A Brief History of Quantum Mechanics

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11/24/2017
Based on his study of optics and on the tendency of light to travel in straight line rays, Isaac Newton described light as particles, while the Dutch physicist Christiaan Huygens and others argued that a wave theory better explained refraction of light as it passes from one medium to another. Newton’s theory was dominant until 1804 when Thomas Young described his double-slit experiment in which constructive and destructive interference of a pair of circular waves produces a checkerboard pattern of high and low intensity. Young accurately calculated the wavelength range of visible light. The wave theory gained wider acceptance with experiments demonstrating diffraction. In 1865 James Clerk Maxwell showed that light is an electromagnetic wave.
A blackbody is an idealized object that perfectly absorbs light. However, thermal vibrations of the atoms in the walls cause a blackbody to emit electromagnetic radiation (mostly infrared at normal temperatures). Thus, in a cavity, radiation is absorbed and re-emitted until equilibrium is reached. According to statistical mechanics, the total amount of energy in the cavity, computed by summing over an infinite number of modes, is infinite.

In 1900, in order to explain the finite energy associated with blackbody radiation, Max Planck postulated that the energy in the electromagnetic field at frequency $\omega$ should be quantized as an integer multiple of $\hbar \omega$ (for $\hbar = 1.055 \times 10^{-34}$ J-s in SI or MKS units). Planck thought of the energy quantization as arising from properties of the walls of a black body. Einstein argued that the quantization was inherent in the radiation. Thus began a rebirth of the particle theory of light.
In 1887 Heinrich Hertz noticed that light was capable of ejecting electrons from metal surfaces. In 1901 it was discovered that electrons are only ejected if the light frequency is high enough, and the result is independent of the light intensity. Contrary to the wave theory, increasing the light intensity, and hence the strength of the electric and magnetic fields, increases the number of electrons emitted but not the energy of each electron. In 1905 Einstein published a paper describing the photoelectric effect in terms of light quanta. He predicted that the maximal kinetic energy of the ejected electrons is $\hbar \nu - W > 0$, where $W$ is the energy barrier that confines electrons to the metal. This was confirmed experimentally. His theory also explained why photoelectrons appeared instantaneously even with low intensity. He won the Nobel prize for this work in 1921. The existence of photons was decisively proved by beam splitting experiments in 1986.
Properties of the photon

Photons have the following properties.

Energy \( E = h\nu = \hbar\omega \)

Momentum \( p = E/c = h\nu/c = \hbar k \)

Rest mass 0 (a nonzero rest mass would imply infinite energy)

Charge 0

Size 0

Spin 1 (in units of \( \hbar \))

Spin leads to left or right circular polarization (rotation of the electric and magnetic fields) measured in a plane normal to the direction of propagation. It can be generated and detected with filters.
In 1911 Ernest Rutherford put forward his model of an atom in which a small nucleus contains most of the mass, has positive charge $nq$ for atomic number $n$, and is surrounded by a cloud of $n$ electrons, each having charge $-q$. Some of the electrons of one atom may be shared with another atom to form a molecular bond. Basic to the theory is that electrons are particles.

In 1913 Niels Bohr postulated that electrons orbit the nucleus with quantized angular momentum $n\hbar$ for integer $n$, and could move from one orbit to another by absorbing or emitting a photon with energy $\hbar \omega$. He received the 1922 Nobel prize for his work. It was later discovered that electrons have an intrinsic angular momentum (spin $= \hbar/2$), analogous to rotation about an axis, that adds to the total angular momentum.
The Planck-Einstein relation for the energy of a photon is $E = \hbar \omega$. From special relativity, $E^2 = p^2 c^2 + m^2 c^4$ so that $E = pc$ for the massless photon. The linear momentum is thus $p = \hbar k$ for wavenumber (spatial frequency) $k = 2\pi/\lambda$ from $c = \lambda \omega/(2\pi)$. In 1923 Louis de Broglie postulated that an electron (and any other particle) can be described by a matter wave with spatial frequency $k$ related to momentum by $p = \hbar k$. Imagine a wave superimposed on the classical (circular) trajectory of the electron. The orbit consists of an integer number of periods: $2\pi r = n(2\pi/k)$ for radius $r$. The de Broglie hypothesis gave an alternative to Bohr’s quantization of angular momentum ($rp = n\hbar$) as an explanation of the allowed energies of hydrogen. Double-slit experiments involving one electron at a time display the interference pattern of a wave.
1922 experiment by Otto Stern and Walther Gerlach in Frankfort: silver atoms travel through an inhomogeneous magnetic field and are deflected up or down depending on their spin. 1: furnace. 2: beam of silver atoms. 3: inhomogeneous magnetic field. 4: expected result. 5: what was actually observed.
Cascaded Stern-Gerlach mesurements

The Stern-Gerlach experiment led to the discovery that an electron has intrinsic angular momentum \( (\text{spin}) \) with values \( \frac{\hbar}{2} \) or \( -\frac{\hbar}{2} \) measured along any axis and which contributes to the magnetic dipole moment of an atom about which it is rotating. Spin is modeled by a qubit as demonstrated by the experiment below in which the devices are oriented along the \( z \) axis to measure spin in the computational basis \( (|+Z\rangle = |0\rangle, |-Z\rangle = |1\rangle) \) or \( x \) axis to measure in the \( |+/-\rangle \) basis \( (|+X\rangle = |+\rangle, |-X\rangle = |-\rangle) \).

![Three stage cascaded Stern–Gerlach measurements diagram](image-url)

Figure 1.24. Three stage cascaded Stern–Gerlach measurements.
In 1925, Werner Heisenberg, Max Born, and Pascual Jordan proposed a model of quantum mechanics based on treating the position and momentum of a particle as matrices of size $\infty \times \infty$. Heisenberg received the 1932 Nobel prize.

In 1926, Erwin Schrödinger published four papers in which he proposed a wave theory of quantum mechanics, along the lines of the de Broglie hypothesis. He showed how the waves evolve in time and showed that the energy levels of an atom can be understood as eigenvalues of a Hamiltonian operator. He also showed that the wave model was equivalent to Heisenberg’s matrix model. He shared the 1933 Nobel prize with Paul Dirac.