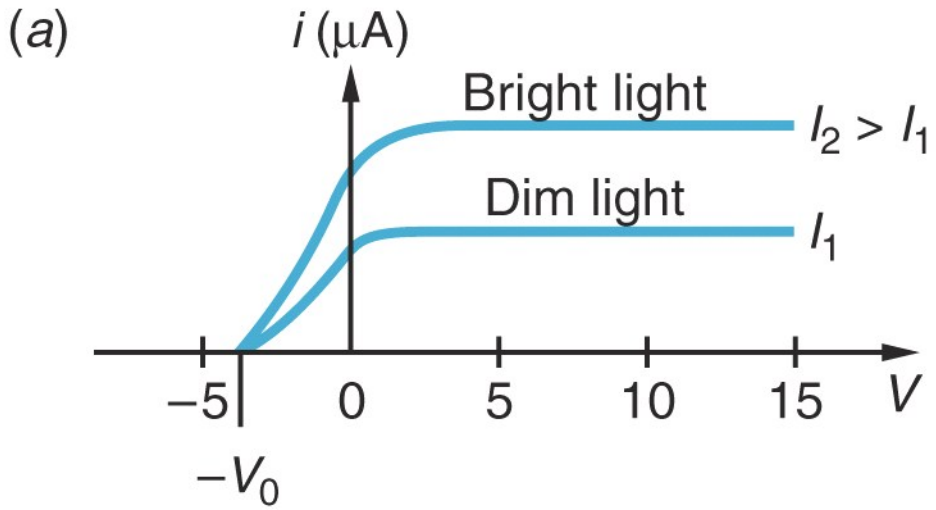
Physics 2D Lecture Slides
Oct 21

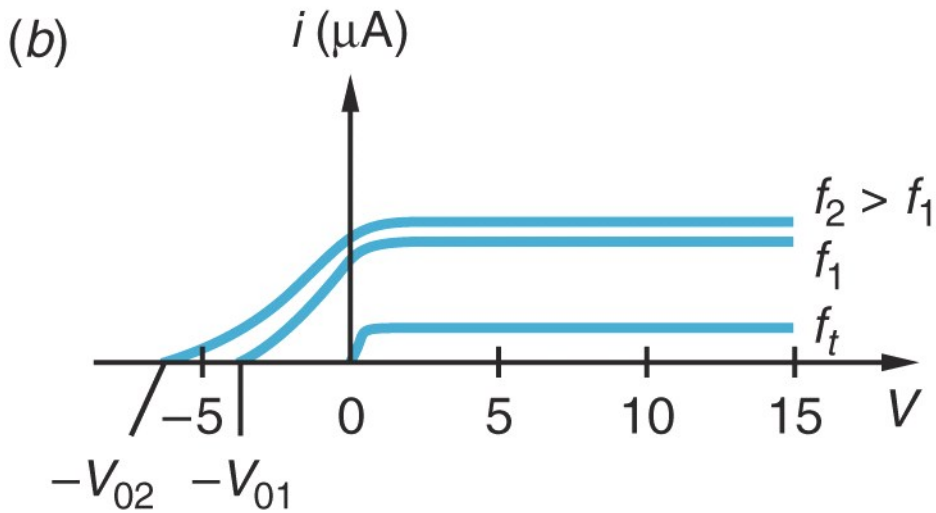
Vivek Sharma

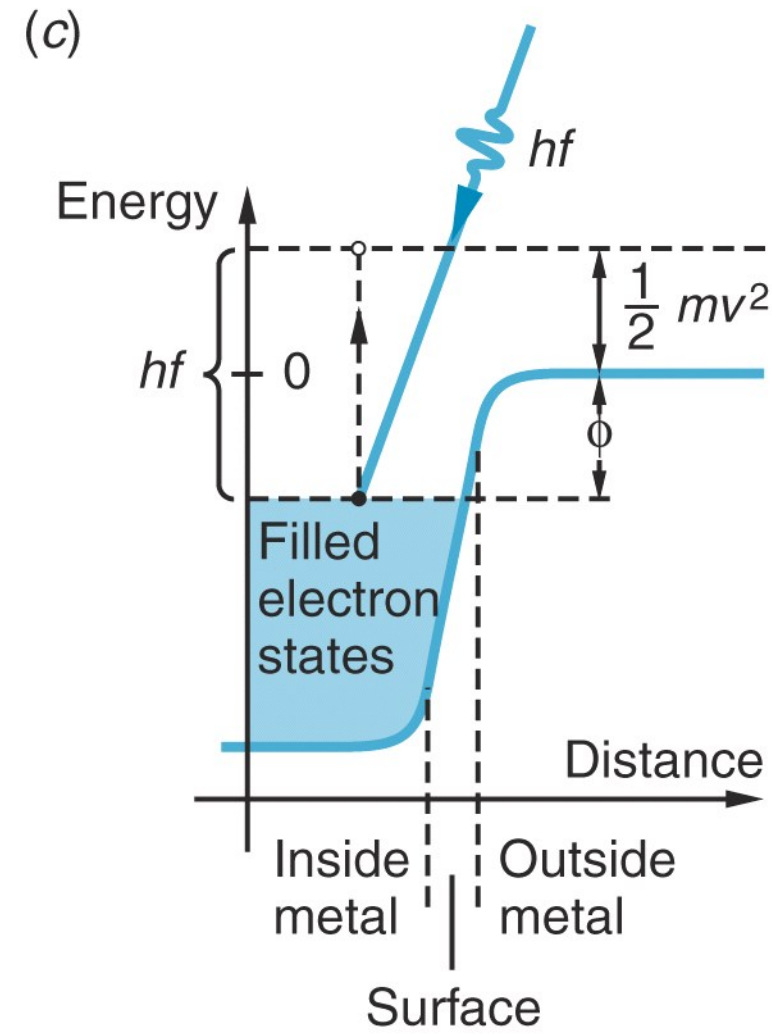
UCSD Physics

Modern View of Photoelectric Effect

$$E = hf = KE + \varphi$$



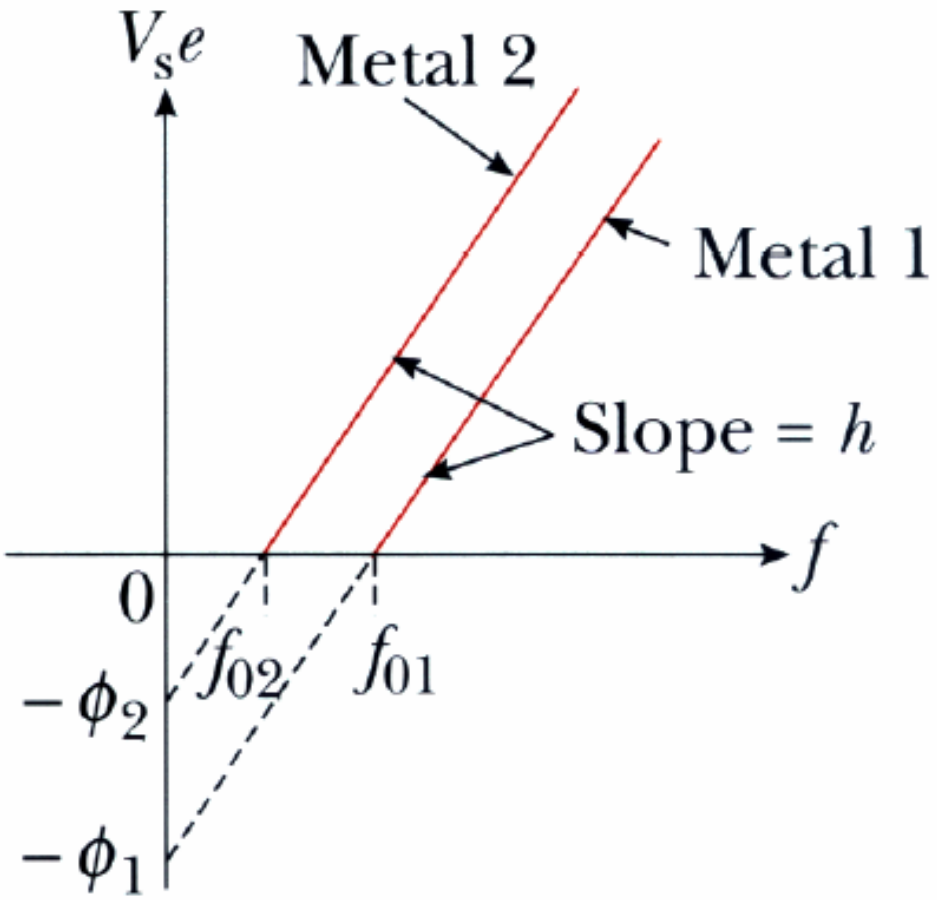




Is “h” same in Photoelectric Effect as in BBQ Radiation?

Slope h = 6.626×10^{-34} JS

Einstein → Nobel Prize!



No matter where you travel in this galaxy and beyond…
h = Planck’s constant is the

SAME !!!

NOBEL PRIZE FOR Herr PLANCK

Work Function (Binding Energy) In Metals

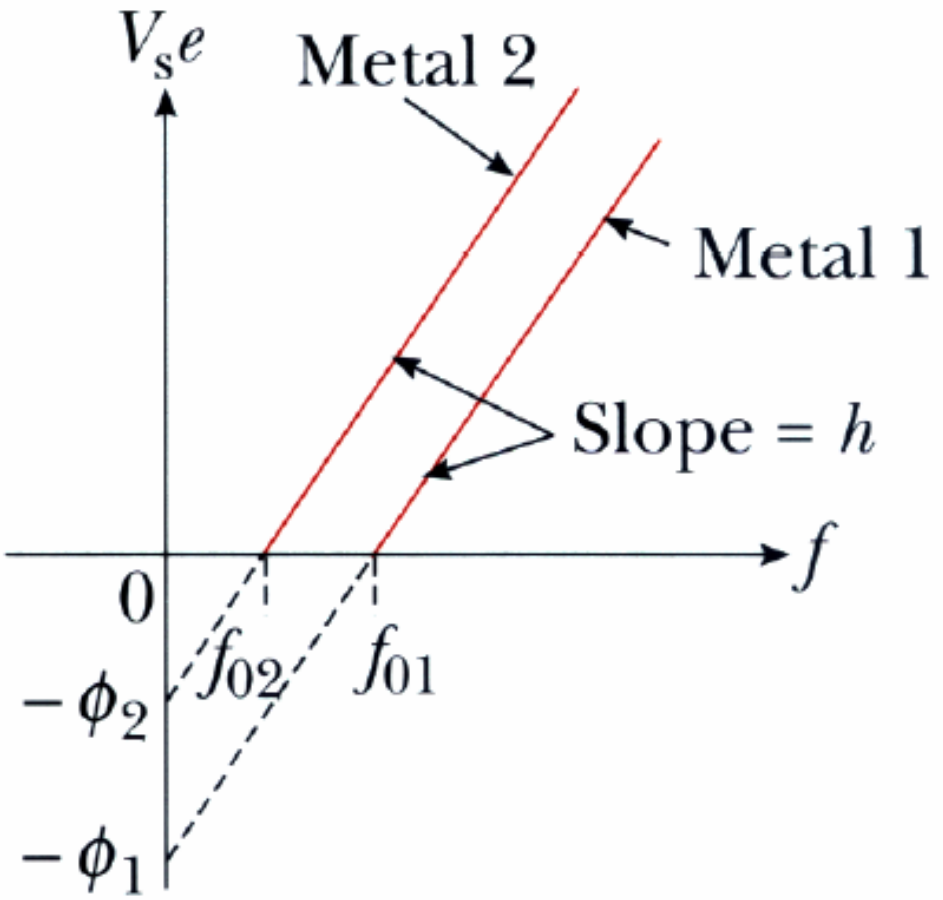


TABLE 3-1 Photoelectric work functions

Element	ϕ (eV)
Na	2.28
C	4.81
Cd	4.07
Al	4.08
Ag	4.73
Pt	6.35
Mg	3.68
Ni	5.01
Se	5.11
Pb	4.14

Photoelectric Effect on An Iron Surface:

Light of Intensity I = 1.0 μW/cm^2 incident on 1.0cm^2 surface of Fe

Assume Fe reflects 96% of light

further only 3% of incident light is Violet region (λ = 250nm)

barely above threshold frequency for Ph. El effect

(a) Intensity available for Ph. El effect I = 3% $\times$ 4% $\times$ (1.0 μW/cm^2)

(b) how many photo-electrons emitted per second ?

$$\#\ \text{of photoelectrons} = \frac{\text{Power}}{h f} = \frac{3\% \times 4\% \times (1.0\ \mu W/cm^2)\ \lambda}{hc}$$

$$= \frac{(250\times10^{-9}\,m)(1.2\times10^{-9}\,J/s)}{(6.6\times10^{-34}\,J\cdot s)(3.0\times10^{8}\,m/s)}$$

$$= 1.5\times10^{9}$$

(c) Current in Ammeter : $i = (1.6\times10^{-19}C)(1.5\times10^{9}) = 2.4\times10^{-10}\,A$

(d) Work Function $\Phi = hf_0 = (4.14\times10^{-15}eV\cdot s)(1.1\times10^{15}\,s^{-1})$

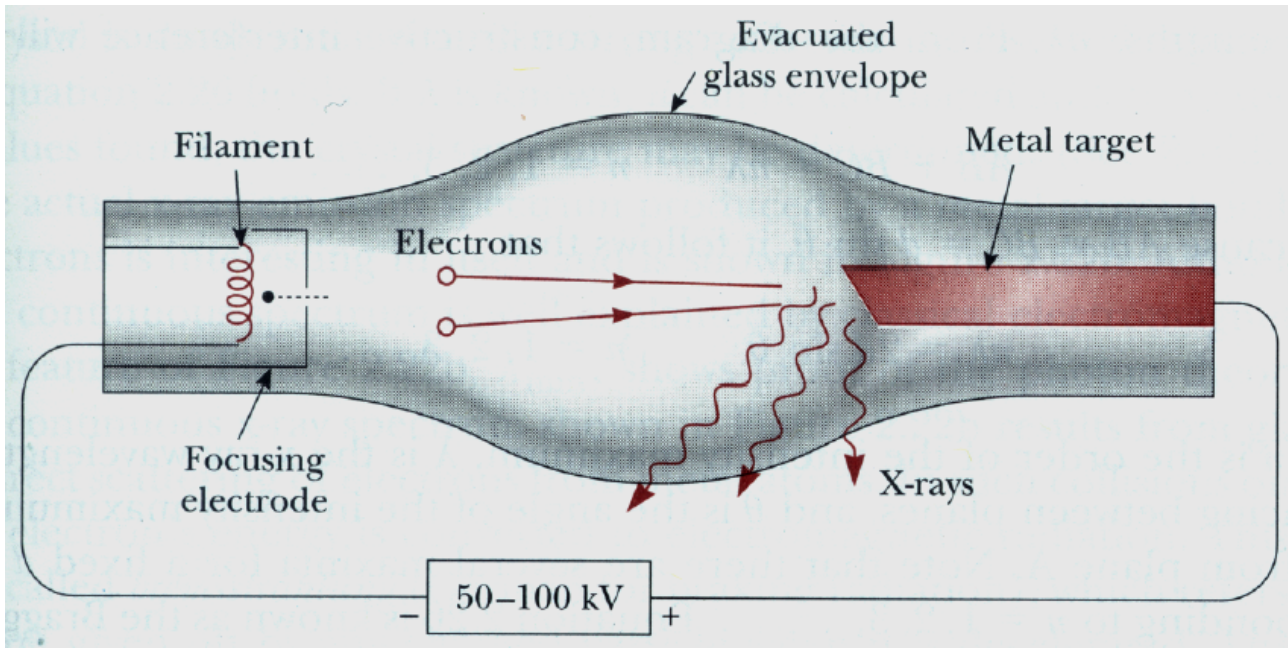
$$= 4.5\ \text{eV}$$

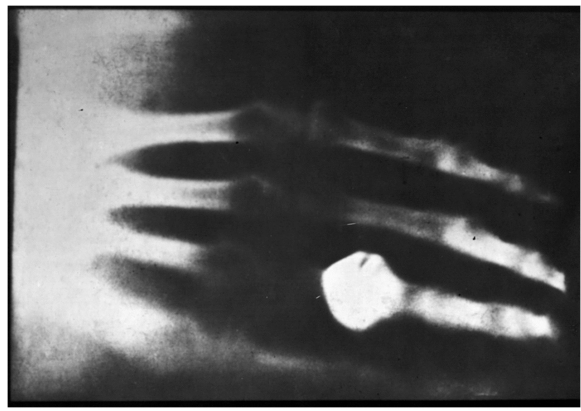
Photon & Relativity: Wave or a Particle ?

- Photon associated with EM waves, travel with speed =c
- For light (m =0) : Relativity says $E^2 = (pc)^2 + (mc^2)^2$
- $\Rightarrow E = pc$
- But Planck tells us : $E = hf = h\,(c/\lambda)$
- Put them together : $hc/\lambda = pc$
  - $\Rightarrow$ $p = h/\lambda$
  - Momentum of the photon (light) is inversely proportional to λ
- But we associate λ with waves & p with particles ….what is going on??
  - A new paradigm of conversation with the subatomic particles : Quantum Physics

X Rays : "Bremsstrahlung": Braking Radiation

- EM radiation, produced by bombarding a metal target with energetic electrons.
- Produced in general by ALL decelerating charged particles
- X rays : very short $\lambda \cong$ 60-100 pm (10^{-12}m), large frequency f
- Very penetrating because very energetic E = hf !!

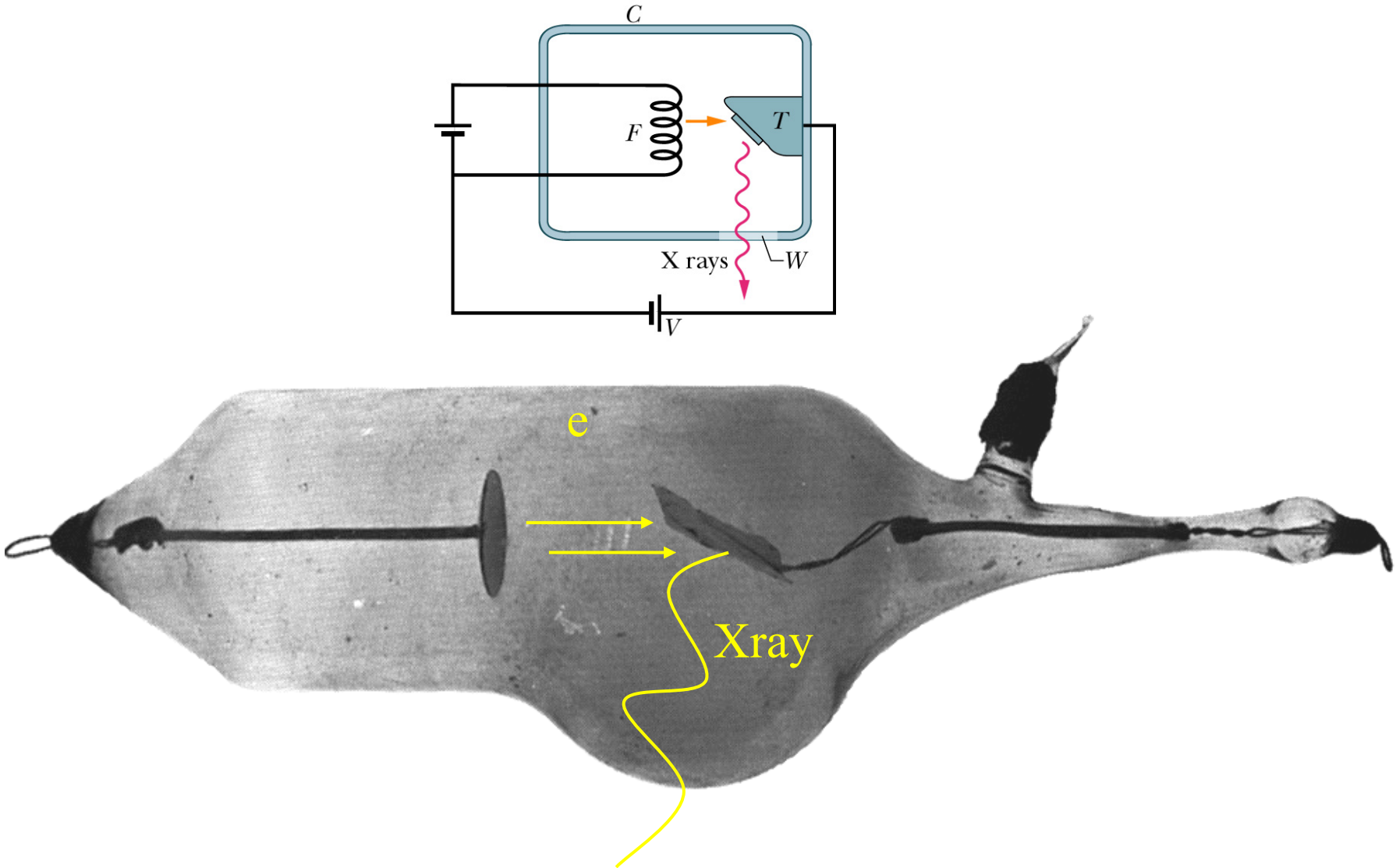




Useful for probing structure of sub-atomic Particles

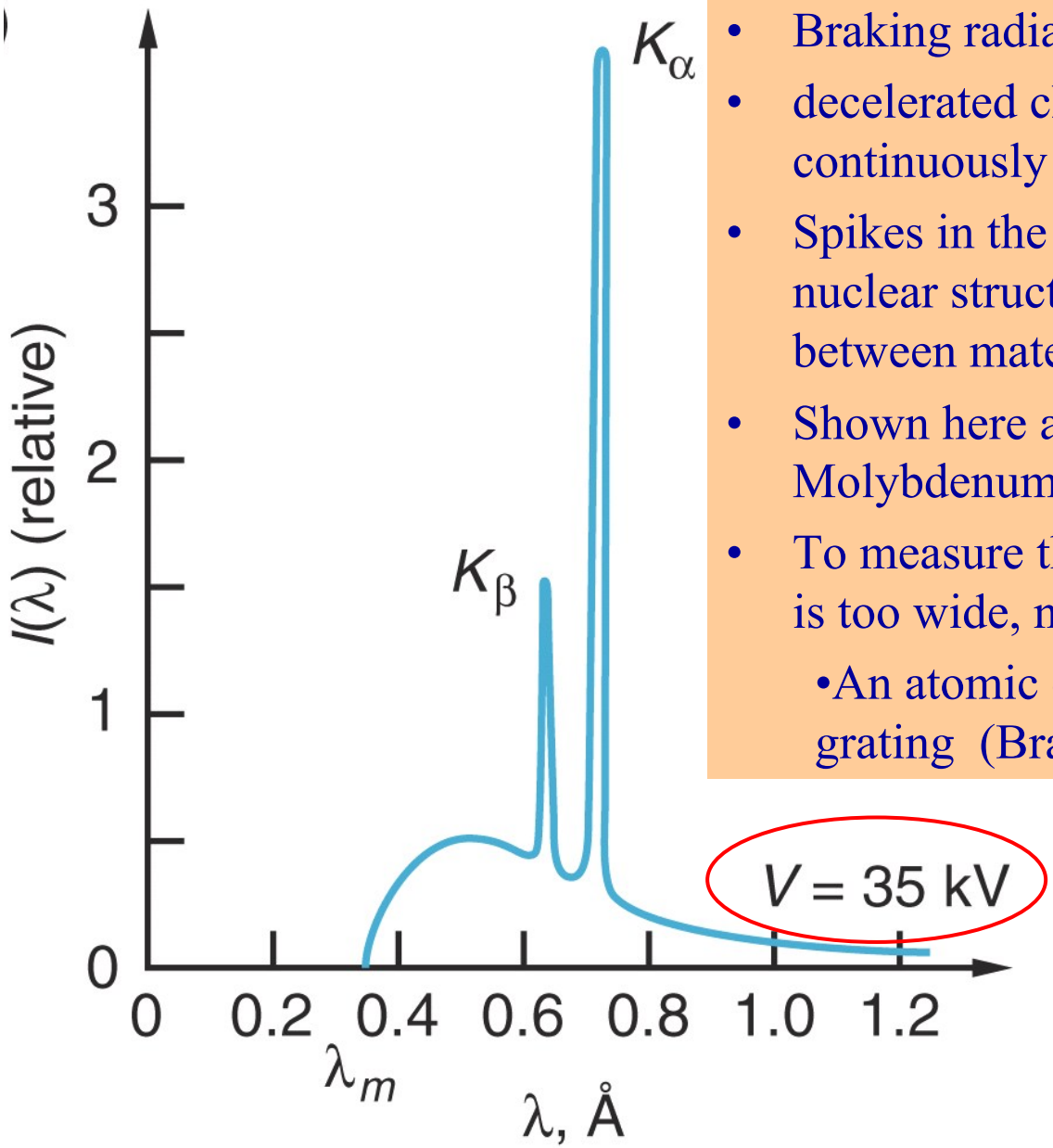
(and your teeth)

An X-ray Tube from 20th Century



The "High Energy Accelerator" of 1900s: produced energetic light : X Ray , gave new optic to subatomic phenomena

X Ray Spectrum in Molybdenum (Mo)

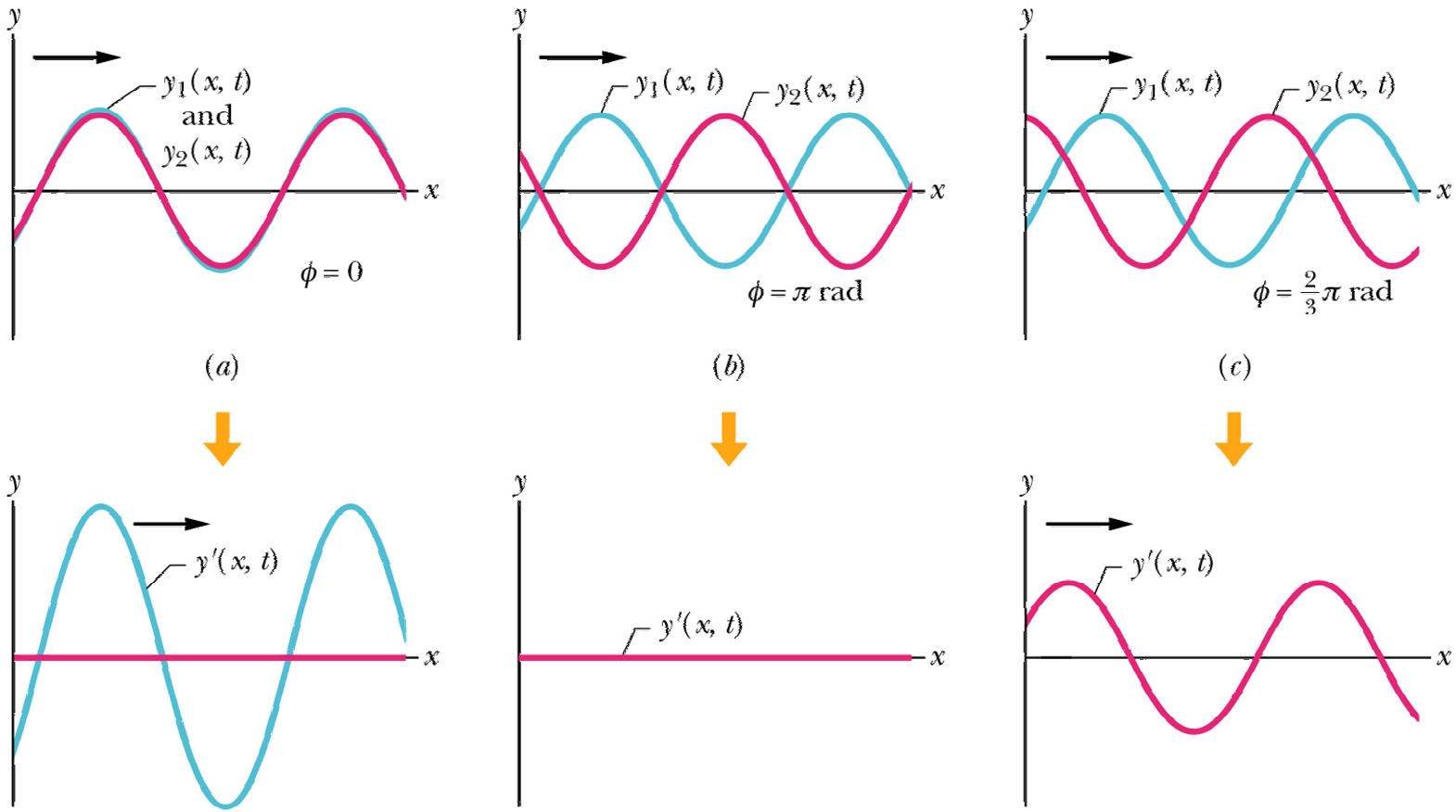


- Braking radiation predicted by Maxwell's eqn
- decelerated charged particle will radiate continuously
- Spikes in the spectrum are characteristic of the nuclear structure of target material and varies between materials
- Shown here are the α and β lines for Molybdenum (Mo)
- To measure the wavelength, diffraction grating is too wide, need smaller slits
  - An atomic crystal lattice as diffraction grating (Bragg)

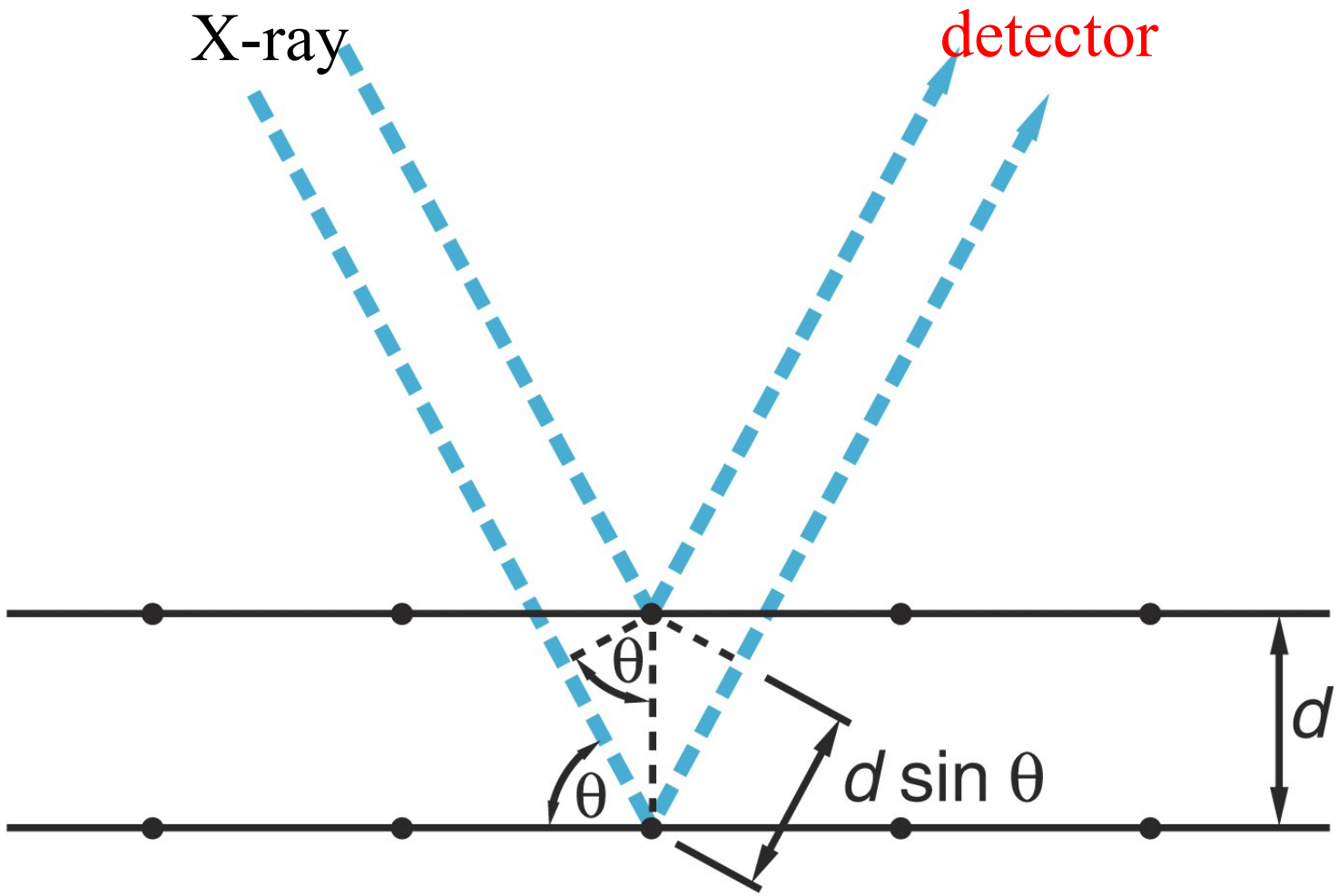
Interference of Waves: A Reminder

Two Identical waves $y_i(x,t) = y_{\max} \sin(k_i x - \omega_i t + \phi_i)$ travel along +x and interefere to give a resulting wave $y'(x,t)$. The resulting wave form depends on relative phase difference between 2 waves. Shown for $\Delta\phi = 0,\ \pi,\ \frac{2}{3}\pi$

Read Ch17-8 from Resnick etal held in Ereserve



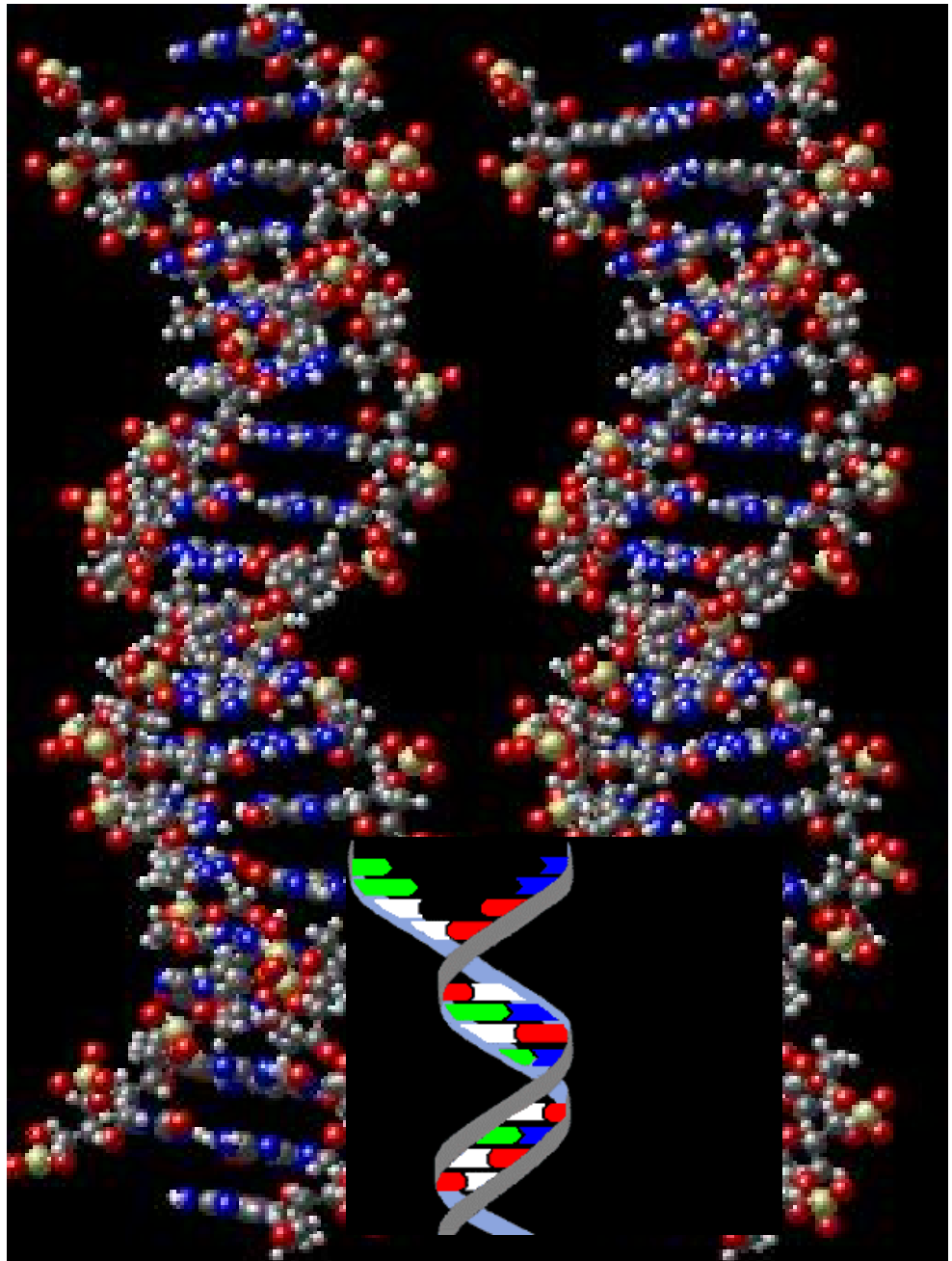
Bragg Scattering: Probing Atoms With X-Rays



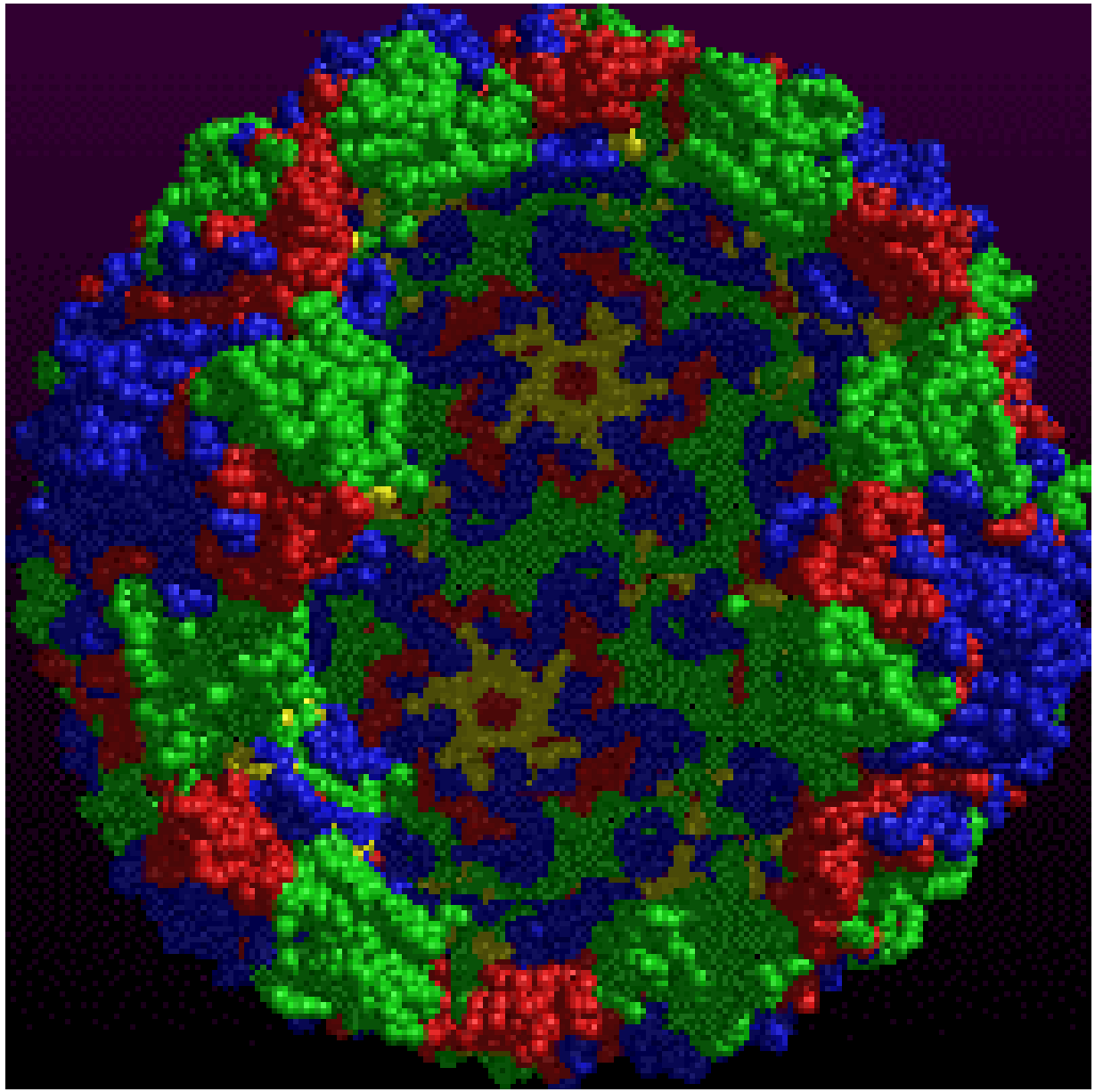
Constructive Interference when net phase difference is 0, 2π etc

This implied path difference traveled by two waves must be integral multiple of wavelength : **$n\lambda=2d\sin\vartheta$**

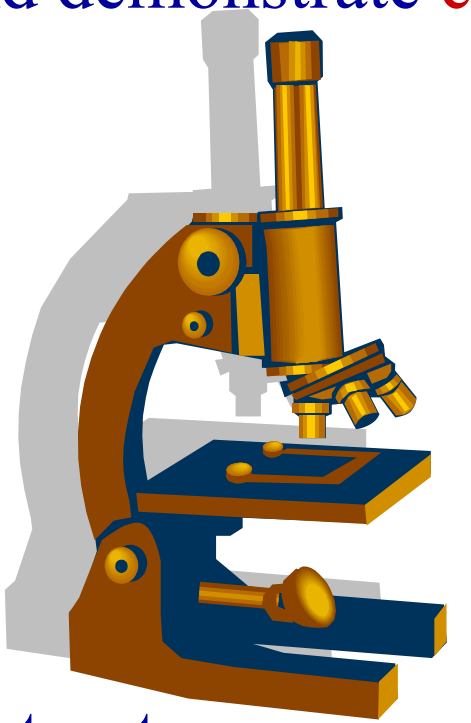
Xray picture of a DNA Crystal



Proteins inside Rhinovirus reconstructed by x-ray diffraction



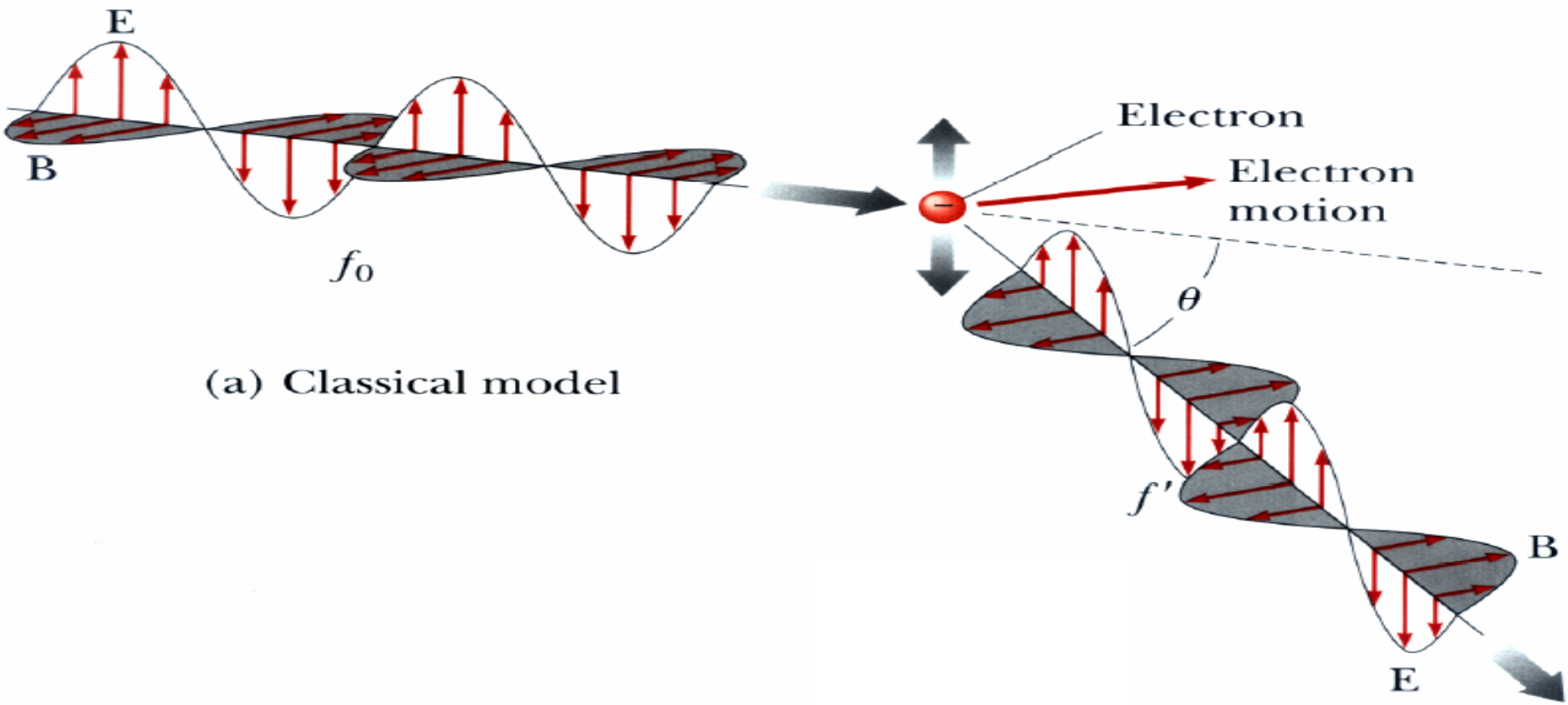
- X rays are EM waves of low wavelength, high frequency (and energy) and demonstrate characteristic features of a wave
  - Interference
  - Diffraction



- To probe into a structure you need a light source with wavelength much smaller than the features of the object being probed
  - Good Resolution → $\lambda << \Delta$
- X rays allows one probe at atomic size (10^{-10})m

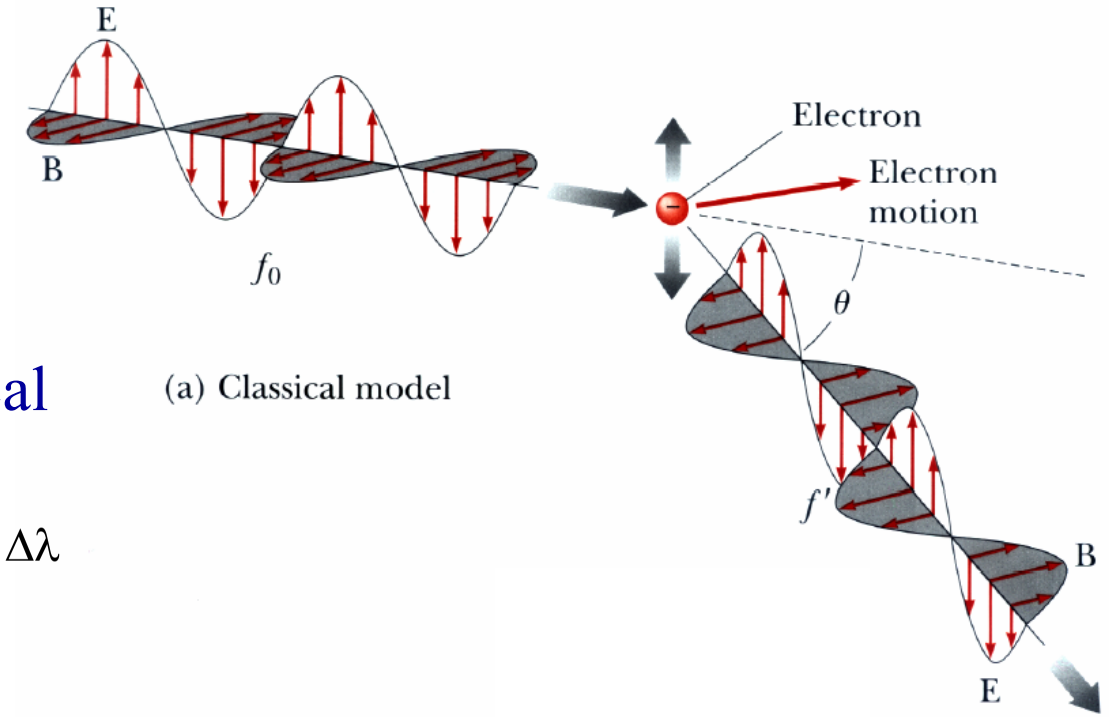
Compton Scattering : Quantum Pool !

- 1922: Arthur Compton (USA) proves that X-rays (EM Waves) have particle like properties (acts like photons)
  - Showed that classical theory failed to explain the scattering effect of
    - X rays on to free (not bound, barely bound electrons)
- Experiment : shine X ray EM waves on to a surface with "almost" free electrons
  - Watch the scattering of light off electron : measure time + wavelength of scattered X-ray



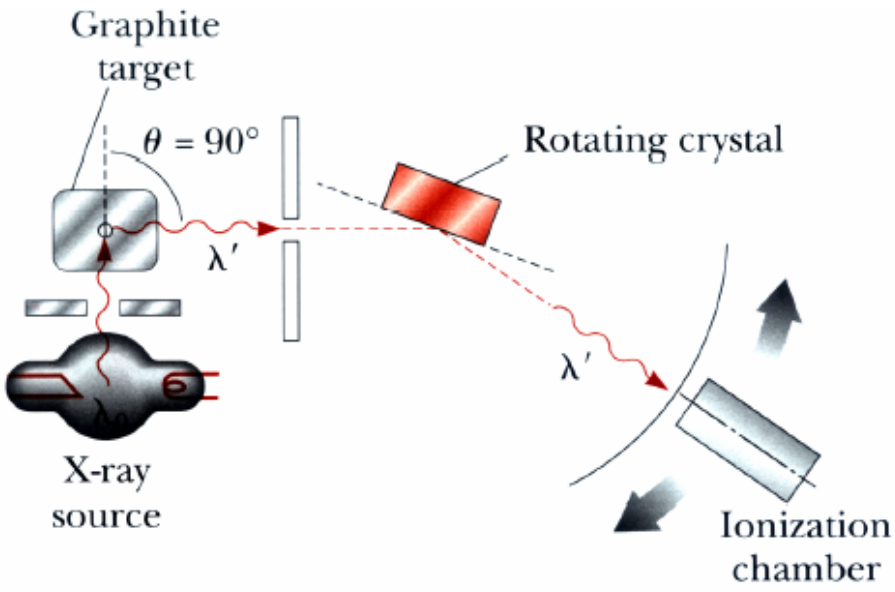
Compton Effect: what should Happen Classically?

- Plane wave [f,λ] incident on a surface with loosely bound electrons →interaction of E field of EM wave with electron: **F** = e**E**
- Electron oscillates with $f = f_{incident}$
- Eventually radiates spherical waves with $f_{radiated} = f_{incident}$
  - At all scattering angles, Δf & Δλ must be zero
- Time delay while the electron gets a "tan" : soaks in radiation



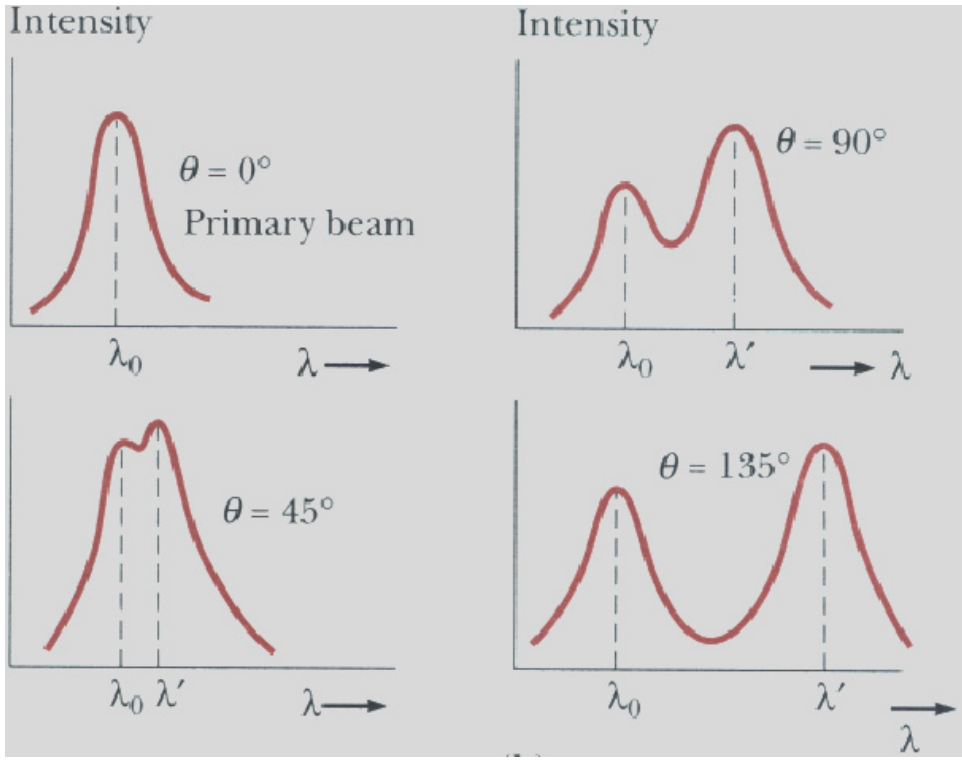
(a) Classical model

Compton Scattering : Setup & Results



$$\Delta\lambda = (\lambda' - \lambda) \propto (1 - \cos\theta)$$

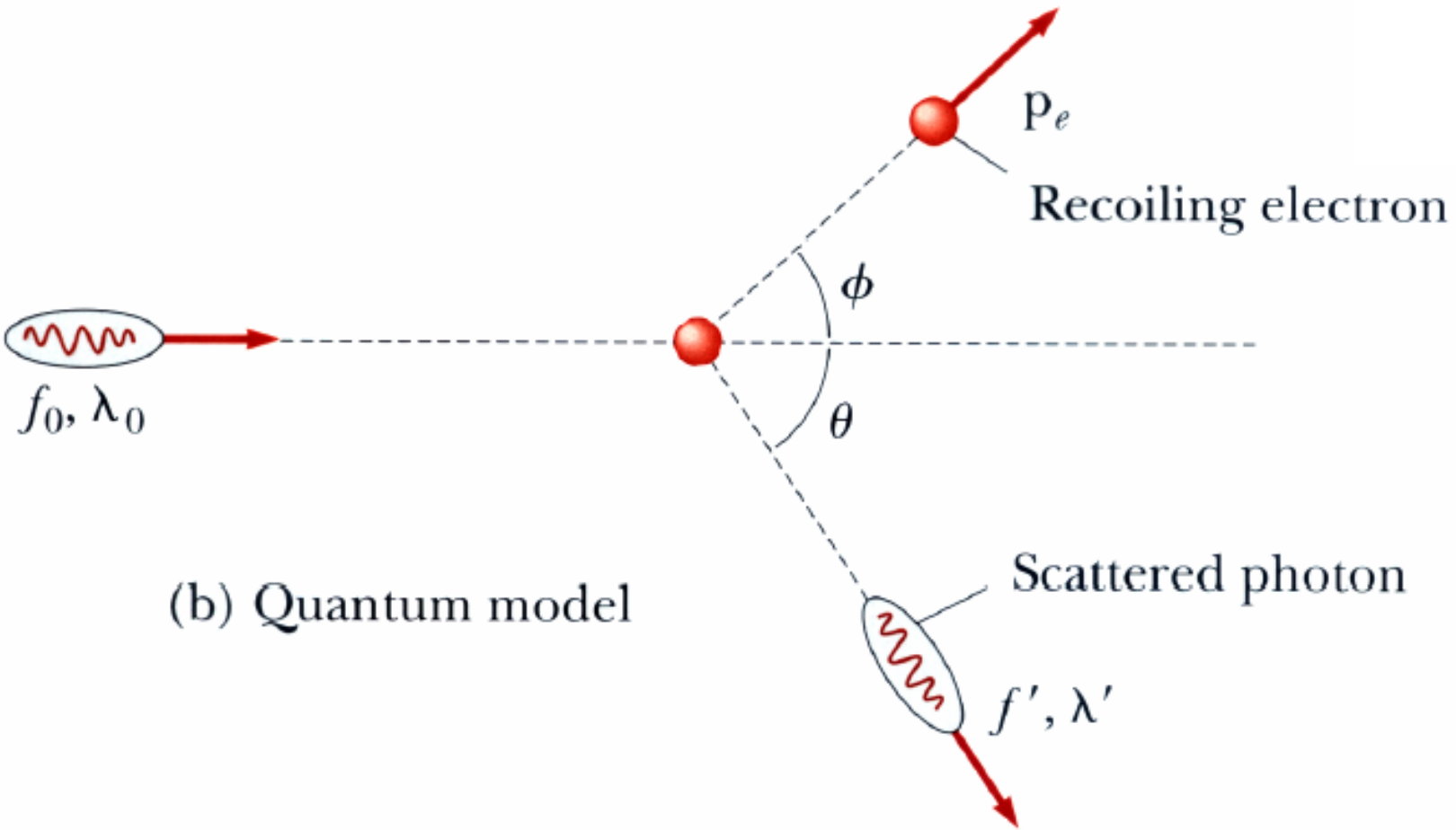
Scattered λ' larger than incident



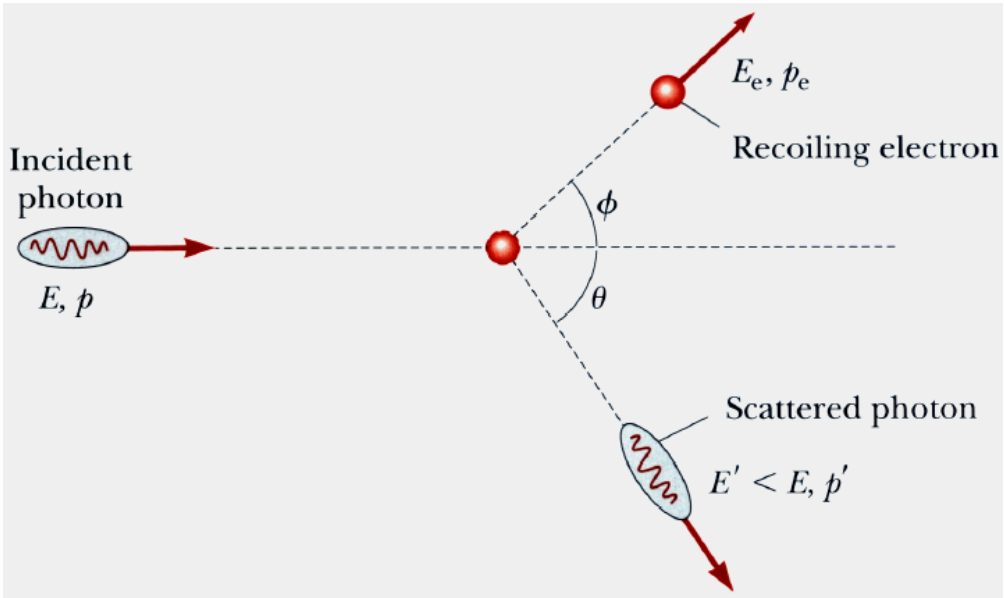
$$\Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos\theta)$$

How does one explain this startling anisotropy?

Compton Effect : Quantum (Relativistic) Pool



Compton Scattering: Quantum Picture



$p_e \cos\phi = p - p'\cos\theta$

$p_e \sin\phi = p'\sin\theta$

Square and add $\Rightarrow$

$p_e^2 = p^2 - 2pp'\cos\theta + p'^2$

Eliminate p_e & E_e using

$E_e^2 = p_e^2c^2 + m_e^2c^4$ &

$E_e = (E - E') + m_ec^2$

Energy Conservation:

$E + m_ec^2 = E' + E_e$

Momentum Conserv:

$p = p'\cos\theta + p_e\cos\phi$

$0 = p'\sin\theta - p_e\sin\phi$

Use these to eliminate electron deflection angle (not measured)

$$\left((E - E') + m_ec^2\right)^2 = \left[p^2 - 2pp'\cos\theta + p'^2\right] + (m_ec^2)^2$$

For light $p = \frac{E}{c} \Rightarrow$

$$E^2 + E'^2 - 2EE' + 2(E - E')mc^2 = \left[\frac{E^2}{c^2} - 2\frac{EE'}{c^2}\cos\theta + \frac{E'^2}{c^2}\right]c^2$$

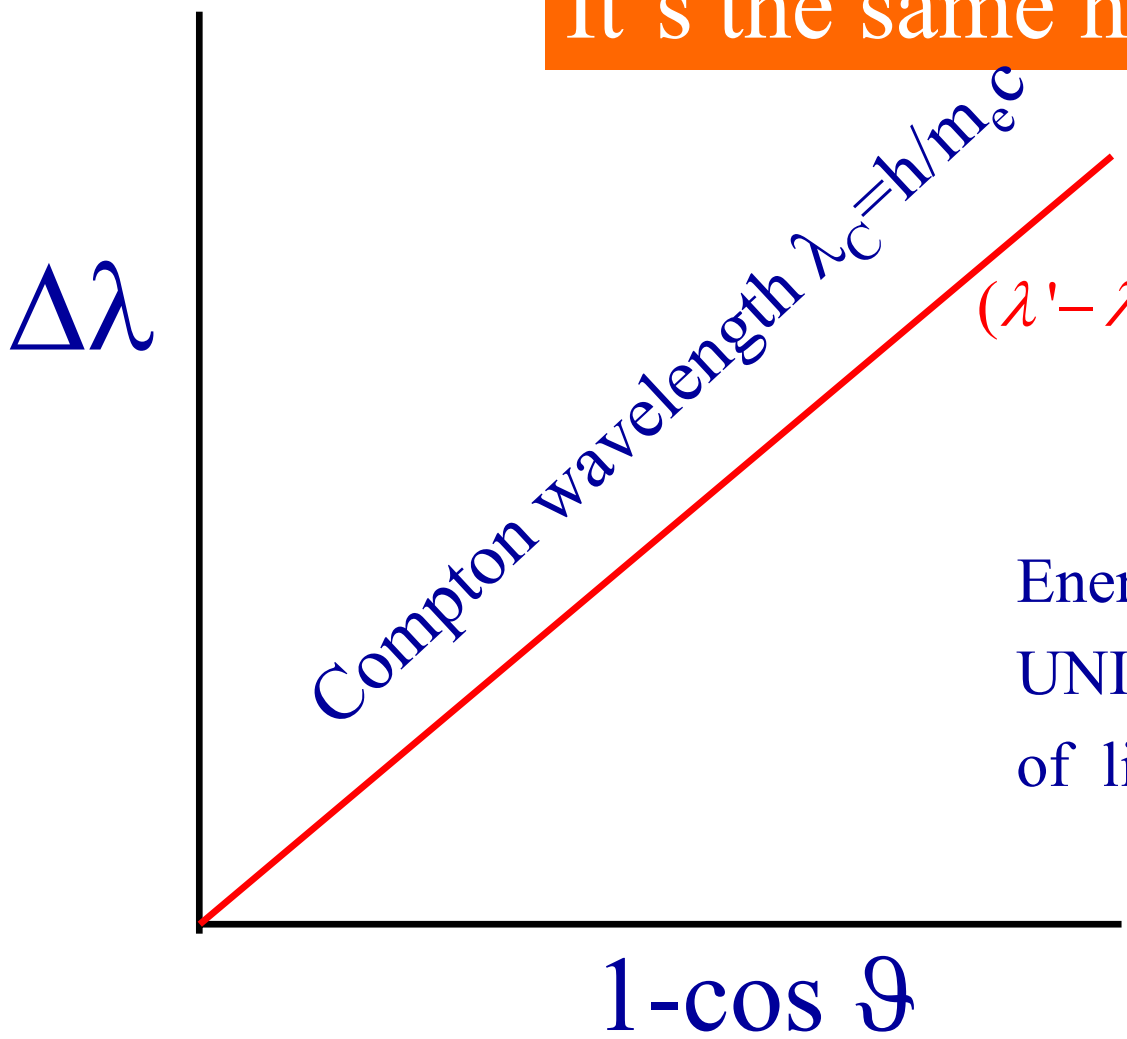
$$\Rightarrow -EE' + (E - E')mc^2 = -EE'\cos\theta$$

$$\Rightarrow \frac{E - E'}{EE'} = -\frac{1}{m_ec^2}(1 - \cos\theta) \Rightarrow (\lambda' - \lambda) = \left(\frac{h}{m_ec}\right)(1 - \cos\theta)$$

Checking for h in Compton Scattering

Plot scattered photon data, calculate slope and measure h

It's the same h !!



$$(\lambda' - \lambda) = (\frac{h}{m_e c})(1 - \cos\theta)$$

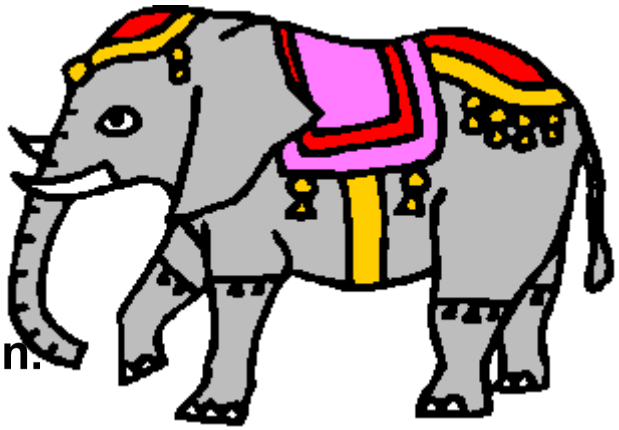
Energy Quantization is a UNIVERSAL characteristic of light (EM Waves)

Blindmen & an Elephant

touched the trunk of the elephant, said elephant was like a **branch of a tree**.

touched the tail of the elephant, said elephant was like a **snake.**

touched an ear. He said elephant was a **huge fan.**



felt a leg of the elephant., elephant was like a **pillar**.

touched the side of the elephant, said the elephant was like a **wall**

Gentlemen, all five of you have touched only one part of the elephant ..elephant **is all of above**

LIKEWISE WITH LIGHT !