Quantum Theory of Radiation and Matter

around 1900 Scientists thought they knew it all! except (of course) for a few minor details

Newton’s Laws
Mechanics, gravity
Maxwell’s Equations
Electromagnetism
Thermodynamics
Statistical Mechanics

Numerous experiments could not be explained the accepted laws would occasionally fail!
large distances, fast speeds ⇒ Relativity
small distances, atomic sizes ⇒ Quantum Mechanics

Atomic Spectra
spectrograph separates light according to \( \lambda, f \)

continuous spectrum
sun
hot filament

line spectrum
each element unique fingerprint for identification

now spectrographs use diffraction grating mirror etched with fine lines separates \( \lambda \)
Some materials give off light when "excited"
   i.e. when they gain extra energy (gas discharge above)

Fluorescence - light for a very short time (~msec)
Phosphorescence - (glow-in-the-dark) lasts minutes - hours

Radiation and Radioactivity - mysterious "rays"
   smashing as an experimental method
   use electric potential - High Voltage
   to accelerate charged particles
   smash them into something

noticed that nearby
flour/phosphorescent screens
would glow!

some rare materials - radium, uranium
would also cause screens to glow!

X-Rays - Roentgen
November 8, 1895
X = unknown
electromagnetic radiation
\( \lambda \sim 1 \ \text{Å} = 10 \text{ nm} \)
penetrates many materials
exposes film in dark

Radioactivity
release of energy from
an unstable atomic nucleus

Marie and Pierre Curie
Nobel prizes
Marie twice!

classification into different types
can electric or magnetic fields
bend path of the "rays"?

\( \alpha \)  ALPHA particles - "heavy" positive charge
   He nucleus - 2 protons + 2 neutrons
\( \beta \)  BETA particles - "light" negative charge
high energy electrons
\( \gamma \) GAMMA particles - no observable charge or mass
very high frequency (small \( \lambda \)) radiation \( \Rightarrow \) waves
more energetic than X-rays

CATHODE RAYS from CRT (Cathode Ray Tube) TV/monitor
= electrons = \( \beta \) particles

Path of charged "rays" is deflected (bent or changed)
by electrically charged plates or magnetic fields.

Remember Electromagnetic spectrum!

Early Models of the Atom
Neutral - must have equal positive and negative charge

**J.J. Thomson** (shown with Rutherford)
discovered electron in 1897
early cathode ray tube
plum pudding model of the atom
electrons as raisins
in continuous positive pudding

Rutherford Model of the Atom
test of how electric charge
distributed in solids
\( \alpha \) particles shot at gold foil
most went straight through
or with small scattering
but a few
came straight back!

**Conclusion**
positive charge must be highly concentrated!
then light electrons must "orbit" positive nucleus
as planets around sun
Rutherford's model of the atom

**Problem:**
moving charges lose energy by radiation
Maxwell's equations
electrons would fall into nucleus
atoms would collapse
Why don't electrons in "orbits" radiate energy?

Planck's Quantum Hypothesis

- **WAVE** - electromagnetic radiation
- **LIGHT** acts as a **PARTICLE** - PHOTON or quantum

known as **DUALITY**
- nature doesn't follow our prejudices

Energy of Quantum (photon) proportional to Frequency
\[ E = hf \]
\[ h = \text{Planck's constant} = 6.63 \times 10^{-34} \text{ joule-s} \]
for light
\[ c = \lambda f \Rightarrow f = c/\lambda \]
\[ E = hc/\lambda \]
Energy of a photon (light quantum) depends only on f (or \( \lambda \))
- not on brightness of light
- brightness \( \Rightarrow \) number of photons/sec

**Photoelectric Effect**
explained by Einstein \( \Rightarrow \) Nobel Prize

- shine dim high \( f \) light (BLUE) on a metal:
  - Electrons emitted!
- shine bright low \( f \) light (RED) on same metal:
  - No electrons emitted!

**Metal:**
- **work function** \( W = \text{minimum energy needed to eject electron} \)
- related to \( L_v \)

measured in eV (electron volts) small unit of energy
\[ 1 \text{ eV} = (1.6 \times 10^{-19} \text{ C})(1 \text{ V}) = 1.6 \times 10^{-19} \text{ joule} \]

- low \( f \) RED light \( hf < W \), electrons remain trapped!
- high \( f \) BLUE light \( hf > W \), electrons ejected!

In the photoelectric effect, light behaves as a particle (photon)
- with energy \( hf \).
In dispersion through a prism, light behaves as a wave
- with wavelength \( \lambda \).
PHONONS - quantum particles of sound.

Matter Waves - Duality - Louis De Broglie

If light (a wave) can behave as a particle (photon),
then particles must also behave like waves.
The quantum wavelength of a particle
depends on its velocity \( v \) and mass \( m \):
\[
\lambda = \frac{h}{mv}
\]

Note: quantum effects involve \( h \) (Planck's constant).

A bullet of mass 10 gm travels at 1000 m/s, what is \( \lambda \)?

\[
\lambda = \frac{h}{mv} = \frac{(6.63 \times 10^{-34} \text{ js})}{(10^{-2} \text{ kg})(10^3 \text{ m/s})} = 6.63 \times 10^{-35} \text{ m}
\]

For macroscopic (normal, bigger than microscopic) objects
quantum \( \lambda \) too small to have observable effects.

Electrons in atom \( \Rightarrow \) standing waves in a string
lowest energy level \( \Rightarrow \) fundamental frequency
only certain \( f \) (energies) allowed

Bohr Energy-Level Atom explains atomic spectra

Electron "orbits" have different sizes
larger orbits \( \Rightarrow \) larger energy \( E \)
Quantum resonance: wavelength must match size
only certain sizes/energies, unlike planets around sun
allowed energies are quantized (discrete, not continuous)
called energy levels, or permitted orbits
depend on \( Z \), number of protons in nucleus

Excitation of Atoms
energy is required to move from one level to another
Upward Transition electron gains energy
\[
\Delta E = E_{\text{upper}} - E_{\text{lower}} \quad \text{very precise}
\]
energy can come from
1) collision with other atoms
2) absorption of a electromagnetic photon
with exactly the correct energy/wavelength
\[
\Delta E = E_{\text{photon}} = \frac{hc}{\lambda}
\]
Downward Transition - Emission - atoms are lazy (like people!)

short time in excited upper level ~ $10^{-9}$ to $10^{-6}$ sec.
excited electron falls back to ground state (lowest energy state)
emits a photon with $E_{\text{photon}} = \Delta E = \frac{hc}{\lambda}$

same energy for emission as needed for absorption
but direction random

explains atomic spectra
emission and absorption lines at same $\lambda$