Early Quantum Theory & Models of the Atom (Ch 27)

Modern physics
- special relativity
- quantum theory

Discovery of electron

J. J. Thomson (1856-1940)
- measured e/m directly
- set-up was similar to mass spectrometer
- believed the electron was part of an atom

Millikan (1868-1953)
- oil-drop experiment
- measured charge of electron, e

Blackbody Radiation

Blackbody
- perfect absorber & emitter of light

Wien’s Law
\[ \lambda_p T = 2.90 \times 10^{-3} \text{ m K} \]

ultraviolet catastrophe
- models predicted too much flux at ultraviolet wavelengths

Max Planck (1858-1947)
- developed equation to predict spectra

The blackbody spectrum of light emitted by hot objects was unexplained at end of 1800’s
**Planck's Quantum Hypothesis**

- Energy is quantized
  - \( E = h f \)
  - \( h = 6.626 \times 10^{-34} \text{ J s} \)
- Energy of molecular vibrations can only be multiples of \( hf \)
  - \( E = n hf, n=1,2,3 \)
  - \( n \) is quantum number
  - \( E = 0.2 hf, 0.33 hf, 0.5 hf, ... \)
- Planck considered this a mathematical device
  - did not realize he started a revolution!

**The Photoelectric Effect**

- Einstein provided interpretation for Planck's work (1905)
- Photon theory of light
  - \( E = hf \)
  - energy per photon (particle) of light
- Photoelectric Effect
  - provides a test for photon theory of light
  - Einstein won Nobel Prize for his work on the Photoelectric Effect

**The Photoelectric Effect**

- Wave theory
  - as intensity of light increases, max KE of e\(-\) increases b/c higher intensity -> higher E field -> higher KE
  - frequency of light should not effect KE of e\(-\), only intensity does
- Particle theory
  - increasing intensity should produce more e\(-\) but should not change max KE of e\(-\)
  - increasing frequency of light should increase max KE of e\(-\)
  - \( hf = KE + W \)
  - Einstein proved right by Millikan

**Photon properties**

- Energy
  - \( E = hf \)
- Mass
  - \( mass = 0 \)
- Momentum
  - \( p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda} \)
Wave-Particle Duality

- some experiments indicate that light is a wave (Young’s double-slit experiment)
- some experiments indicate that light is a particle (Photoelectric effect)
- Principle of Complementarity
  - light is both wave and particle, probably more complex than both
  - light shows different “faces” to experimenters
- models drawn from macroscopic world are inadequate
- true nature of light is not possible to visualize
- Note E=hf links particle and wave properties

Wave Nature of Matter

- Louis de Broglie (1892-1987)
  - extended wave-particle duality to matter in his PhD thesis (12 pages; 1923)
  - won Nobel Prize in 1929 - first award for a thesis!
  - perhaps things we think of as particles (e-, atoms, a ball, you) have wave properties as well
  - wavelength given by:

Problem

- What is the de Broglie wavelength of a 50 kg person traveling at 15 m/s? 
  \( h = 6.6 \times 10^{-34} \text{ J s} \)

Electron Diffraction

- wavelength of e-
  - \(~10^{-10} \text{ m}\)
  - comparable to spacing between atoms in a crystalline structure
  - can use crystal as diffraction grating
- Confirms wave nature of particles
- also confirmed for neutrons, protons, etc
- Again, models are inadequate
Early Models of Atom

Plum Pudding Model

Ernest Rutherford:
- alpha particles at gold foil
- recoiling particles indicate presence of dense nucleus
- solar system model for atom

Atomic Spectra

- Models needed to explain why only discreet lines are emitted by atoms

Bohr Model of Atom

- Following Planck and Einstein, perhaps e⁻'s in atom have quantized energy

\[ hf = E_u - E_l \]

- proposed angular momentum is quantized, results in:

\[ E_n = \frac{-13.6 \text{ eV}}{n^2} \]
de Broglie’s Hypothesis

- Bohr’s theory was *ad hoc* (designed to explain specific observations)
- wave nature of e- provided explanation for Bohr’s model
  - each e- in an orbit is a standing wave
    \[ 2\pi r_n = n\lambda, \quad n = 1, 2, 3, \ldots \]
  - \[ \lambda = \frac{h}{mv} \]
  - quantum condition
- \[ mvr_n = \frac{nh}{2\pi} \]
- Explains Bohr’s conservation of angular momentum!

Bohr Model

- Limitations
  - could not predict spectra for more complex atoms
  - could not explain why emission lines, when viewed at high resolution, consist of 2 or more lines
  - why are some spectral lines brighter than others?
  - could not explain bonding between atoms
  - not satisfactory from a theoretical point of view
- Needed a more comprehensive theory
- Quantum Mechanics
  - provided by
    - Erwin Schrödinger
    - Werner Heisenberg