The Fall of Classicality

The introduction of the fundamental quantum of action by Planck in 1900 was the beginning of the end for determinism, although it took several decades for this to be generally accepted by the scientific community. More and more anomalies were discovered which challenged mechanistic explanations: blackbody radiation, radioactivity, X-rays, and specific heats of solids and gases.

The era of quantum theory commenced on December 14, 1900, when, at a meeting of the German Physical Society in Berlin, Max Planck presented his derivation of the blackbody radiation formula, using a statistical mechanical method that had the unprecedented feature that energy exchange between radiation and radiating body was discontinuous with quanta of energy transfer given by $E = h\nu$, which is:

$$\mathrm{B}(\nu, T) = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1}. \tag{5.3}$$

Here k is the Boltzmann constant that gives a measure of the amount of energy (i.e., heat) corresponding to the random thermal motions of a particle, c is the speed of light, and h is a new constant, now called Planck's constant or Planck's *quantum of action*. Equation (5.3) describes the density of radiant energy at frequency ν given off in thermal equilibrium at temperature T by a *blackbody*, an ideal perfect absorber. This exact expression represents the maximal radiation that a body can emit at thermal equilibrium, whatever the composition or structure and it is governed by the quantum of action.

As has always been known, a heated body glows. The corresponding problem of the heat radiation formula is to understand the dependence of the emitted light on the frequency and temperature, as well as the nature and shape of the body. By the 1860s, it had become accepted from the work of Michael Faraday (1791-1867) and James Clerk Maxwell (1831-1879) that light was electromagnetic radiation and thermal radiation represents a conversion of thermal energy into electromagnetic energy, including visible light. The radiation law should then be understood in terms of the thermodynamics of electromagnetic processes. Quantum theory was thus born at the crossroads of the two sciences of Thermodynamics and Electromagnetism.

In 1859, Gustav Kirchhoff (1824-1887) discovered that for a body in thermal equilibrium with radiation, the ratio of the emission and absorption is independent of the particulars of the body, depending only on frequency and temperature. This is due to the Second Law of Thermodynamics and violation would imply the impossibility of a perpetual mobile of the second kind, i.e., the impossibility of spontaneous conversion of thermal energy into mechanical work. Kirchhoff proposed studying this fundamental result by way of perfect absorbers called *blackbodies*, which can be approximated in the laboratory by an oven with a small hole. It took 40 years of efforts by many physicists to measure the explicit spectrum for blackbody radiation, but by the 1890s, experimental measurements of the spectral distribution had improved rapidly, stimulated by the need for improved temperature measurements and the absolute temperature scale.

As seen in Figure 5.9, at any temperature T there is a preferred frequency ν of emitted light and higher frequency emission is suppressed. In contrast to this, the radiation formula based on classical theory by Lord Rayleigh (1842-1919) and James Jeans (1877-1946) predicted a divergence as ν^3 at high frequencies (later dubbed the *ultraviolet catastrophe*). This is due to the classical equipartition theorem, which predicts that all degrees of freedom will have an average energy of $kT/2$ and therefore most of the energy will be at higher frequencies where most of the modes are. This is contrary to the observations, which are consistent with Planck's expression in Figure 5.9. This means there must be a mechanism preventing energy from going into the high frequency modes and it must be governed by a physical constant with dimensions mixing energy and time so as to relate temperature to frequency. This is precisely the role of Planck's constant h which has the dimensions of energy-time or *action*:

$$h = 6.626 \ x \ 10^{-34} \text{ Joule-second.} \tag{5.4}$$

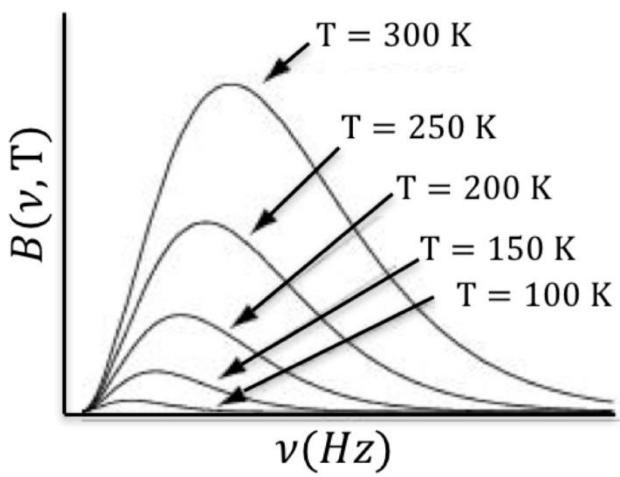

Figure 5.9: Planck's Blackbody Radiation Law.

A reduced Planck's constant $\hbar \equiv h/2\pi$ (pronounced "h-bar") is also often used in expressions to eliminate the frequent appearance of factors of π. Planck also used the newly expanded set of fundamental constants k, c, G and h to propose a now-famous system of natural units, saying they [360]

See the print edition of The Quantum Measurement Problem for quotation.

Today these units have found their way into the area of quantum gravity where the *Planck length* $l_p = \sqrt{\hbar G/c^3}$, *Planck time* $t_p = \sqrt{\hbar G/c^5}$, and *Planck mass* $m_p = \sqrt{\hbar c/G}$ naturally play a role.

There were controversies over the explanation of irreversibility and the second law of thermodynamics between reversible classical mechanics and Boltzmann's statistical-mechanical theory. Although the statistical nature of radioactive decay of atoms was recognized since its discovery, there were attempts for over a decade to explain it from a deterministic and mechanical basis [361] [362]. And for some, Bohr's model of the atom still did not fully rule out the possibility of an underlying causal explanation of radioactivity. That radioactivity was truly nondeterministic was largely accepted only with the more general nondeterminism of quantum mechanics after 1925. The first quantum mechanical explanation of α-particle radioactivity and derivation of the decay law didn't appear until 1928 [363] [364], with a decisive difference in interpretation as concluded by Condon and Gurney:

> *We have had to consider the disintegration as due to the extraordinary conjunction of scores of independent events in the orbital motions of nuclear particles. Now, however, we throw the whole responsibility on to the laws of quantum mechanics, recognizing that the behavior of particles everywhere is equally governed by probability.*

This had followed the 1926 assertion by Max Born (1882-1970) that, although the quantum state evolves deterministically, an individual measurement occurs irreducibly at random and is nondeterministic. Not only was the cause of the measurement event not known, cause did not play a role. Einstein had written the oft-quoted letter to Born of December 4 from that year, objecting that God "is not playing at dice" [365, pp. 90-91]:

> *I, at any rate, am convinced He is not playing at dice*.

Einstein had previously introduced probabilities into quantum dynamics in three papers of 1916-17 [366] [367] [368] on the emission and absorption of the radiation of atoms. In doing so, he had found an alternate way of obtaining Planck's blackbody radiation law and this was also related to the quantum jumps of Bohr's atomic model. Einstein postulated the existence of transition probabilities for spontaneous and induced emission and absorption between the discrete energy levels of an atomic system. He mentioned that his scheme for spontaneous emission was essentially identical to Rutherford's 1900 description of radioactive decay [9, p. 191]. However, he was disturbed about the causality of the model in that he could not predict the direction in which a light-quantum moves after spontaneous emission, saying: "The weakness of the theory lies on the one hand in the fact this it does not get us any closer to making the connection with the wave theory; on the other, that it leaves the duration and direction of the elementary processes to chance" [369]. Rutherford's decay was within his planetary picture of the atom with electrons orbiting a massive nucleus. As discussed in the section *Deductive Thought versus Inductive Thought,* in order for Bohr to deductively construct the first theory of atoms and molecules in 1913 that addressed their structure in terms of the configurations of electrons, he was led to incorporate Planck's quantum of action. Rutherford had responded to Bohr [370]:

> *See the print edition of The Quantum Measurement Problem for quotation.*

Rutherford's instincts led him to notice these symptoms of nondeterminism, describing the "grave difficulty" in this case almost as an act of free will, an aspect of the model that Bohr would eventually answer with his correspondence principle.

Max Planck, the discoverer of the quantum, never completely came to terms with it and retreated into the 'God's-Eye-View' of his religious beliefs. On the eve of his death, Bohr commented during a final interview, Figure 5.10 [371]:

> *Planck was religious…he said that a God-like eye could certainly know what was the energy and the momentum. And that was very difficult you see. And then I said to him when we came back from it… You have spoken about such an eye: but it is not a question of what an eye can see, it is a question of what you mean by knowing.*
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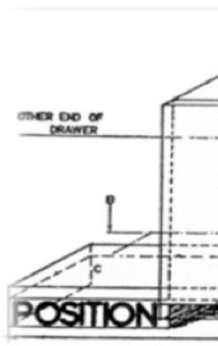
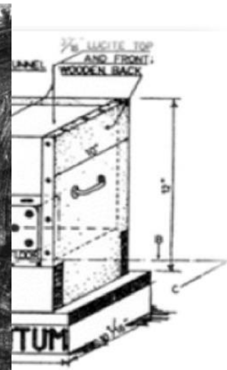

Figure 5.11 Problemat … nilar to the 1939
New York World Fair … wo dice
representing complem … e die faces.
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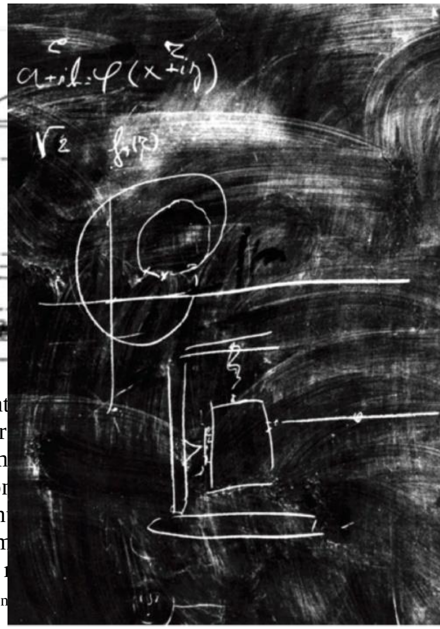

Figure 5.10: Bohr's Last Blackboard, from the eve before his death, illustrating (top) a complex function as an analogy to free will and (bottom) Einstein's photon box which Bohr had shown was consistent with quantum mechanics.
Used by permission of the AIP Emilio Segrè Visual Archives.

Planck's God-like-eye is not unlike Laplace's Demon. Bohr actually had ctoriticized Heisenberg's initial argument of the gamma-ray microscope thought-experiment for the uncertainty principle along similar lines [372, p. 88]. Bohr objected that Heisenberg began by assuming that the electron actually has a definite position and momentum but that the act of observing one of these disturbs the other. Heisenberg had assumed a fixed underlying existence, essentially permitting a "God's-Eye-View" [373], Figure 5.11. A famous "Addition in Proof" in Heisenberg's 1927 indeterminacy paper acknowledges that Bohr, "has brought to my attention that I have overlooked essential points". For Bohr, what we can know determines the conceptual framework of our description and, in particular, our observations are under conditions in which we are also part of the world. Bohr later summarized his view of Laplace's Demon [372, p. 89]:

See the print edition of The Quantum Measurement Problem for quotation.

Nondeterminism had been argued by Heisenberg in 1927 to follow from the uncertainty relations, preventing some observables from having definite values with outcomes being indeterminate before a measurement. The generalized versions of Heisenberg's uncertainty relation [374] [375] specify how precisely non-commuting observables X and Y can be measured in a quantum state in terms of the variances ΔX^2 and ΔY^2:

$$\Delta X^2 \Delta Y^2 \geq \frac{1}{4} |\mathrm{Tr}\rho[X, Y]|^2 \,,$$

where $\Delta X^2 = \mathrm{Tr}\rho X^2 - (\mathrm{Tr}\rho \mathrm{X})^2$ is the variance. Non-vanishing ΔX can represent a randomness due to measurement from non-commuting operators or can also be due to classical noise as well. Although either ΔX and ΔY are allowed to vanish, they cannot vanish simultaneously for a given state ρ unless they commute, $[X, Y] = 0$. It is not straightforward to determine ΔY in the case that ΔX vanishes but more recent developments of uncertainty relations in the form of sums in terms of entropy and variances have been able to address these issues [376]. The entropic approach has generalized the uncertainty paradigm to allow further understanding of joint measurability of non-commuting observables, quantum steering and situations where the measured system is entangled with its environment [377] [378]. The full story of randomness in quantum mechanics can be seen only in the presence of nonlocal quantum correlations. We will see that the local uncertainty of Heisenberg has since become subsumed by the global nondeterminism of Bell.