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A brief history of quantum phenomena

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The development of quantum theory is summarized, highlighting the contributions of Planck, Einstein, Schrödinger and Heisenberg.

In order to address some of the fundamental questions, and paradoxes, of quantum phenomena a brief historical view of the development of quantum mechanics should be considered since, in the words of Schrödinger (1956),

History is the most fundamental of all sciences, for there is no human knowledge that does not lose its scientific character when men forget the conditions in which it originated, the questions it answered and the functions it was created to serve.

More recently this notion has been represented in journals outside the 'mainstream' of physics, for example Brush (1980), Cushing (1998) and Stuewer (1997). The last of these offers:

It comes as no surprise, therefore, that physicists have been vocal and staunch proponents of the idea of introducing history of physics into physics courses. Some have furthered their conviction by writing textbooks from a historical point of view. Others have helped organize conferences on the role of history in physics teaching.

There is, however, a conflict between the historian's point of view and the physicist's point of view. For the physicist the goal is to gain deeper understanding of the universe by reducing the number of physical laws, i.e. by a series of

unifications. The *Holy Grail* of the physicist becomes *simplicity*.

It is, I think, characteristic of the physicist to want to get at the very essence of a phenomenon, to strip away all the complicating features and see as clearly and directly as he can just what is really involved. That is why we prize simple conceptual models so highly. . . .

(Klein 1972)

By contrast the historian would look for the *illogical* and *complex*. Helmholtz (1892) used the analogy of a mountain climber:

I must compare myself to a mountain climber, who without knowing the way climbs up slowly and laboriously, must often turn around because he can go no further, discovers new trails, sometimes through reflection, sometimes through accident, which again lead him forward a little, and finally, if he reaches his goal, finds to his shame a Royal Road on which he could have travelled up, if he would have clever enough to find the right beginning.

This article aims to provide *a history* of quantum phenomena which underlines the philosophical nature of the material.

In the beginning

The starting point of quantum theory will be taken as 1900 and Planck's postulate of the

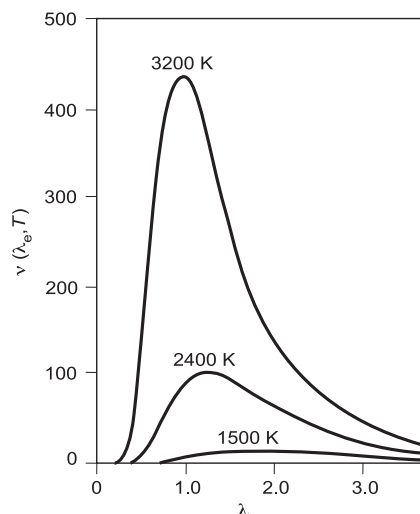


Figure 1. Blackbody radiation curves for the energy density ρ adapted from Cushing (1998).

quantization of energy in blackbody radiation[†]. It had been known for some time that the spectrum of thermal radiation contained in a cavity in thermal equilibrium must be a universal function of the temperature, completely independent of the material of the walls of the cavity. Detailed experimental work by Lummer and Pringsheim (1899) and Rubens and Kurlbaum (1900) had determined the shape of the spectrum; see figure 1.

Planck was able to present an argument that consisted of essentially phenomenological curve fitting, relying on classical ideas of entropy at long wavelengths and an *ad hoc* conjecture due to Wien (1896) for short wavelengths, but which generated a formula that fitted the data perfectly for all wavelengths. However, he was unable to offer any theoretical justification for the results. Planck himself said of the situation:

But even if the absolutely precise validity of the radiation formula is taken for granted, so long as it merely has the standing of a law disclosed by a lucky intuition, it could not be expected to possess more than a formal significance. For this reason, on the very day when I formulated this law, I began to devote myself to the task of investing

[†] In reality, as will become apparent, Planck quantized the energy of the oscillators *in* the radiating body rather than the radiation *from* the body.

it with true physical meaning. This quest automatically led me to study the interrelation of entropy and probability. ... After a few weeks of the most strenuous work of my life, the darkness lifted and an unexpected vista began to appear.

quoted in Klein (1972)

This 'vista' regarded the walls of the cavity as harmonic oscillators which could absorb and emit energy only in discrete amounts, E , which is related to the frequency, f , of the absorbed or emitted radiation by

$$E = hf$$

where h is Planck's constant. Although Planck quantized the oscillators in the wall of the cavity he did not quantize the electromagnetic radiation itself. However, this must be seen against the background of Maxwell's equations of electrodynamics, the success of which was based on an electromagnetic field that could carry energy of any continuously varying amount. Qualitatively, it can be seen how Planck's energy formula was able to explain the shape of the spectrum for blackbody radiation:

Using the equation of a wave, $c = f\lambda$,

$$E = hf \text{ becomes } E = hc/\lambda.$$

Therefore for any given finite amount of energy in the cavity there is some shortest wavelength which can be excited. Thus for a given temperature, T , each curve in figure 1 peaks at a most probable value.

And then came Albert

In 1905, during his *Annus Mirabilis*, Einstein took the notion of quantization further by suggesting that electromagnetic radiation exists in the form of 'packets' of energy which we now call photons. With this new way of thinking Einstein was able to treat the radiation from the blackbody as a 'gas' of photons, and by application of statistical mechanics, as used in thermodynamics, supply an alternative derivation of Planck's formula. Further application of the photon model supplied Einstein with the means to solve the classically inexplicable photoelectric effect. Classical electromagnetic

theory predicted that the energy available in light is proportional to the *intensity* and independent of *frequency*, but experimental evidence pointed to the opposite result. Einstein argued that if light, or any electromagnetic radiation, consists of a stream of photons of energy hf , then the maximum energy that an electron can absorb in a collision with a photon must also be hf . Considering that some energy is required to liberate the electron from the metal surface, now called the work function, ϕ , Einstein postulated that the maximum kinetic energy of the liberated electron must be given by

$$KE_{\max} = hf - \phi.$$

This result was verified by Robert Millikan and led to the Nobel Prize for Einstein.

In 1913, Bohr extended the notion of quantization of energy to the hydrogen atom. Rutherford's work on the scattering of alpha particles by atoms led to the concept of an atom as a small, very hard nucleus around which orbit electrons. In considering the line spectrum of hydrogen Bohr accepted Rutherford's nuclear atom to be as shown in figure 2; for further historical details see Heilbron and Kuhn (1969).

The condition for a stable orbit was considered to be that the electrostatic attraction between the electron and the nucleus provides the required centripetal force. However, this model could not be supported by classical theory since the accelerating electron should radiate energy and hence spiral into the nucleus. In order to obtain a discrete set of stable orbits Bohr postulated[†], without any explanation, that electrons are confined to certain stationary states, with circular orbits, and that they emit radiation only when they make transitions from one stationary state to another. The possible stationary states have quantized values of orbital angular momentum, L , such that

$$L = nh/2\pi$$

where n is an integer. The notion of transition from one stationary state to another considers that the atom emits a single photon of an energy equal

[†] The presentation here is based on Bohr's original line of argument (Bohr 1913) and may differ from that given in a 'standard' text, but the multiplying factor of $\frac{1}{2}$ appears to have been, as in Planck's case, rather *ad hoc*, and the fact that the Balmer series could be derived by using $\frac{1}{2}$ prompted Bohr to argue the $\frac{1}{2}$ is arrived at as the mean value of 0 and f .

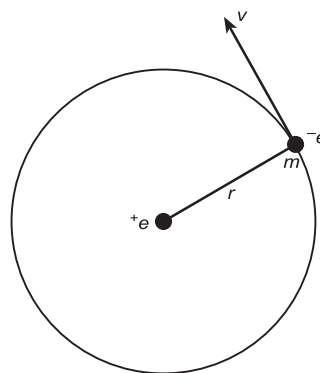


Figure 2. Bohr's model of the atom adapted from Cushing (1998).

to the difference between orbit energies. For example, the transition between the first excited state E_2 and the ground state E_1 would emit a photon of energy hf such that

$$hf = E_2 - E_1.$$

In accordance with Planck's quantization of energy emitted or absorbed by a harmonic oscillator in multiples of hf , Bohr considered an electron infinitely far away from the nucleus falling into an allowed orbit and quantized the energy, hf , of the photon in terms of the energy of the electron in its final orbit as

$$-E = \frac{1}{2}nhf$$

where n is a positive integer.

In developing his theory Bohr considered only circular orbits. Sommerfeld and Wilson both, independently, extended Bohr's quantization rules for the angular momentum to elliptical orbits with periodic motion. This led to the Sommerfeld-Wilson quantization rule:

$$\int \rho \delta q = \frac{nh}{2\pi}$$

where q is the canonical coordinate and ρ the momentum.

In order to maintain the notion of transition from one stationary state to another Bohr was forced to regard the transition as 'instantaneous'. It is now common to refer to such instantaneous transitions as 'quantum jumps' or 'quantum leaps'. Einstein demonstrated that quantum theory could not predict the timing of such a jump and neither

could it predict the direction of the emitted photon of electromagnetic radiation. Quantum theory could, and still can, predict only the probability of such a jump taking place. This led to the often misquoted comment from Einstein's letter to Max Born, 'You believe in a God who plays dice and I in complete law and order', quoted in Stewart (1989).

In Newtonian mechanics understanding the universe was based on stability rather than probability. Einstein's struggle with the probabilistic nature of quantum theory appears to be based on the notion that it violates what is regarded as being 'normal'.

Wave mechanics

The early studies in quantum mechanics relied on Newtonian ideas and sought to supplement Newton's laws with quantization conditions. This allowed for the selection of the preferred stationary states in the Bohr model of the atom.

Roughly, we can say that the old quantum theory accepted Newtonian kinematics, but sought to modify Newtonian dynamics with supplementary conditions. In the 1920s, physicists finally recognised that this attempt to graft quantum structure on the Newtonian roots was unworkable, and they recognised that both Newtonian kinematics and dynamics had to be discarded.

(Ohanian 1990)

The first move away from the Newtonian influence was de Broglie's notion that 'particles' have 'wave' properties. de Broglie postulated that the frequency of the wave associated with a particle is related to the energy of that particle by the same equation as for the energy of a photon:

$$E = hf.$$

By building on the relativistic connection between energy and momentum *and* frequency and wavelength de Broglie was able to postulate that the wavelength of the wave associated with the particle was related to the momentum of the particle such that

$$\lambda = h/p.$$

From this de Broglie proposed the wavefunction[†]:

$$\psi = \sin[2\pi(ft - x/\lambda)] = \sin[(2\pi/h)(Et - \rho x)].$$

The widely accepted confirmation of particle diffraction was due to the experimental work of Davisson and Germer (1927), using crystals to scatter electrons, and Thomson, using thin metallic films. The results of these experiments not only established the wave properties of the electron but also that 'particle waves' obeyed the principle of superposition.

Whilst this work was in progress Schrödinger formulated what is now commonly called the Schrödinger wave equation:

$$\frac{\delta^2}{\delta x^2} \psi(x, t) + \frac{2m(E - V(x))}{h^2} \psi(x, t) = 0.$$

Application of the three-dimensional version of this equation to the hydrogen atom generated the quantization of both angular momentum and energy. Schrödinger initially interpreted these results as the wavefunction representing the distribution of electric charge in space. However, this would have allowed for the possibility of an electron being cut in two by an obstacle. The wavefunction idea was, in some ways, rescued by Born, who proposed that the absolute magnitude of the wavefunction, $|\psi|^2$, represented the probability distribution for the position of the electron.

The wave properties of particles and the description of particles by probability waves implied a profound revision of the foundations of physics. Instead of specifying the state of a particle by position as a function of time, we now have to describe the state by a wave function and we can never predict exactly where the particle will move as a function of time—we can predict only probabilities for motion from one position to another.

(Ohanian 1990)

It is this formulation of the 'new' quantum mechanics which was to become the most popular amongst physicists. However, even before the Schrödinger wave equation had been published an alternative formulation was developed by Heisenberg.

[†] Here it must be stated that ψ —the wavefunction—has a purely abstract significance: 'an electromagnetic field carries the power to move objects, whereas ψ carries nothing more tangible than information' (Cassells 1982).

Matrix mechanics

Heisenberg took the view that classical quantities such as position and momentum had no meaning in quantum mechanics since they could not be measured. He replaced all such classical quantities with ones directly related to the quantum mechanical stationary states. Born and Jordan were able to see that Heisenberg's formulation was nothing but matrix multiplication and hence this formulation became known as 'matrix mechanics'. Both approaches generated the same results and soon Schrödinger was able to generate a mathematical proof that any formula constructed in wave mechanics could be translated into matrix mechanics and vice versa.

Where are we now?

It could be argued that the *mathematical formalism* of quantum mechanics is no longer the problem. The problem is now one of interpretation. It

Box 1. Alternative interpretations of quantum physics.

Many Worlds Interpretation: Proposed by Hugh Everett III in his PhD thesis, the act of making a measurement splits the whole universe into a number of *branches* with a different result in each. See Everett (1957).

Hidden Variable Interpretations: The wavefunction in quantum physics provides us with probabilities—initial knowledge of a wavefunction provides a probabilistic statement of the outcome of measurements. The aim of hidden variable theories is to remove the probabilistic or random outcomes. This is approached by giving *apparently identical* initial states new or *hidden variables* which in reality distinguish them.

Pilot Wave Interpretation: This is an example of a hidden variable theory. de Broglie, circa 1926, proposed that rather than an entity being interpreted as a particle or a wave depending on the experiment being carried out, reality is composed of particles and waves. *Particles* move in *Wave Fields* and it is these fields which guide the particles—the probability of *finding* a particle is greatest in a region of space where the field wave amplitude is greatest.

is outside the scope of a brief article such as this to discuss details, but many interpretations, for example many worlds, hidden variable and pilot wave, exist (see box 1) but *the jury is still out*. Perhaps the next development will come from experimental physics; could an experiment be carried out that produces results that quantum theory cannot predict?

If something could be shown to be wrong with the experimental predictions of orthodox quantum theory then we would, at last, perhaps have a real clue to understanding it.

(Squires 1994)

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Suggested bibliography

Quantum theory is not always (or at all) accessible to the reader, student or teacher new to it. However, I have found the following to be both well written and technically accessible for a good A-level or undergraduate student.

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