

Lecture #10 Tues 2 Mar 2010 Quantum mechanics

Quantum mechanics

Quantum mechanics = mechanics of very small objects, e.g., atoms.

quantum = packet. Sometimes (not always) the change in a system is discrete, *not* continuous.

Like relativity, quantum mechanics (QM) originates from questions about light and other particles.

Is light really a wave? Is the electron really a particle?

3 elements:

- * photoelectric effect
- * blackbody radiation and the ultraviolet catastrophe
- * electrons in atoms

The Photoelectric effect

Last time: Light is a wave but without anything that “waves.” This turns out not to be the *whole* story....

1897: J J Thompson discovers electron at Cavendish laboratory, Cambridge.

“Crookes tube” = modern cathode ray tube

“Cathode rays” have a constant ratio of electric charge to mass

→ they are particles with fixed (quantized) charge and fixed mass. These are electrons.

1899: shining UV light on cathode encourages production of electrons = “photoelectric effect.”

1902: Phillip von Lenard discovers threshold for photoelectric effect depends on *frequency*. Intensity merely determines *how many* electrons ejected.

Frequency = how many oscillations per second wavelength \times frequency = velocity = constant for light.

Blackbody radiation and the ultraviolet catastrophe

If you heat up a box (‘blackbody’) you predict an *infinite* amount of electromagnetic radiation inside! (the ‘ultraviolet catastrophe’)

1900: Max Planck shows if you *assume* energy in electromagnetic wave is proportional to frequency, no UV catastrophe.

Electrons in the atom

Electrons live in matter...but where? J J Thompson: “plum pudding” model of atom.

1909: at Cavendish Lab, Ernest Marsden & Hans Geiger (under direction of Rutherford) discover atom has massive, tiny nucleus... “Planetary model.”

Size of atom = one ten billionth of a meter (= 1 angstrom)

Size of nucleus = 100,000 times smaller (= 1 fermi)

But opposite charges attract...why don’t electrons get sucked into the nucleus?

Summary: 3 major puzzles:

- * threshold of photoelectric effect depends on frequency, not intensity
- * Planck's energy-frequency relation for blackbody radiation to solve UV catastrophe
- * why does electron "orbit" atomic nucleus?

ANSWER: Everything has properties of both waves and particles.

1900: Planck "solves" blackbody radiation by
assuming $E = hf$. f = frequency, h = Planck's constant.

1905: Einstein uses Planck's equation to explain photoelectric effect: Electrons trapped by a energy barrier. Light must have a minimum energy (and thus minimum frequency) to kick electron out! Einstein awarded Nobel prize 1921 for this. "Light comes in discrete packets—particles"

1923: Louis de Broglie: Maybe electrons (particles) act like waves! This explains atoms Must fit a complete number of wavelengths in orbit around atom, otherwise "not allowed."

Modern quantum mechanics

1925-26 complete quantum theory developed by Schrodinger, Heisenberg, Born, Bohr:

Classical mechanics: each particle has a *trajectory* computed from forces and Newton's laws.

Quantum mechanics (QM): each particle has a *wavefunction* $\Psi(x,t)$.

The wavefunction $\Psi(x,t)$ changes with time according to Schrodinger's equation:

$$i\hbar \frac{\partial}{\partial t} \Psi(x,t) = \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V(x) \right) \Psi(x,t)$$

Classical mechanics: $x(t)$ tells you position of particle at time t

QM: $|\Psi(x,t)|^2$ is the *probability* to find the particle at time t and at position x .

1927: Davisson and Germer experiment shows electrons *are* waves (diffraction and interference).

QM is a *probabilistic* theory. You cannot predict the outcome of any *single* measurement. But you can predict probabilities for *many* measurements. Einstein did not like this.

There are many "interpretations" of the same math for QM.

Most physicists use the "Copenhagen interpretation" developed by Niels Bohr: after experimenter observes/measures the (say) atom, the wavefunction collapses because probability to be elsewhere is zero.

One alternate interpretation (of many): Everett-Wheeler many-worlds interpretation: there are infinite universes and in each one the atom is measured at a different place.

Quantum mechanics in SF

QM generally misused in SF (worse than relativity). QM used to justify faster-than-light jumps or faster-than-light communication via entanglement (won't really work).

Also: many-world interpretation used to justify parallel universes (better, but still not accurate)

Both *Timescape* and *The Dispossessed* argue **against** the probability (random) nature of quantum mechanics.

Quantum mechanics summary

The mechanics of very small objects

size of atom = 10^{-10} meters (= 1 Angstrom)

size of atomic nucleus = 10^{-15} m (= 1 fermi)

Basic results:

waves (like light) can act as particles

-- photoelectric effect

-- no "ultraviolet catastrophe" for blackbody radiation

particles (like electrons) can act as waves

-- fixed ("quantized") orbits for electrons around atoms

-- Davisson-Germer showed electrons have diffraction (interference)

Objects (light, electrons) described by *wave function*

The wavefunction predicts the *probability* of any outcome, not the specific outcome itself
Copenhagen interpretation: wavefunction "collapses" upon making a measurement / observation

Many-worlds interpretation: at each quantum event universe splits into separate universes