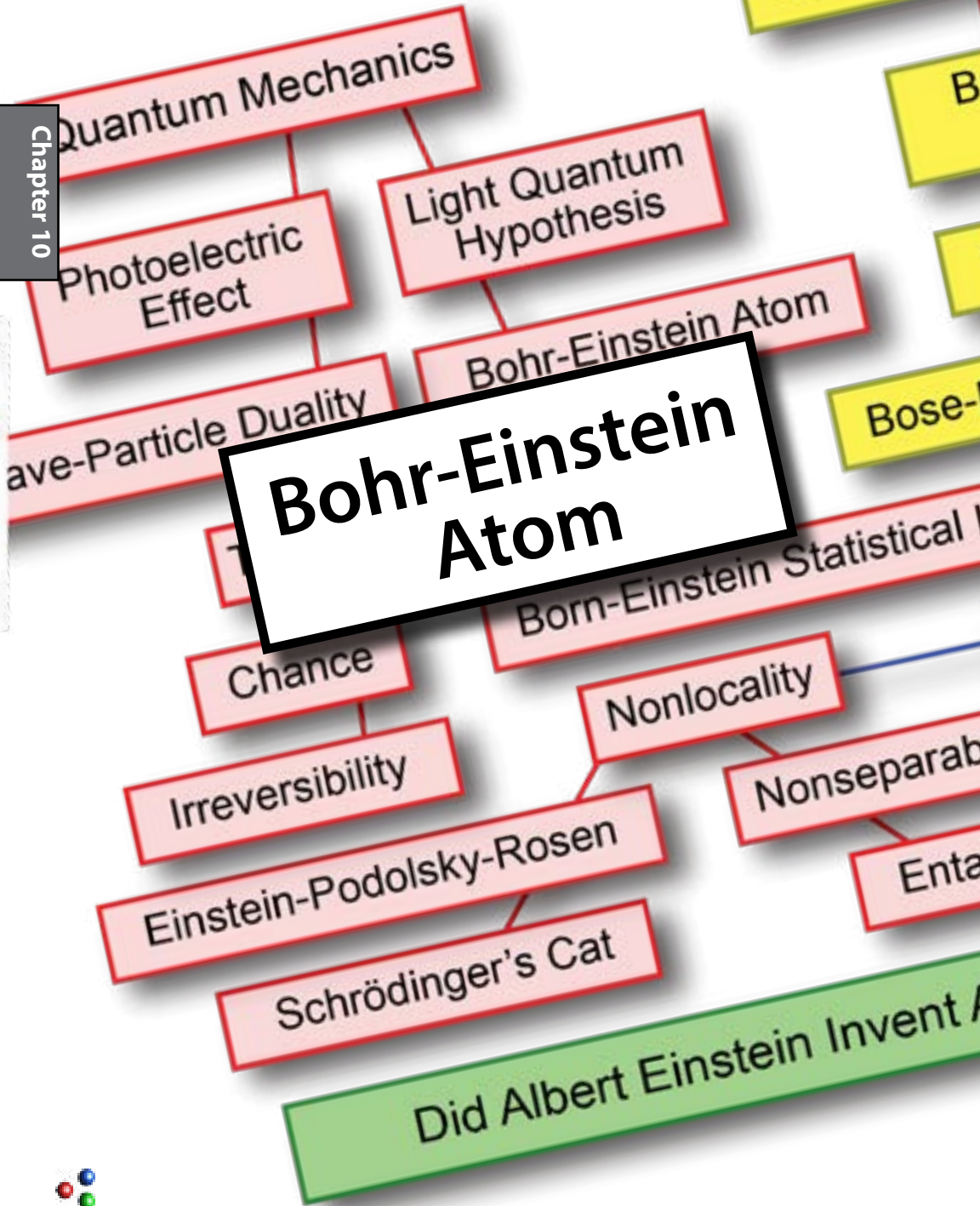Einstein-Podolsky-Rosen

Enta

Schrödinger's Cat

Did Albert Einstein Invent

Bohr-Einstein Atom

Niels Bohr is widely, and correctly, believed to be the third most important contributor to quantum mechanics, after Max Planck and Albert Einstein. Bohr is said to have introduced quantum numbers, quantization of properties, and "quantum jumps" between his postulated energy states in the atom.

But we have seen that Einstein made predictions of such "jumps" between energy levels in solid state matter several years earlier. The "quantum condition" for Bohr was quantization of the angular momentum, following a suggestion of J. W. Nicholson. Angular momentum has the same dimensions as Planck's "quantum of action" h. And we shall see that the integer numbers of quantum mechanics could be seen decades earlier in the empirical formulas for spectral-line frequencies.

Today the "Bohr atom" is described in many textbooks as making quantum jumps between energy levels, with the emission and absorption of *photons*. But this is a serious anachronism, because Bohr denied the existence of Einstein's localized light quanta for well over a decade after his 1913 model of the atom.

For Bohr, as for Planck, radiation was always a *continuous* wave, without which it was thought that one can not possibly explain the interference and diffraction phenomena of light. Planck himself did not accept Einstein's 1905 hypothesis of light quanta, although in 1913 Bohr suggested that "Planck's theory" did so.

> Now the essential point in Planck's theory of radiation is that the energy radiation from an atomic system does not take place in the continuous way assumed in the ordinary electro-dynamics, but that it, on the contrary, takes place in distinctly separated emissions, the amount of energy radiated out from an atomic vibrator of frequency v in a single emission being equal to $\tau h v$, where τ is an entire number, and h is a universal constant. [1]

This mistake is a source of much confusion about Einstein. Bohr did mention Einstein, but not his light quanta. His remarks indicate that Bohr knows about Einstein's work on specific heats, which showed in 1907 that there are energy levels in matter.

---

1   Bohr, 1913, p.4

> The general importance of Planck's theory for the discussion of the behaviour of atomic systems was originally pointed out by Einstein. The considerations of Einstein have been developed and applied on a number of different phenomena, especially by Stark, Nernst, and Sommerfeld.[2]

This theory is not the work of Planck, who denied Einstein's light quantum hypothesis, but of Einstein, in the 1905 paper cited by Bohr as "considerations.". Planck had only quantized the energy of his radiating oscillators. And as we saw in chapter 4, Planck's quantum of action was just a "fortunate guess" at a mathematical formula that fit experimental spectroscopic data for the *continuous spectrum* of electromagnetic radiation in thermal equilibrium.

Bohr had been invited by ERNEST RUTHERFORD to study in England, where Rutherford had shown that the nucleus of an atom is confined to a small central mass of positive charge, suggesting that the electrons might orbit about this center as planets orbit the sun. Rutherford's model conflicted with the fact that accelerated electrons should radiate a *continuous* stream of radiation of increasing frequency, as the electron spirals into the nucleus.

Bohr made two radical hypotheses about orbits, one of which Einstein would *derive* from quantum principles in 1916.

1) Orbits are limited to what Bohr called "stationary states," discrete energy levels in which the electrons do not radiate energy.

2) Electrons can emit or absorb radiation with energy hv only when they "jump" between energy levels where $E_m - E_n = hv$.

It is most odd that Bohr maintained for the next ten years that the energy radiated in a quantum jump is *continuous* radiation, not Einstein's *discrete* and localized quanta. Bohr would only accept Einstein's photons after the failure of the Bohr-Kramers-Slater proposal of 1925, which claimed energy is only statistically conserved in the emission and absorption of continuous radiation. Einstein insisted energy is conserved for individual quantum interactions, and experiments showed he was correct.

Apart from these mistakes in his physics, Bohr's atomic model was a work of genius at the same level as Planck's radiation law. They both are deservedly famous as introducing quantum theory to the world. Strangely, they both began as *fitting* their theory

---

2   *ibid.*, p.5

directly to spectroscopic data, Planck to the *continuous* spectrum of light, Bohr to the *discrete* spectroscopic lines of matter.

Einstein regarded their work as *constructive* theories, based primarily on experimental observations. His idea of the best theories are those based on *principles*, like the constant velocity of light, conservation laws, or Boltzmann's Principle, that entropy is *probability,* a function of the number of available *possibilities*.

Planck had spent the last three decades of the nineteenth century in search of a fundamental *irreversibility* that might establish the second law of thermodynamics as an *absolute* and not a statistical law. He wanted an absolute radiation law independent of matter. Where Planck took years, Bohr spent only several months refining the Rutherford atomic model of lightweight electrons orbiting a heavy central nucleus.

Yet for both Planck and Bohr, it was a matter of only a few weeks between the time they first saw the spectroscopic data and the final development of their expressions that fit the data perfectly. Although the experimental data on the continuous spectrum was accurate to only a few percent, Planck nevertheless was able to calculate the natural physical constants far more accurately than had been done before him. And it was his accurate estimates of the natural constants that made physicists accept his radical ideas.

By contrast, the data on spectroscopic lines was accurate to a few parts in ten thousand, so Bohr could calculate spectral line frequencies in hydrogen to four decimal places, starting with the values of m_e, the mass of the electron*, e*, the electron charge and especially *h,* Planck's new quantum of action, all of which greatly impressed Bohr's colleagues.[3]

But it was *not* Bohr who discovered the highly accurate fit of a simple theoretical expression to the experimental data. That was the work of the Swiss mathematical physicist Johann Balmer, who in the 1880's carefully studied the wavelength measurements by the Swedish inventor of spectroscopy, Anders Ångström.

Ångström had in 1862 discovered three hydrogen lines in the solar spectrum and in 1871 found a fourth, all to several significant figures of accuracy. He named the tiny Ångström unit (10^{-8}cm) after himself as a unit of length. And he measured hydrogen wavelengths to one thousandth of an Ångström!

<div style="text-align: right">Chapter 10</div>

4101.74 Å   4340.47Å   4861.33Å   6562.852 Å

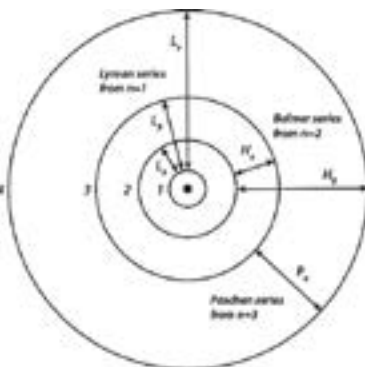Hδ   Hγ   Hβ   Hα

With just these four hydrogen-line wavelengths, and by extraordinary trial and error, Balmer in 1885 found a simple formula that represents all four spectral lines to a high degree of accuracy.

λ (in Å) = 3645.6 n^2 / (n^2 -2^2), where n = 3, 4, 5, and 6.

Note that it would be four decades before these arbitrary integers of Balmer's formula would acquire a physical meaning, becoming the quantum numbers in Bohr's energy levels with E_m - E_n = $h\nu$.

Balmer's colleagues entered n = 7 and 8 into the formula, then looked in the spectrum for lines at those wavelengths and found them! Note that when n = ∞, Balmer's formula predicts the wavelength of the series limit. Shorter wavelengths ionize hydrogen.

In 1886, the Swede JOHANNES RYDBERG generalized Balmer's formula as a reciprocal of the wavelength,

$1/\lambda = R_H$ ($1/m^2$ - $1/n^2$).

This reduces to the Balmer formula for m = 2, but it describes all possible electronic transitions in hydrogen. R_H is the Rydberg constant that Bohr calculated theoretically. Bohr's result amazed physicists as well beyond the accuracy normally achieved in the lab.

Now the reciprocal of wavelength (multiplied by the velocity of light) is a frequency, and Bohr surely saw that multiplying by Planck's constant h would make it an energy. The right hand side of the Balmer formula looks like the difference between two energies that are functions of integer numbers. This was the first appearance

of *quantum numbers.* They point directly to the discrete nature of reality that Einstein saw in Planck's work nearly a decade earlier.

Bohr would also have seen in the Balmer formula the obvious fact that radiation is the consequence of something involving not one state, but the *difference between two states.* Just looking at Rydberg's version of the Balmer formula, Bohr could "read off" both of his hypotheses or what he called his "quantum postulates."

Bohr's writings nowhere say how one can visualize the energy levels as being implicit in what spectroscopists call the "terms" in their diagrams. Bohr seems to create them out of thin air. He says:

1) There are "stationary" states with integer quantum numbers *n* that do not radiate energy.

2) Quantum "jumps" between the states, with $E_m - E_n = h\nu$ yielding the precise energies of the discrete spectral lines. [4]

As with Planck, Bohr's discovery of a perfect fit with an experimental spectroscopic formula now needed a more physically satisfying interpretation. What can explain the integer numbers and implicit discreteness of Balmer's formula? Bohr set out to find a *derivation*. Otherwise it would appear to be another case of a "lucky guess" like that Planck had called his "fortunate interpolation."

What needs to be derived from fundamental principles is the *origin* of the *discreteness*, the so-called "quantum condition." As we saw in chapter 3, chemists had thought since the early nineteenth century that the chemical elements come in discrete units, though the "atoms" remained controversial for many physicists.

Ludwig Boltzmann's statistical mechanics (chapter 5) showed that atoms can explain the second law of thermodynamics. And Einstein extended his statistical mechanics to explain Brownian motions, proving that the atoms are real. It was therefore Einstein who established the fact that matter comes in discrete particles, just a year before Boltzmann's death. And it was also Einstein who hypothesized that energy comes in discrete particles the same year.
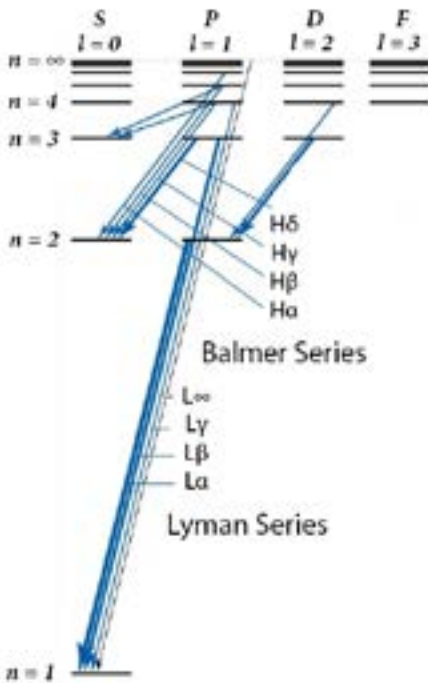
Now we must give some credit to James Clerk Maxwell, the author of electromagnetic theory and its continuous waves, for

---

4   As we saw in chapter 8, Einstein had pointed out that Planck's theories implied "jumps" between energy levels as early as 1907 in his work on specific heats.

seeing the *stability* of the atoms that underlies Bohr's notion of "stationary." Maxwell's famous equations require that an electron going around in a circular orbit should be generating electromagnetic waves at the orbital frequency. The energy radiating away from the atom should cause the electron to lose energy and spiral into the nucleus. Maxwell knew that did not happen. He marvelled that the microscopic atoms do not wear out, like macroscopic matter. They seem to be indestructible.

And the spectral lines of the hydrogen atom are *discrete* frequencies, not the continuously varying values of Maxwell's theory.

To "quantize" energy levels, Bohr used the original suggestion of J. W. Nicholson that the angular momentum of the electron in its orbit is an integer multiple of Planck's constant divided by 2π. Quantization of angular momentum is key to the future development of quantum theory. We shall see that this is the heart of the discreteness seen by Louis de Broglie, Werner Heisenberg, and Erwin Schrödinger, though all three for different reasons!

Atomic Spectra and Atomic Structure

Bohr's atomic model explains how spectroscopy can be transformed from a vast catalogue of thousands of measurements of spectral line wavelengths into a visual image of the stationary states that are the starting and ending points for quantum jumps.

The "term diagrams" of spectroscopists that reduce a huge number of spectral lines to the differences between a much smaller number of "terms," show plainly that the "terms" correspond to

Bohr's energy levels and his stationary states, from which we can "read off" the Bohr model.

Although it does not yield precise calculations for atoms with more than a single electron, Bohr's model gave us a theory of atomic structure that predicts electronic transitions between higher orbits with principal quantum number n out to infinity. Later an angular momentum number l between 0 and $n-1$, a magnetic quantum number m between l and $-l$, and ultimately an electronic spin, s = ±½ added greatly to understanding the digital and discrete nature of quantum reality.

Bohr's picture led to a complete theory of the periodic table. He explained isotopes as atoms with the same atomic number (number of protons), but different atomic weights (numbers of neutrons). He convinced Rutherford that radioactivity comes from changes in the nucleus and not electrons, that α-particles reduce the atomic number by 2 and the emission of β-particles (electrons) increases it by 1.

Chance in Atomic Processes

When Rutherford received the draft version of Bohr's theory, he asked Bohr the deep question about *causality* that would be answered just a few years later by Einstein,[5]

> There appears to me one grave difficulty in your hypothesis, which I have no doubt you fully realize, how does an electron decide which frequency it is going to vibrate at when it passes from one stationary state to the other? It seems to me that the electron knows beforehand where it is going to stop?[6]

We don't have Bohr's reply, but it might have been the answer he would give years later when asked what is going on in the microscopic world of quantum reality, "We don't know" or "Don't ask!" Or perhaps he would offer his positivist and analytic language philosophy answer - "That's a meaningless question."

But we are getting ahead of the story. We must ask why the young Bohr did not connect his work more clearly in 1913 to that of Einstein, and why he gave so much credit to Planck that clearly

5   See the next chapter.
6   Bohr, *Collected Works*, vol.2, p. 583.

belongs to Einstein. This was the beginning of decades of sidelining Einstein's contributions to quantum mechanics.

Bohr especially ignores Einstein's hopes to see what is going on at the microscopic quantum level, something Einstein called "objective reality," while Bohr maintained "There is no quantum world."

An Independent Criticism of Bohr on Einstein

As I was finishing editing this book and returning the ten volumes of Bohr's *Collected Works* to Widener library, a tiny slip of paper fell out. On it were notes by some unknown person who appears to have detected an effort by the editors of the *Collected Works* to minimize Bohr's references to Einstein's extraordinary original work on the light quantum hypothesis and on specific heat, at least in the English translations.

This unknown critic noticed that a very significant paragraph in Bohr's original Danish had not been translated in the English version, effectively hiding it from all but native Danish speakers.

It does not mention Einstein by name but does reference specific heat and radiation at high frequencies, where the particle nature of light became clear to Einstein

We quote this short note in its entirety, including the critic's rough translation.

Bohr on "non-mechanical forces"…

Den omtalte Antagelse er ikke paa Forhaand selvfølgelig, idet man maa antage, at der i Naturen ogsaa findes Kræfter af ganske anden Art end de almindelige mekaniske Kræfter; medens man nemlig paa den ene Side har opnaaet overordentlig store Resultater i den kinetiske Lufttheori ved at antage, at Kræfterne mellem de enkelte Molekyler er af almindelig mekanisk Art, er der paa den anden Side mange af Legemernes Egenskaber, det ikke er muligt at forklare, dersom man antager, at de Kræfter, der virker indenfor de enkelte Molekyler (der efter den almindelig antagne Opfattelse bestaar af Systemer, i hvilke indgaar et stort Antal »bundne« Elektroner), er af en saadan Art. Foruden for-skellige almindelig kendte Eksempler herpaa, f. Eks. Beregningen af Legemernes Varmefylde og Beregningen af Varmestraaling-sloven for korte Svingningstider, skal vi i det følgende ogsaa se et

yderligere Eksempel herpaa, nemlig ved Omtalen af Legemernes magnetiske Forhold.

In this important paragraph Bohr cites Einstein's work on specific heat and high frequency radiation. Specific heat (Einstein 1907) is regarded as first establishing the quantum nature of matter. At high frequencies, the particle nature of light becomes apparent (Einstein 1905) For no apparent reason this paragraph is eliminated in the English translation of Bohr's thesis (presumably by Leon Rosenfeld, the collected works editor, or J. Rud Nielsen, the editor of volume 1.)

Bohr clearly knows that Einstein has established quantum properties that he will exploit in his landmark atomic models with only vague references to Planck's merely heuristic quantum and less often, the real quantum of Einstein.

Here is a very rough translation...

The aforementioned assumption is not obvious, of course, assuming that in nature there are also forces of a very different nature than mechanical forces; While, on the one hand, one has achieved very great results in the kinetic theory of gases by assuming that the forces between the individual molecules are of a common mechanical nature, there are on the other hand many properties of bodies it is not possible to explain by assuming that the forces that work within the individual molecules (which, according to the generally accepted perception, consist of systems in which a large number of "bound" electrons belong), are of such a kind. In addition to various common known examples herein, e.g., the calculation of the specific heat capacity and the calculation of thermal radiation for high frequencies, we will also see a further example, namely the mention of the magnetic properties of the bodies.

We will see in later chapters that Leon Rosenfeld was a fierce defender of the Copenhagen Interpretation of quantum mechanics, especially its most extreme idea that particles lack any properties when they are not being observed in a physical experiment.

Despite the fact that Einstein was first to prove that matter is discrete particles (atoms) and that light consists of discrete quanta (now *photons*), Bohr and his colleagues worked hard to establish Copenhagen as the originators of the atomic theory.