Nuclear Physics: Lecture 2

Quantum Mechanics

and

Wave-Particle Duality

Prevailing View of Physics, circa ~ 1890

"Nature and nature's laws lay hid in night:
God said, Let Newton be!, and all was light"
-- Alexander Pope

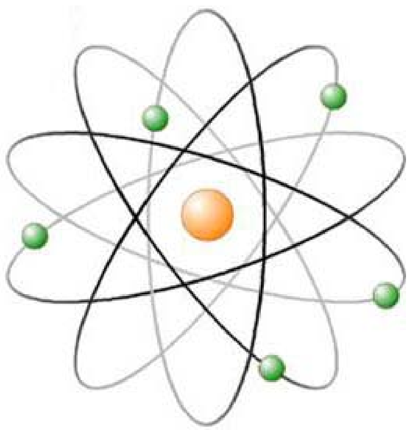
"Give me the initial data on the particles,
and I'll predict the future of the universe!"
-- Marquis Pierre de Simon LaPlace
(~1860)

Observations Implying Wave-Particle Duality

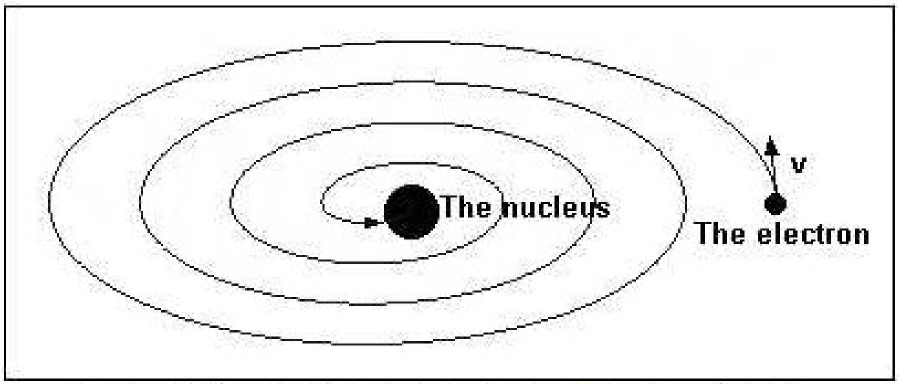
- “Wave” behavior from “particles”
  - Rutherford atom dilemma
  - Davisson Germer
  - deBroglie wave hypothesis
  - Bohr Atom
- “Particle” behavior from “waves”
  - Photoelectric effect
  - Blackbody radiation
  - Compton scattering

Fundamental Problem with Rutherford "Atom"

HOW TO AVOID ELECTRON ORBIT COLLAPSE



Accelerating electrons radiate electromagnetic energy => spiral into nucleus!



In the planetary model of atom, the electron should emit energy and spirally fall on the nucleus.

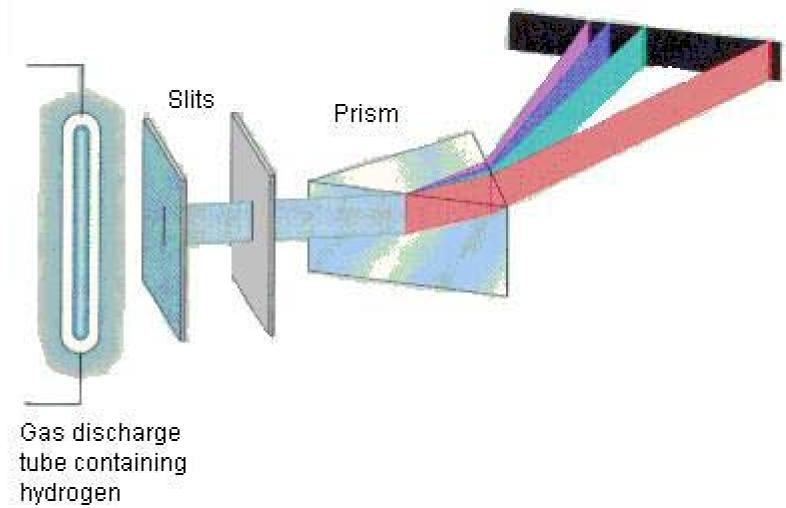
WHAT MAINTAINS STABLE ATOM STRUCTURE?

Answer: This will be a very long, convoluted answer involving Quantum Mechanics!

Wave Behavior from "Particles"

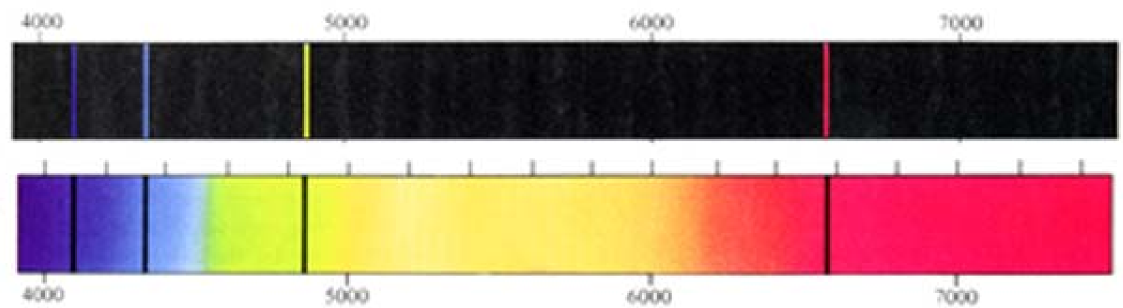
Light Emission from Excited Atoms:

WHAT IS EXPECTED FROM RUTHERFORD PICTURE?



Answer: Continuous frequency spectrum of light from classical EM radiation theory

BUT observed Spectral LINES are DISCRETE!

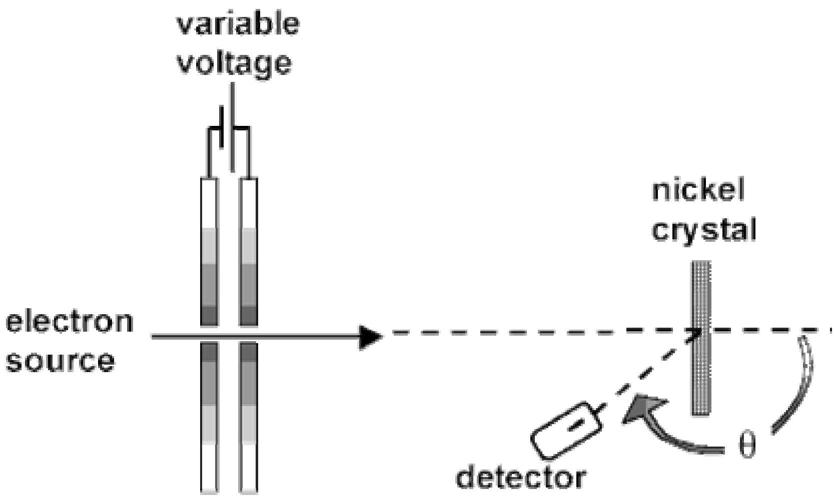


The Hydrogen Spectrum
Above: Emission
Below: Absorption

Wave Behavior from "Particles" . . . Cont'd

Davisson Germer Experiment:

Electrons scattered through crystal lattice



Scattered electrons form "Diffraction" pattern characteristic of "waves"??

DeBroglie Wave Hypothesis

Every particle has an associated "Wave" . . . "psi" denotes the wave . . .

$$\Psi \approx \cos(kx) = \cos(2\pi x / \lambda)$$

Wavelength found from Planck's constant & MOMENTUM:

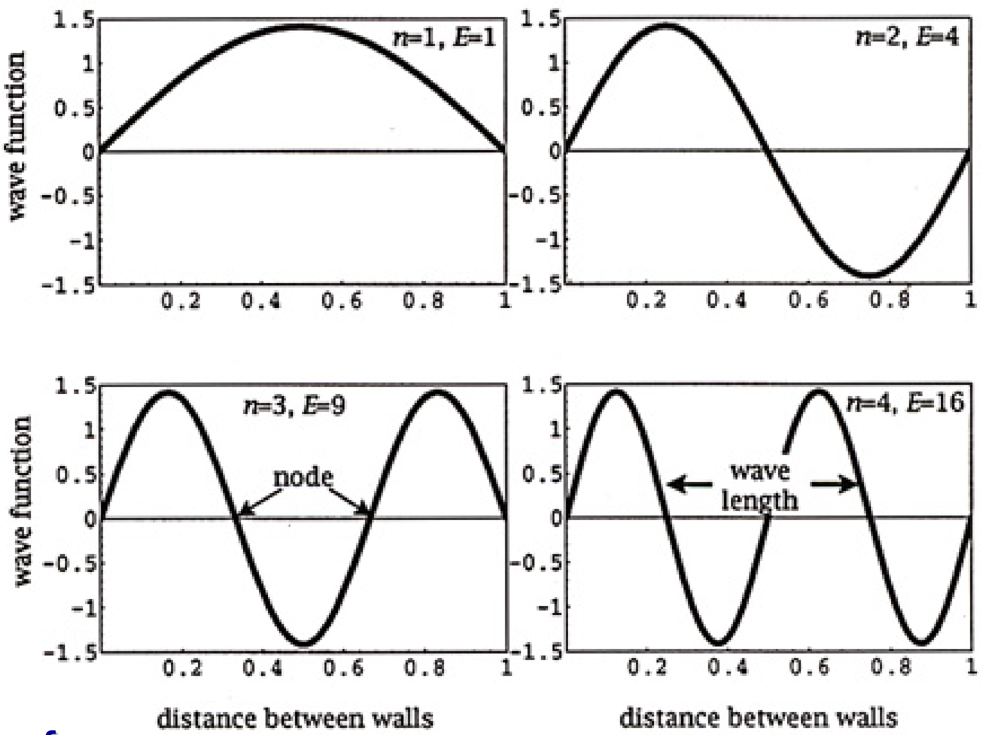
$$\lambda = \frac{h}{mv}$$

$$mv = \frac{h}{\lambda} = \hbar k$$

The method for determining this wave and how it was used to actually determine particle behavior was left to others . . . And yet the Nobel prize in physics for the 55 page thesis!

$$\hbar \equiv \frac{h}{2\pi}$$

Waves in a "Box"

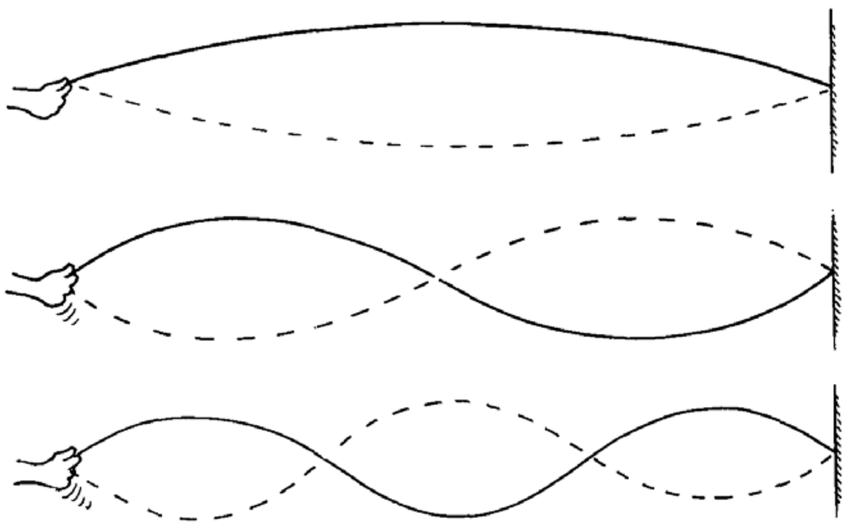


Waves have to "fit" in the "box":

=> Box must contain integer number of (half) wavelengths

$$L = n\lambda / 2$$

Like natural frequencies of:



- Organ Pipe
- Trumpet
- Drum Head
- Coke Bottle
- Violin

What are the "Waves"?

- Waves of Probability . . .
- Particle has no definite position (we don't know where in box/atom/nucleus the particle is actually located).

$$P(x,t) = |\Psi(x,t)|^2$$

- Is probability of finding the particle at position, x
- Probabilities for particle in box are "strange" (see blackboard . . .)

Discrete Energy Levels

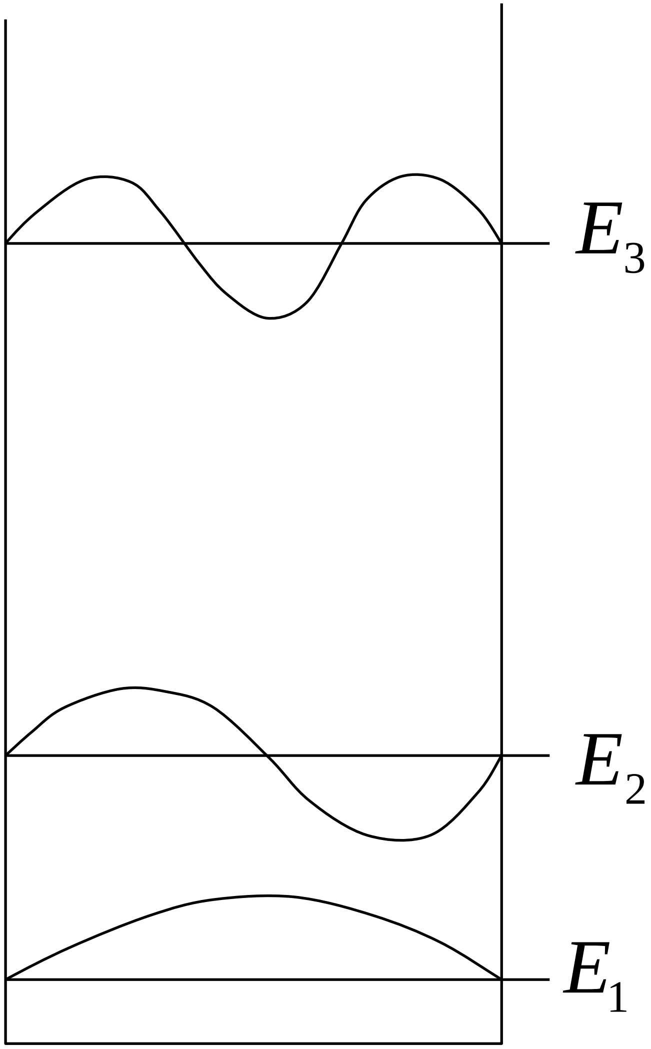
- If the wavelength determines the momentum . . .

$$mv = \frac{h}{\lambda}$$

- The Energies must be Quantized

$$E_n = \frac{mv^2}{2} = n^2 \frac{h^2}{8mL^2}$$

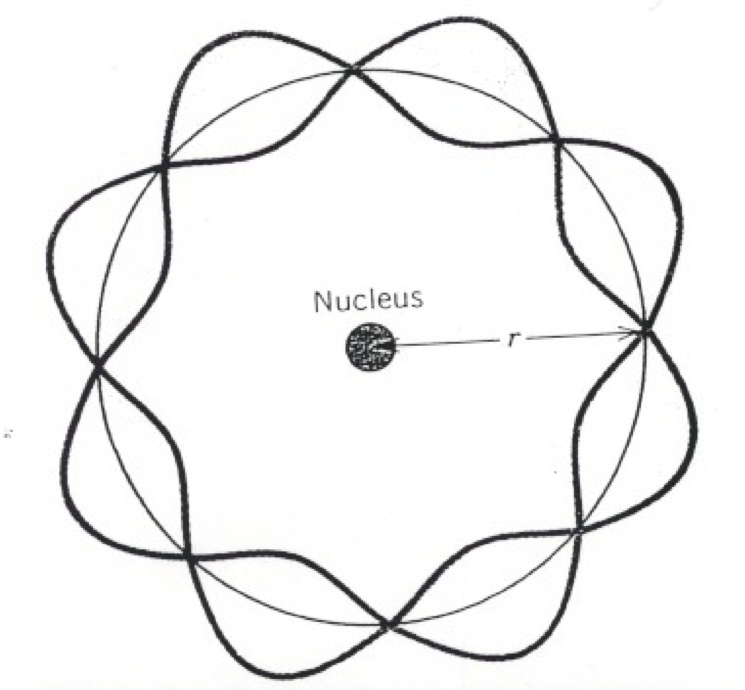
This is the origin of the term, "Quantum Mechanics"



WHAT IS EXPECTED FROM RUTHERFORD PICTURE?

The Bohr Atom

Neils Bohr (1913) applied the quantum principles to electrons orbiting nucleus:



- Quantized Wavelengths: $$2\pi r = n\lambda$$
- deBroglie hypothesis: $$\lambda = h/mv$$

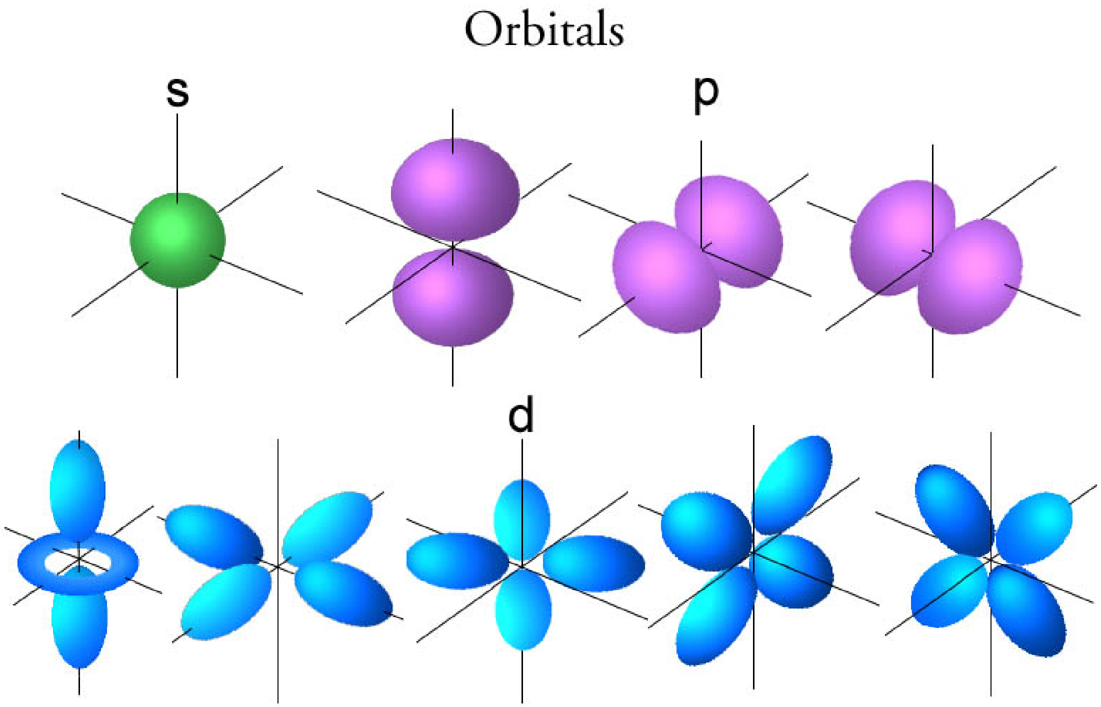
•Force Balance (Centrifugal vs. Coulomb): $$\frac{e^2}{r^2} = \frac{mv^2}{r}$$

=> Energy Levels of Hydrogen atom EXACTLY predicted!

$$E_n = \frac{1}{2}mv^2 - \frac{e^2}{r} = -\frac{1}{n^2} m_e c^2 \frac{e^4}{2\hbar^2 c^2}$$

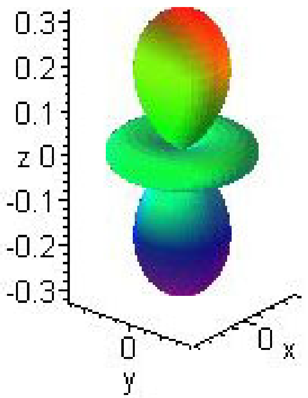
$$E_n = -13.6\ eV$$

Atomic Electron Probabilities ("Orbitals")



- Probability clouds of electron in atom
- Note disconnected structure – For one electron!

$$P\left(x,,y,z,t\right)=\left|\Psi\left(x,y,z,t\right)\right|^{2}$$



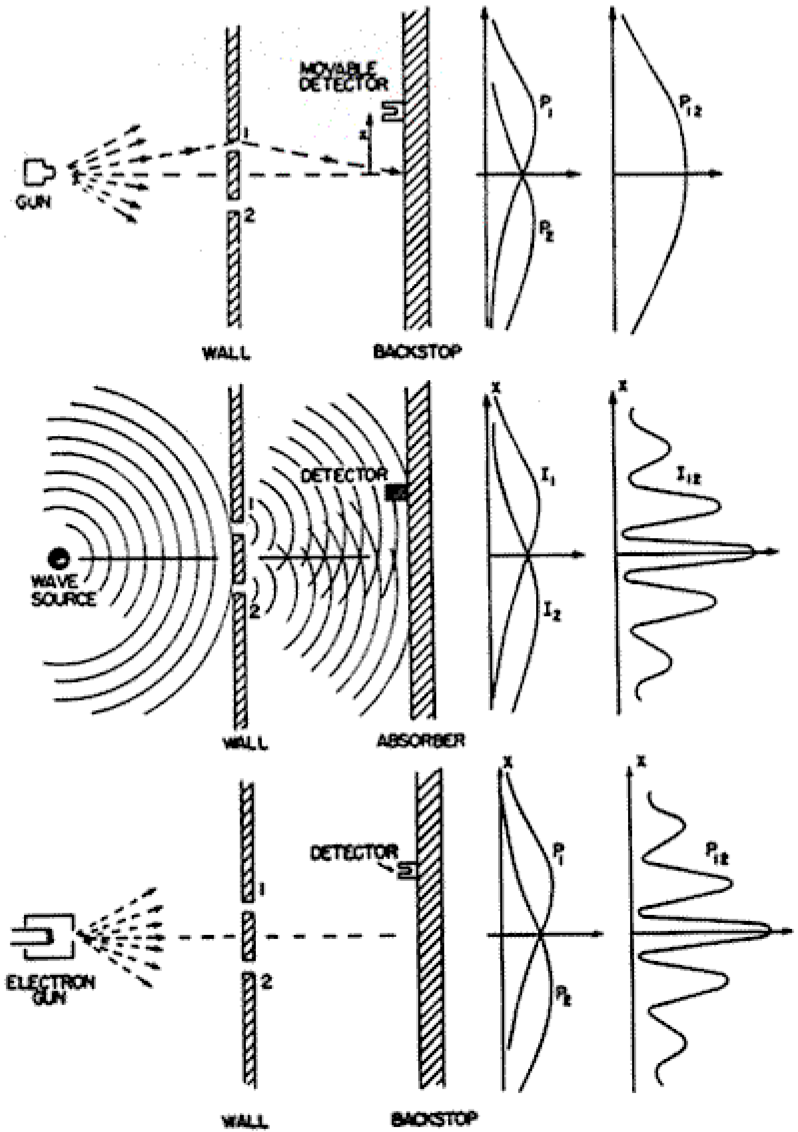
Particle "Diffraction"

Explain Davisson-Germer if electrons scatter from crystal lattice atoms as deBroglie waves:

Interference minima when path length from holes differs by half wavelength:

$$d\sin(\theta_{\min}) = \lambda/2$$

Electrons @ KeV energies "interfere" with Angstrom ($\sim 10^{-8}$ cm) scale atomic lattice structure

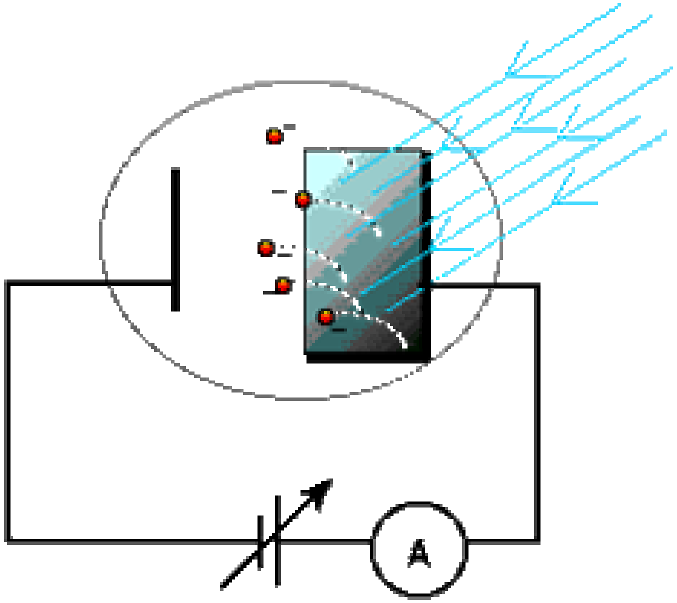


Particle Behavior from "Waves"

This is the final aspect of the "wave-particle duality" that is Quantum Mechanics

Photoelectric Effect:

Electrons ejected from metal by incoming light



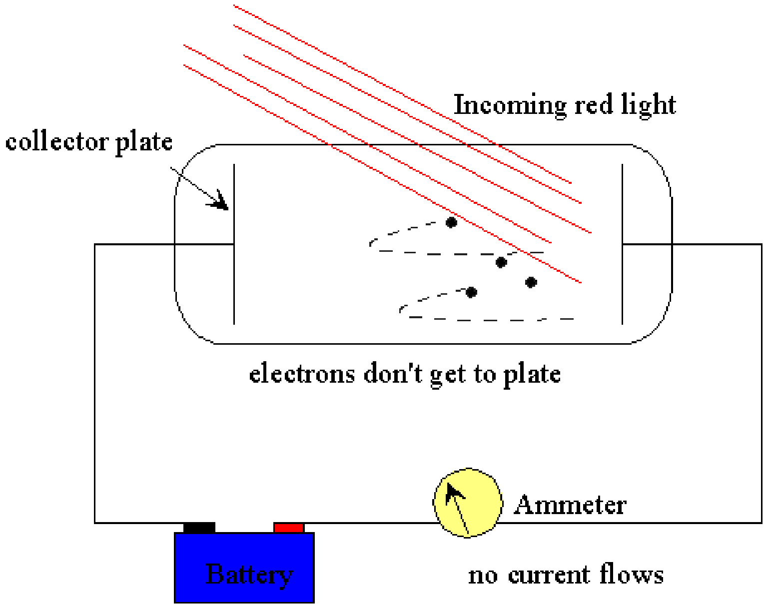
WHAT IS EXPECTED, CLASSICALLY, AS FUNCTION OF LIGHT INTENSITY & FREQUENCY?

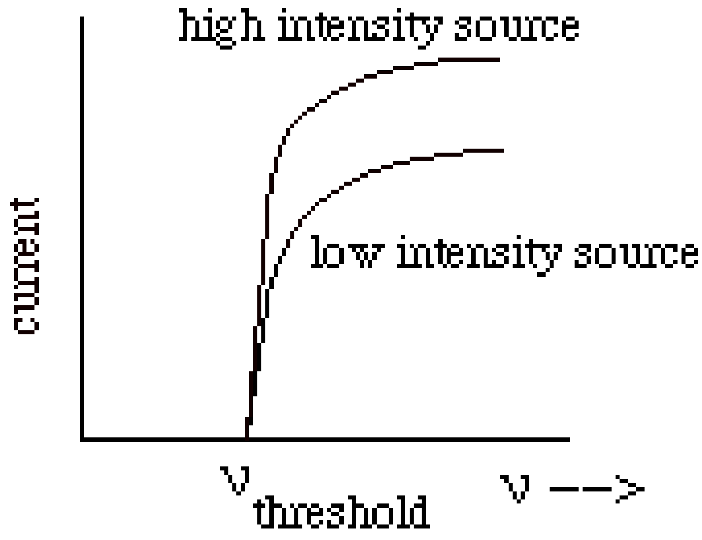
Answer: Higher intensity => higher electron energy & frequency of light irrelevant

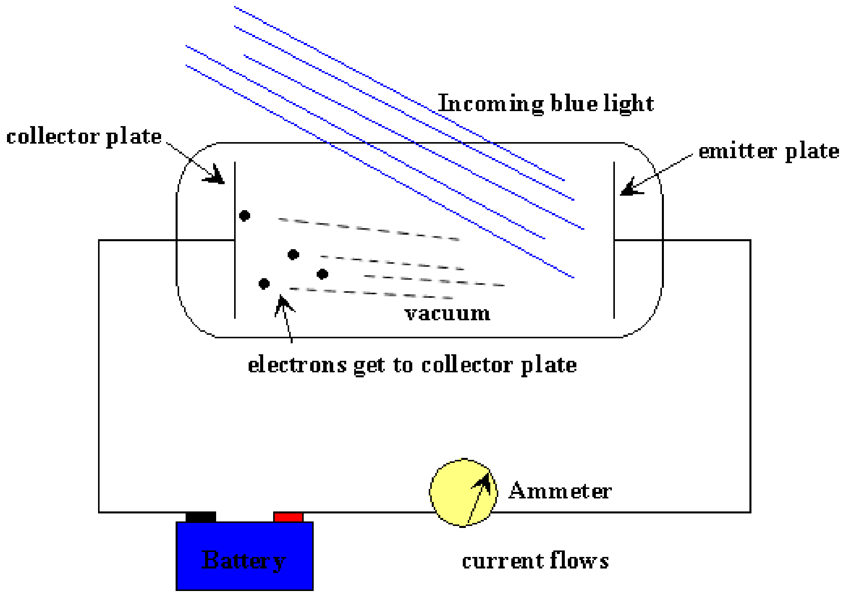
Photoelectric Effect -- Observations

Experiment shows:

- Electron energy proportional to light frequency
- Intensity effects current but not electron energy







Photons of Light

Photoelectric Effect explained if Light "waves" exchange energy with matter via PHOTON quanta

$$E_\gamma = hf$$

The frequency is denoted by the symbol f

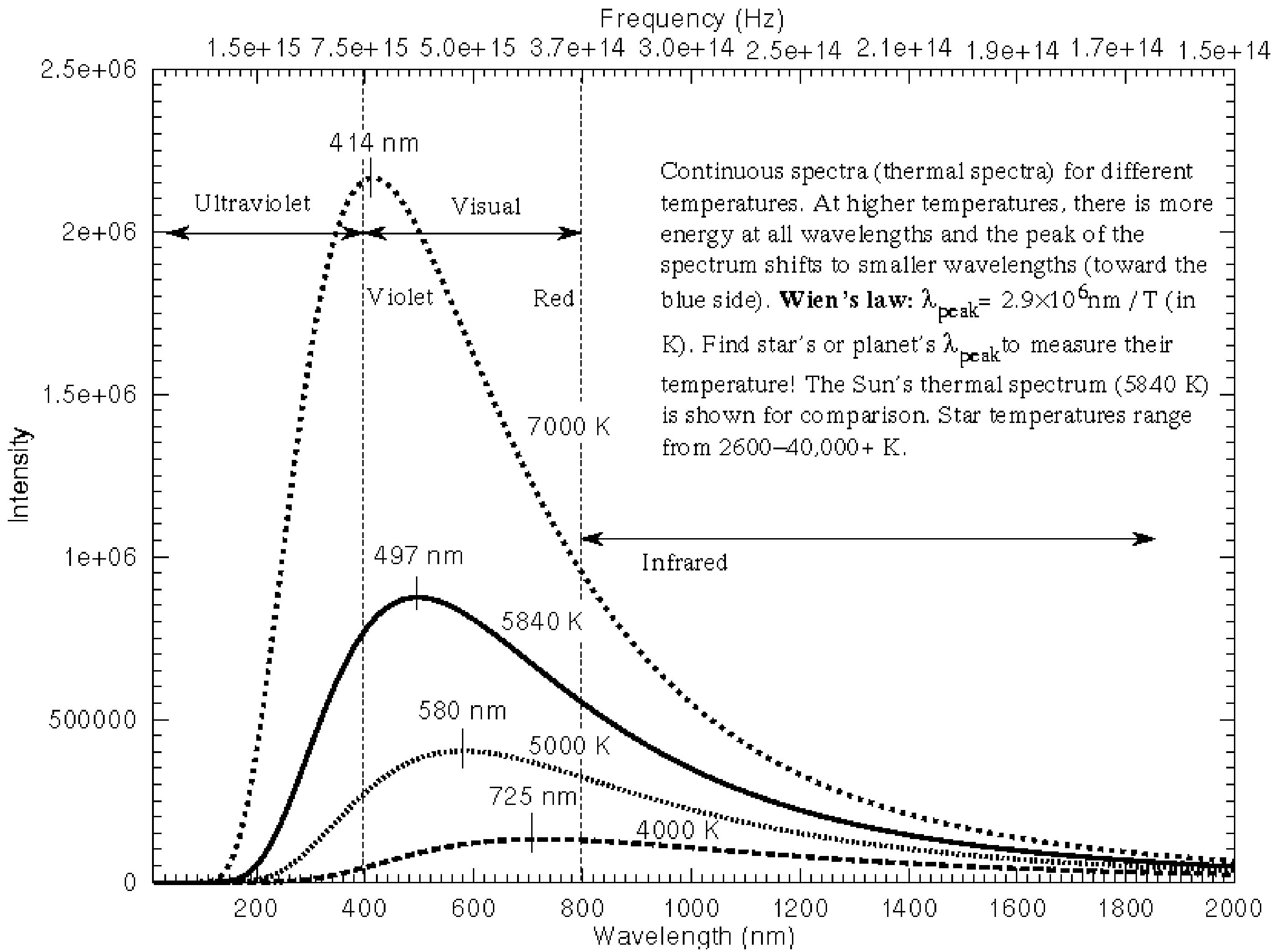
$$p = E_\gamma / c = h / \lambda$$

$$E_\gamma = \hbar\omega$$

$$p = E_\gamma / c = \hbar k$$

- Higher frequency => higher photon energy
- Number of photons proportional to intensity
- Einstein (1905)

Blackbody Radiation Spectrum



$$E_\gamma = hc/\lambda$$

Compton Scattering

Formal Quantum Mechanics

- Schrodinger Equation
- Measurement Probabilities
- Wave Mechanics
- Eigenvalue Problem
- "Confused" picture of matter
- Fundamental philosophical dilemma:
    - => "God doesn't play dice"

$$i\hbar\frac{\partial\Psi}{\partial t} = \widehat{H}\Psi$$

BEST LEFT FOR ANOTHER DAY!