



# Physics 2D Lecture Slides

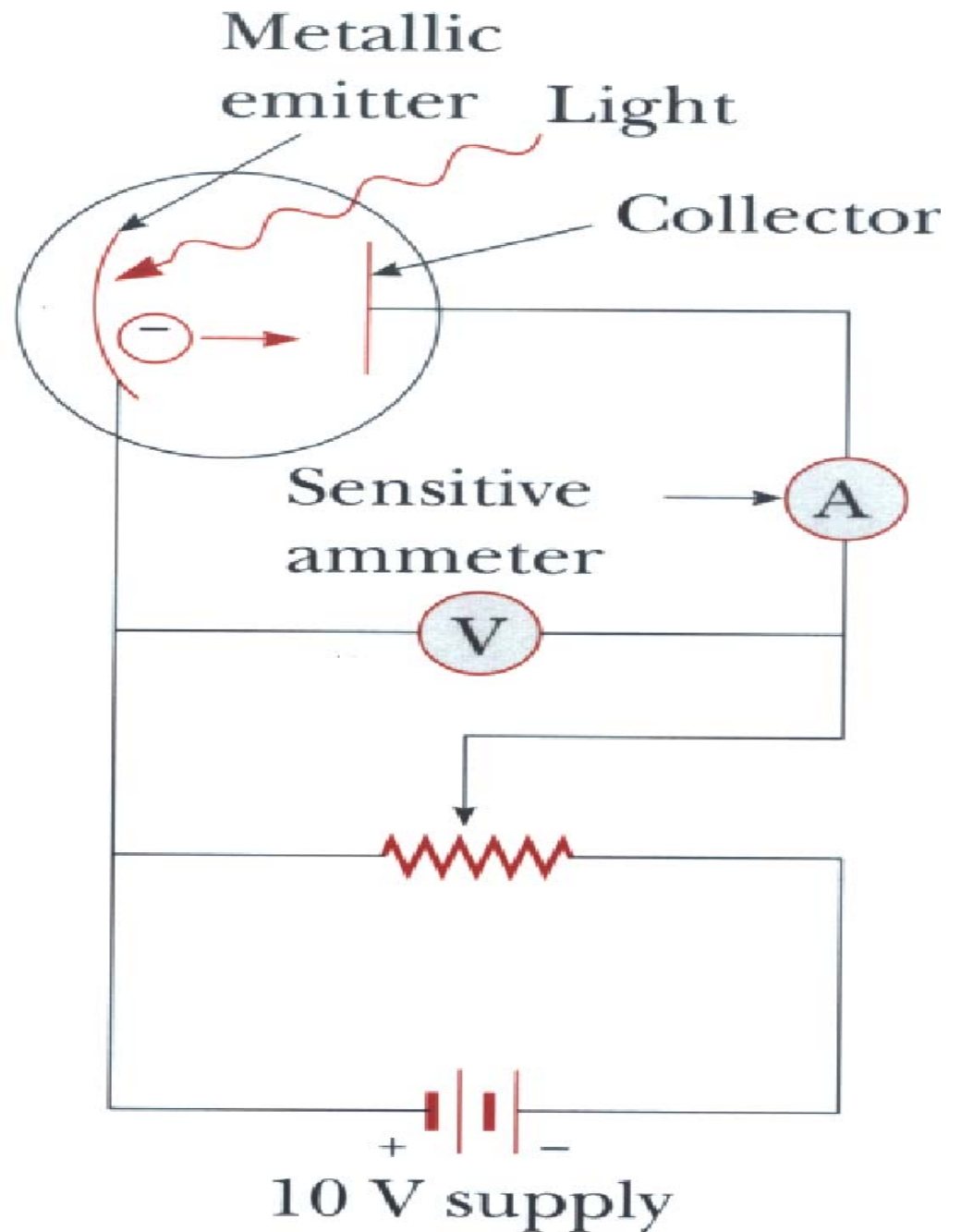
## Jan 29

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UCSD Physics

# Disasters in Classical Physics (1899-1922)

- Disaster → Experimental observation that could not be explained by Classical theory (Phys 2A, 2B, 2C)
  - Disaster # 1 : Nature of Blackbody Radiation from your BBQ grill
  - Disaster # 2: Photo Electric Effect
  - Disaster # 3: Scattering light off electrons (Compton Effect)
- Resolution of Experimental Observation will require radical changes in how we think about nature
  - → QUANTUM MECHANICS
    - The Art of Conversation with Subatomic Particles

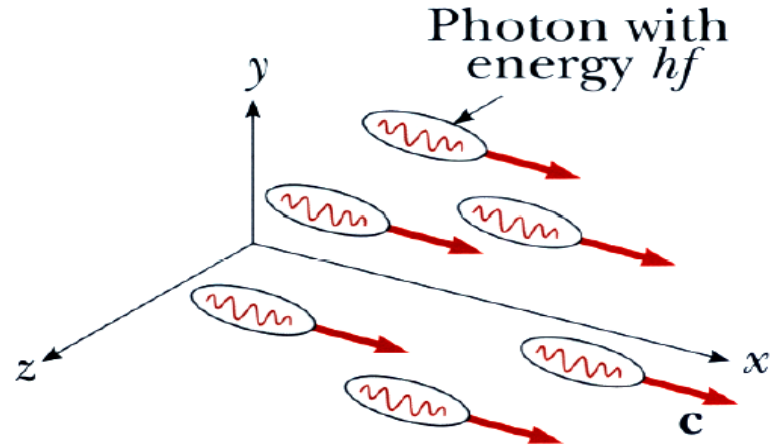
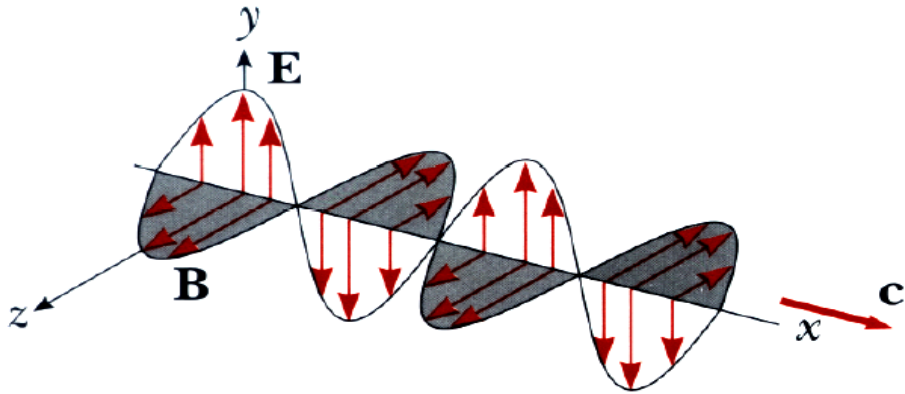
# Photo Electric Effect



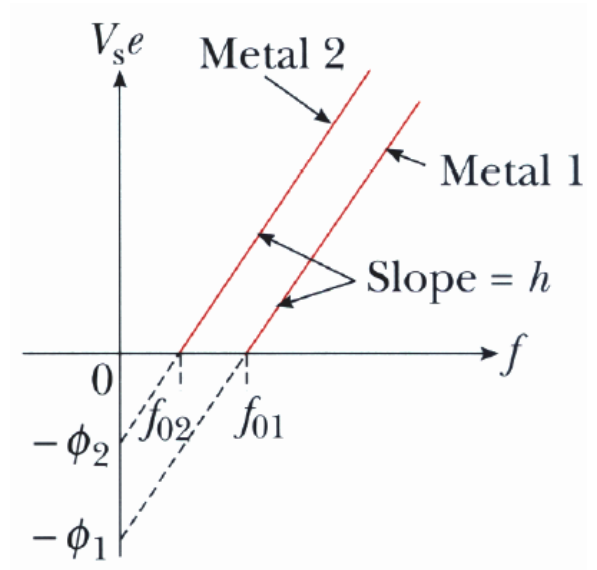
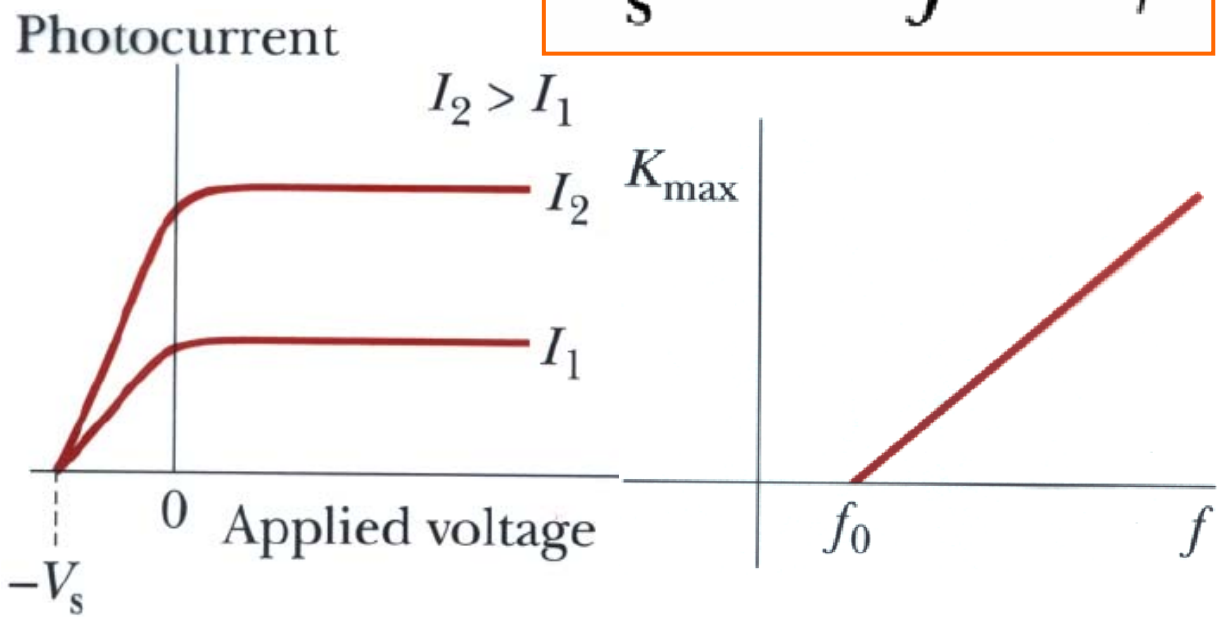
# Einstein's Explanation of Photoelectric Effect

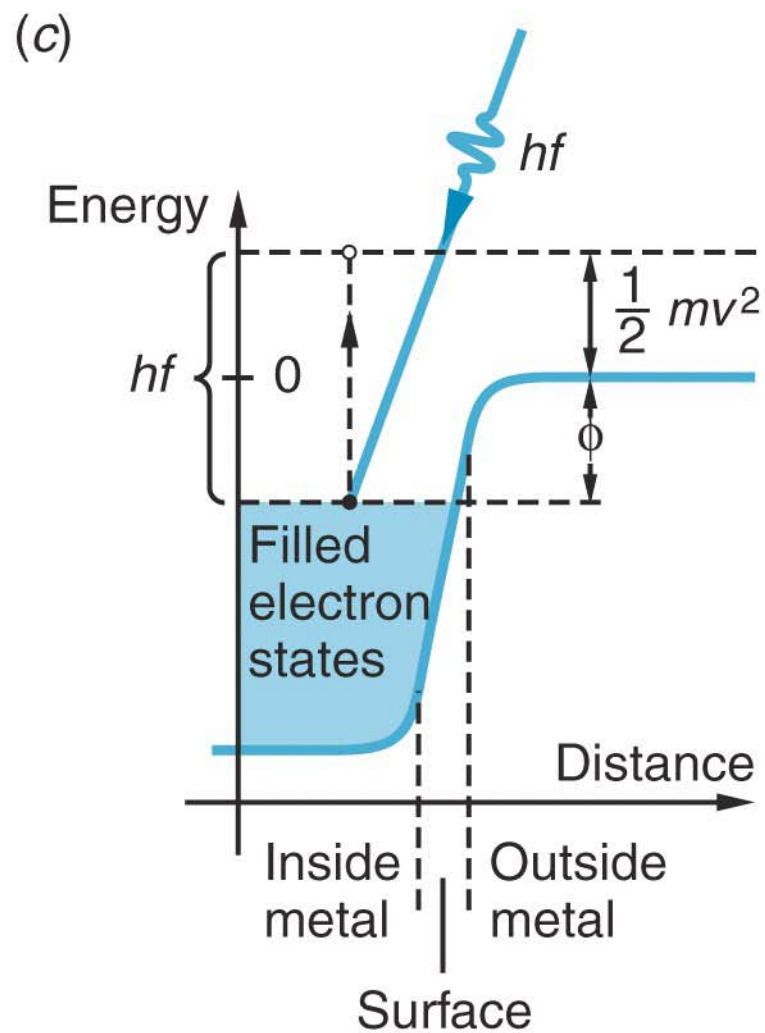
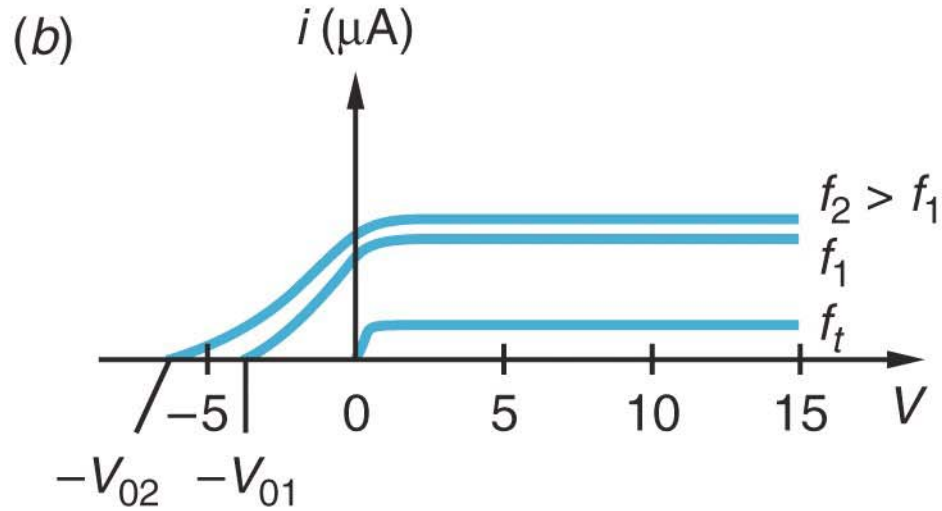
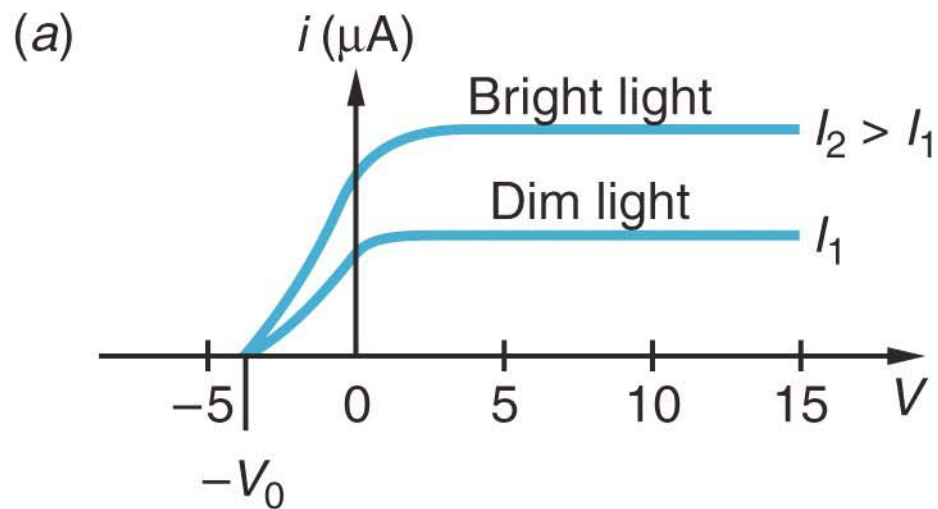
- Energy associated with EM waves is not uniformly distributed over wave-front, rather is contained in packets of “stuff”  $\Rightarrow$  PHOTON
- $E = hf = hc/\lambda$  [ but is it the same  $h$  as in Planck's th.?? ]
- Light shining on metal emitter/cathode is a **stream of photons** of energy which depends on frequency  $f$
- Photons knock off electron from metal instantaneously
  - Transfer all energy to electron
  - Energy gets used up to pay for Work Function  $\Phi$  (Binding Energy)
    - Rest of the energy shows up as KE of electron  $KE = hf - \Phi$
- Cutoff Frequency  $hf_0 = \Phi$  (pops an electron,  $KE = 0$ )
- Larger intensity  $I \rightarrow$  more photons incident
- **Low frequency light**  $f \rightarrow$  not energetic enough to overcome work function of electron in atom

# Einstein's Explanation of PhotoElectric Effect



$$V_s e = hf - \phi$$

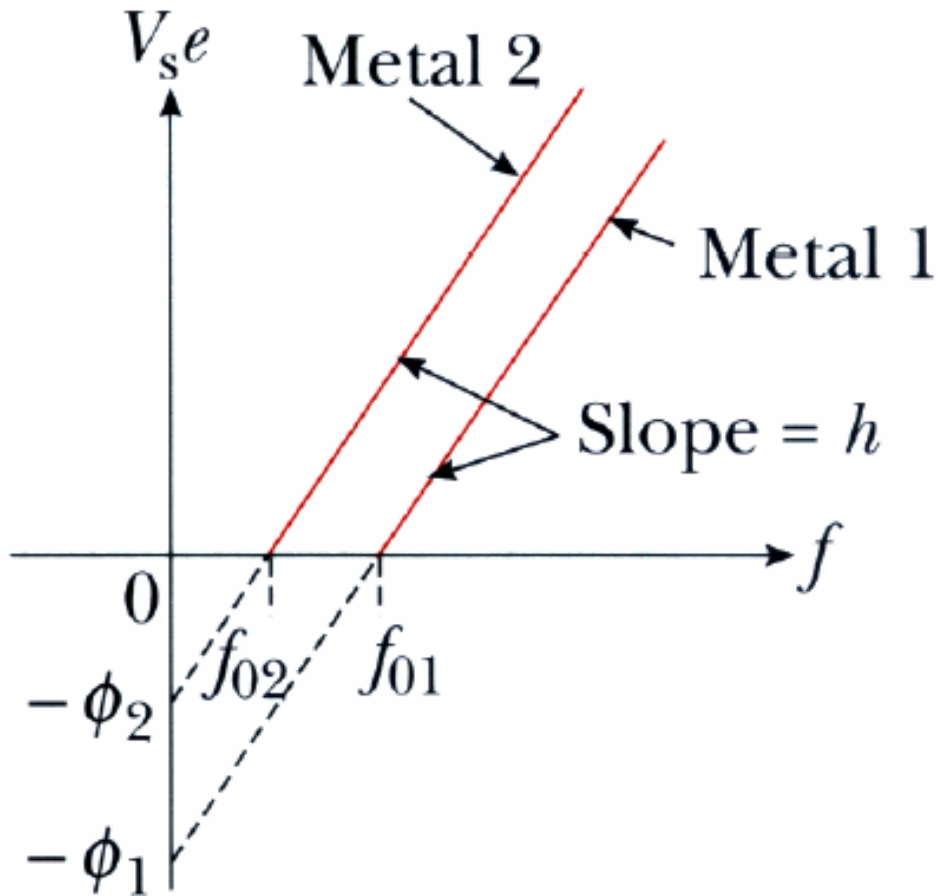




# Is “h” same in Photoelectric Effect as BB Radiation?

Slope  $h = 6.626 \times 10^{-34} \text{ JS}$

Einstein  $\rightarrow$  Nobel Prize!



No matter where you travel  
in the galaxy and beyond...  
..no matter what experiment  
You do

$h$  : Planck's constant is same

**NOBEL PRIZE FOR PLANCK**

# Work Function (Binding Energy) In Metals

**TABLE 3-1** Photoelectric work functions

Element	$\phi$ (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 some Iron Surface:

Light of Intensity  $I = 1.0 \mu\text{W}/\text{cm}^2$  incident on  $1.0\text{cm}^2$  surface of Fe

Assume Fe reflects 96% of light

further only 3% of incident light is Violet region ( $\lambda = 250\text{nm}$ )

barely above threshold frequency for Ph. El effect

(a) Intensity available for Ph. El effect  $I = 3\% \times 4\% \times (1.0 \mu\text{W}/\text{cm}^2)$

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

$$\begin{aligned}\# \text{ of photoelectrons} &= \frac{\text{Power}}{h f} = \frac{3\% \times 4\% \times (1.0 \mu\text{W}/\text{cm}^2) \lambda}{hc} \\ &= \frac{(250 \times 10^{-9} \text{ m})(1.2 \times 10^{-9} \text{ J} / \text{ s})}{(6.6 \times 10^{-34} \text{ J} \cdot \text{ s})(3.0 \times 10^8 \text{ m} / \text{ s})} \\ &= 1.5 \times 10^9\end{aligned}$$

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

(d) Work Function  $\Phi = hf_0 = (4.14 \times 10^{-15} \text{ eV} \cdot \text{ s})(1.1 \times 10^{15} \text{ s}^{-1})$   
 $= 4.5 \text{ eV}$

# 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 :  $hc /\lambda = pc$ 
  - $\Rightarrow \mathbf{p = h/\lambda}$
  - Momentum of the photon (light) is inversely proportional to  $\lambda$
- But we associate  $\lambda$  with waves &  $p$  with particles ....what is going on??
  - A new paradigm of conversation with the subatomic particles : **Quantum Physics**

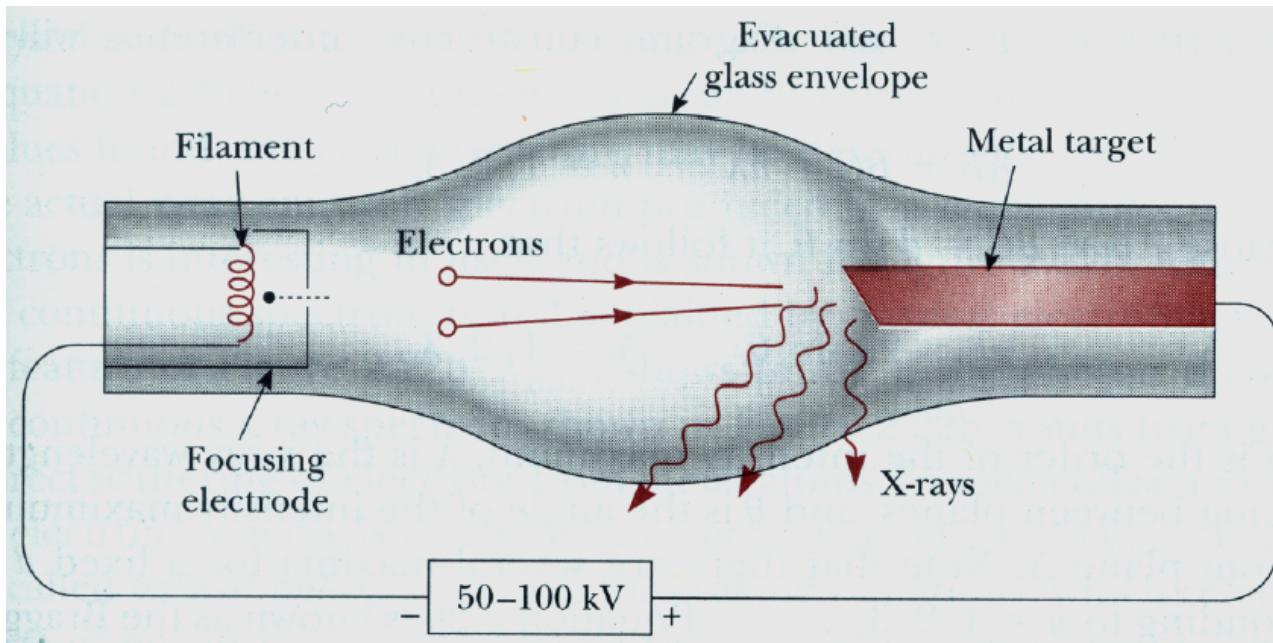
# X Rays : “Bremsstrahlung”: Braking Radiation

Produced by bombarding a metal target with energetic electrons

Produced in general by ALL accelerating charged particles

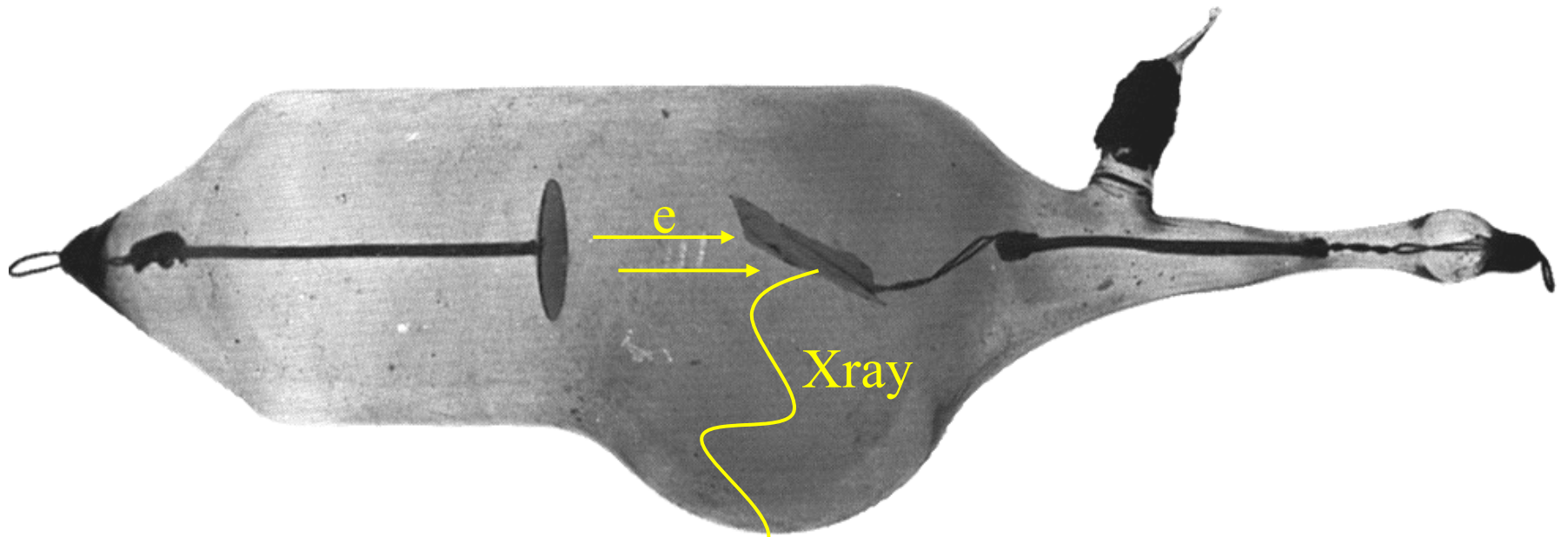
X rays : very short  $\lambda \cong 60\text{-}100 \text{ pm}$  ( $10^{-12}\text{m}$ ), large frequency  $f$

Very penetrating because energetic



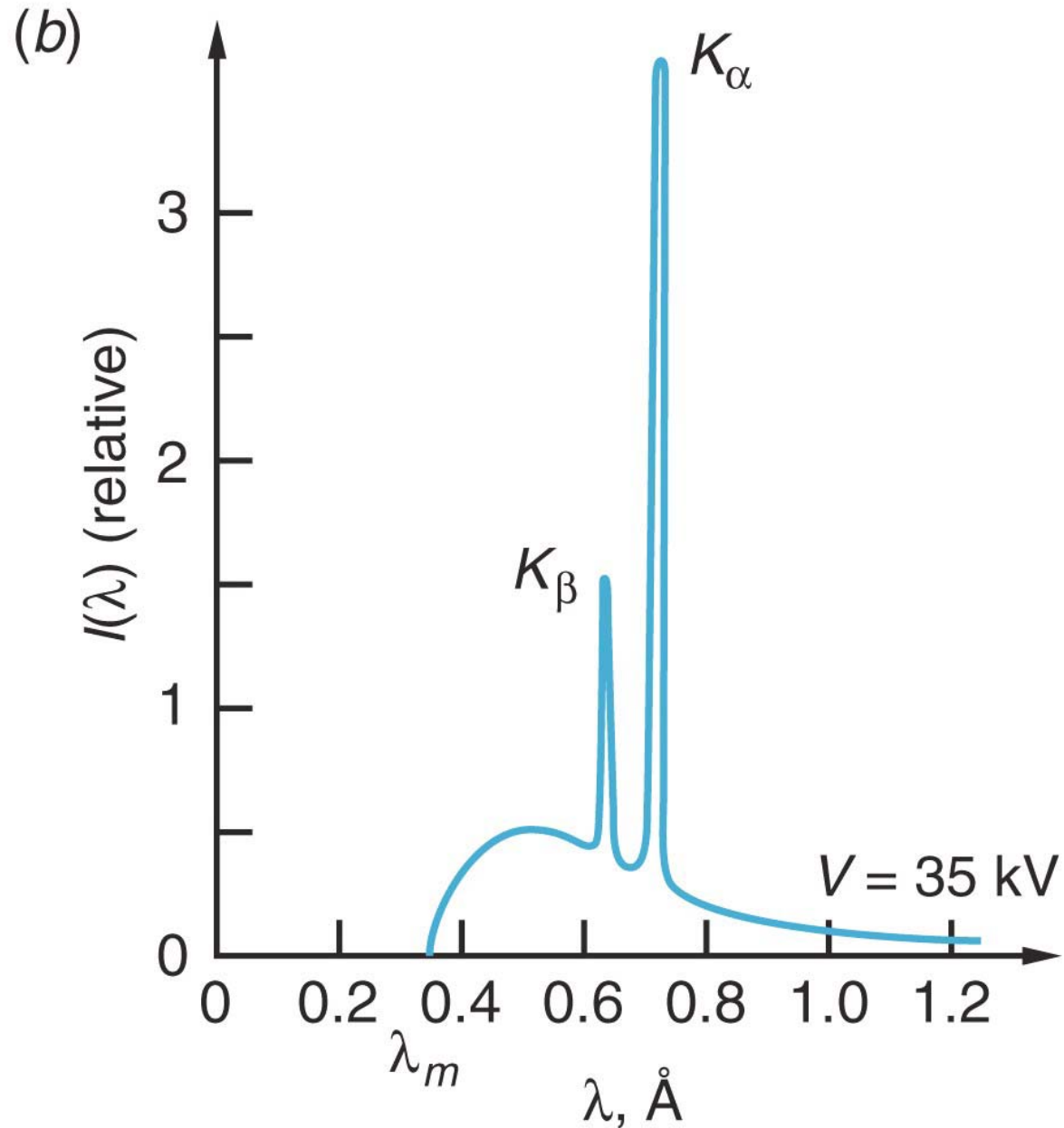
Useful for probing structure of sub-atomic Particles

# An X-ray Tube from 20<sup>th</sup> Century



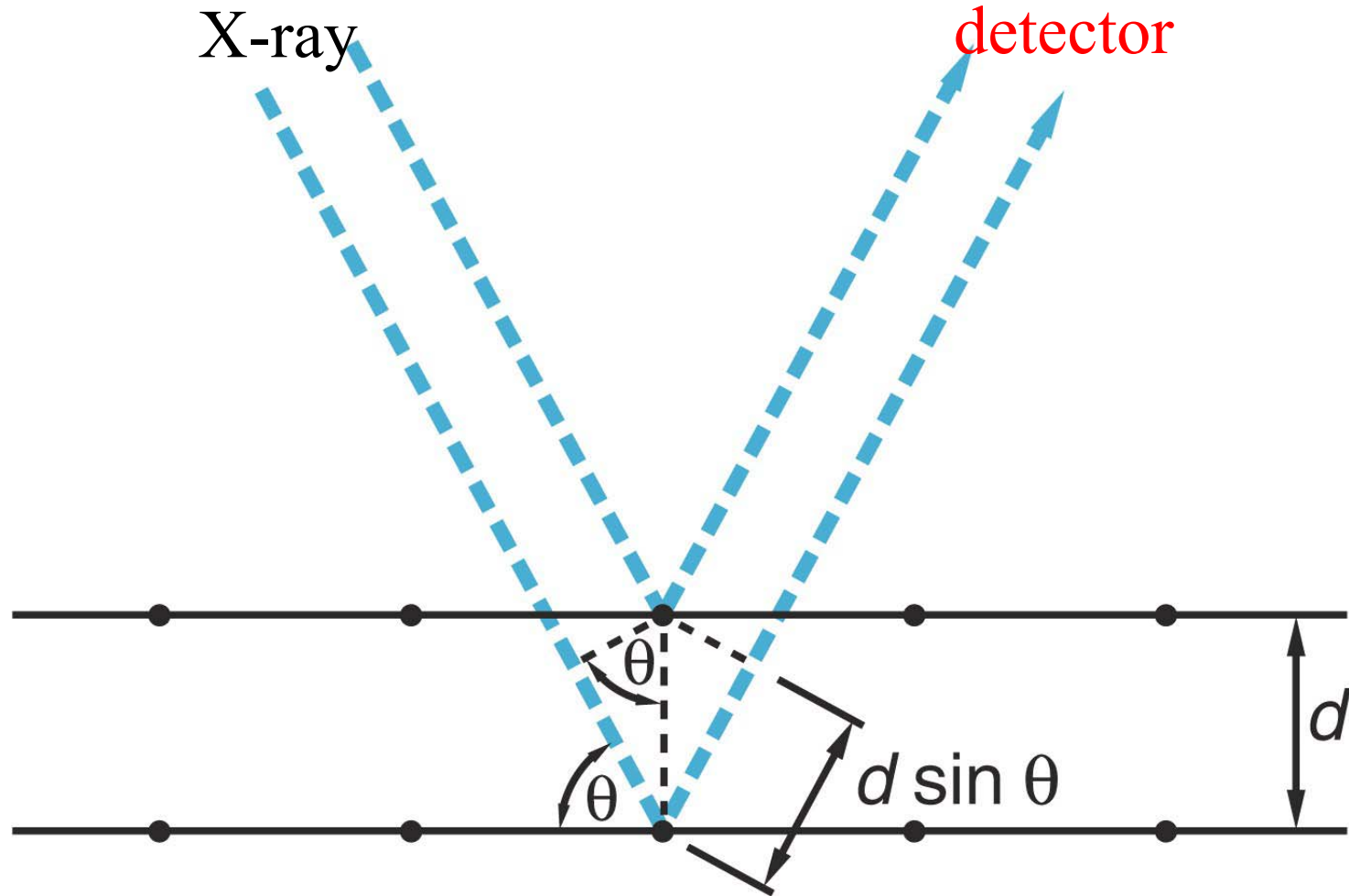
The “High Energy Accelerator” of 1900s:  
produced energetic light : X –Ray , gave new optic  
to subatomic phenomena

# X Ray Spectrum in Molybdenum (Mo)



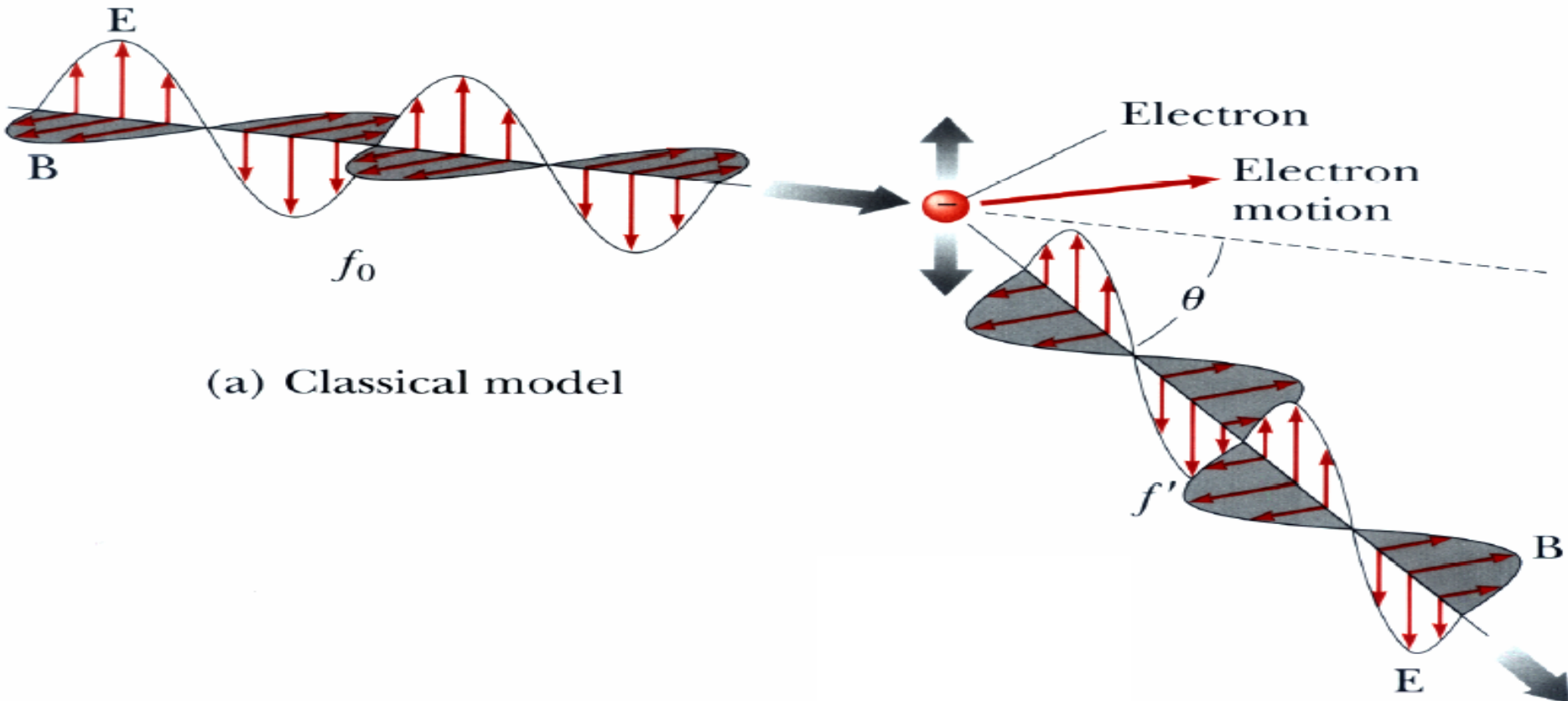
# Bragg Scattering: Probing Atoms With X-Rays

Constructive Interference:  $n\lambda = 2d \sin \theta$



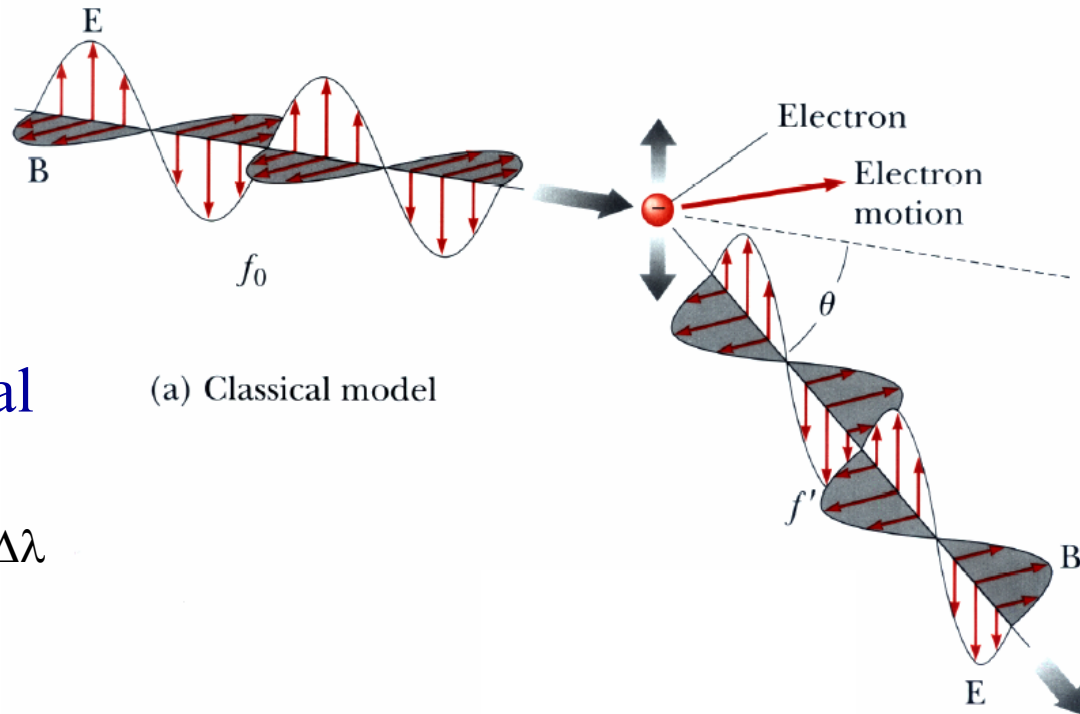
# Compton Scattering : Quantum Pool !

- 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

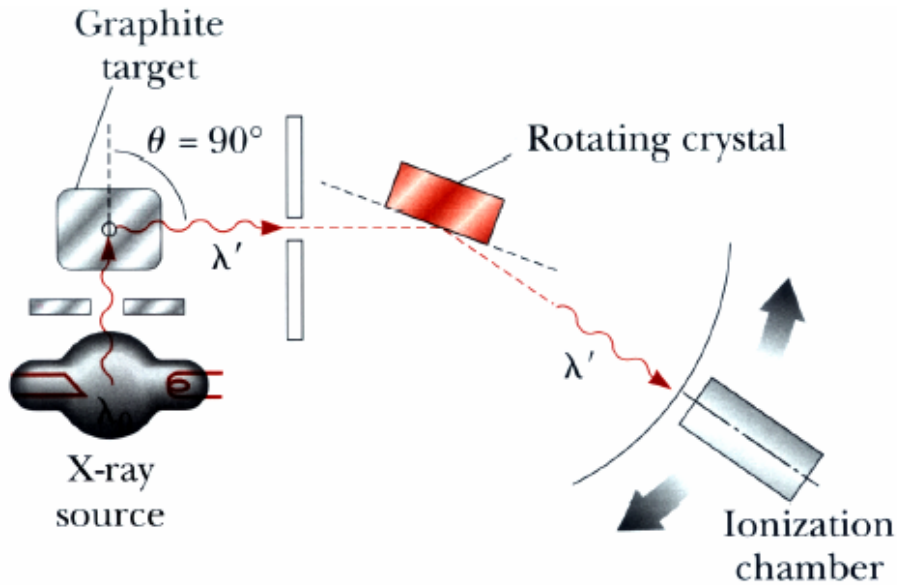


# Compton Effect: what should Happen Classically?

- Plane wave  $[f, \lambda]$  incident on a surface with loosely bound electrons  $\rightarrow$  interaction of E field of EM wave with electron:  $\mathbf{F} = e\mathbf{E}$
- Electron oscillates with  $f = f_{\text{incident}}$
- Eventually radiates spherical waves with  $f_{\text{radiated}} = f_{\text{incident}}$ 
  - At all scattering angles,  $\Delta f$  &  $\Delta \lambda$  must be zero
- Time delay while the electron gets a “tan” : soaks in radiation

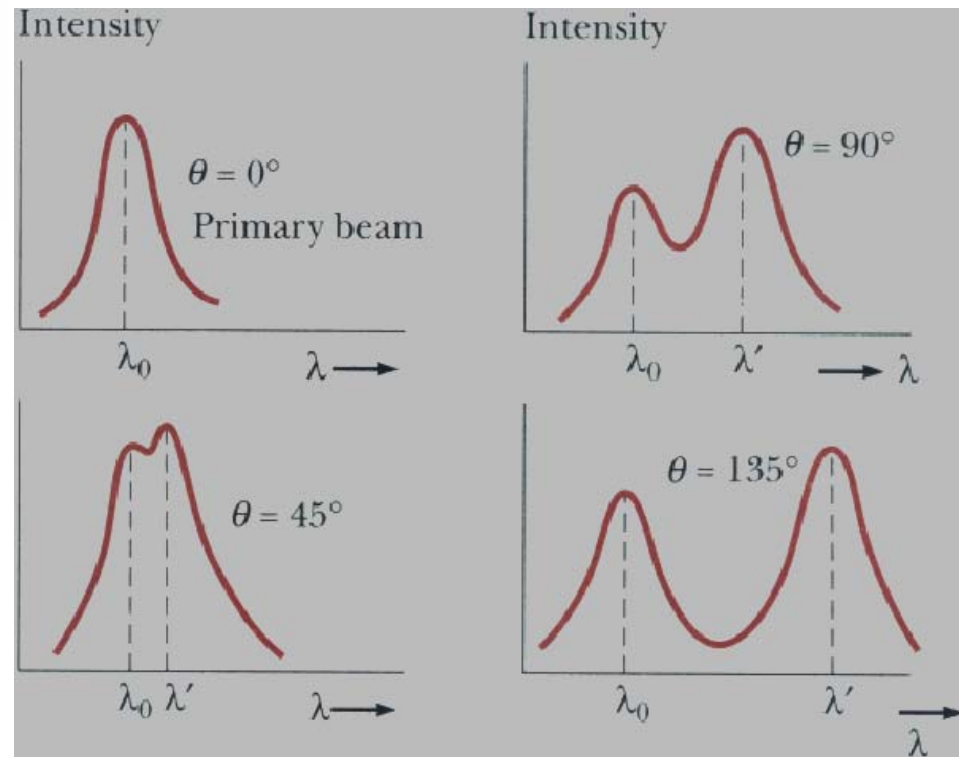


# Compton Scattering : Setup & Results



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

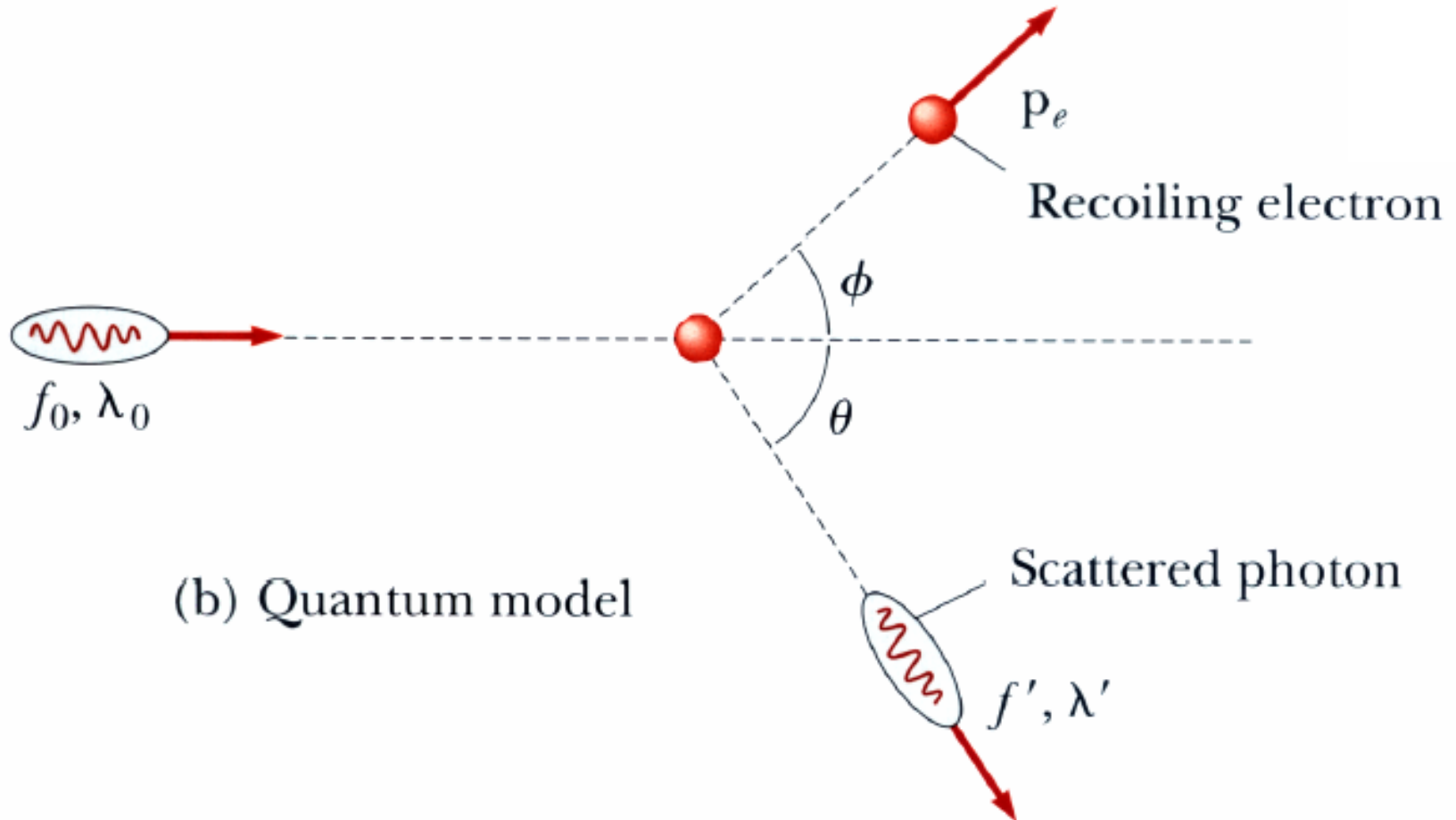
Scattered  $\lambda'$  larger than incident



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

How does one explain this startling anisotropy?

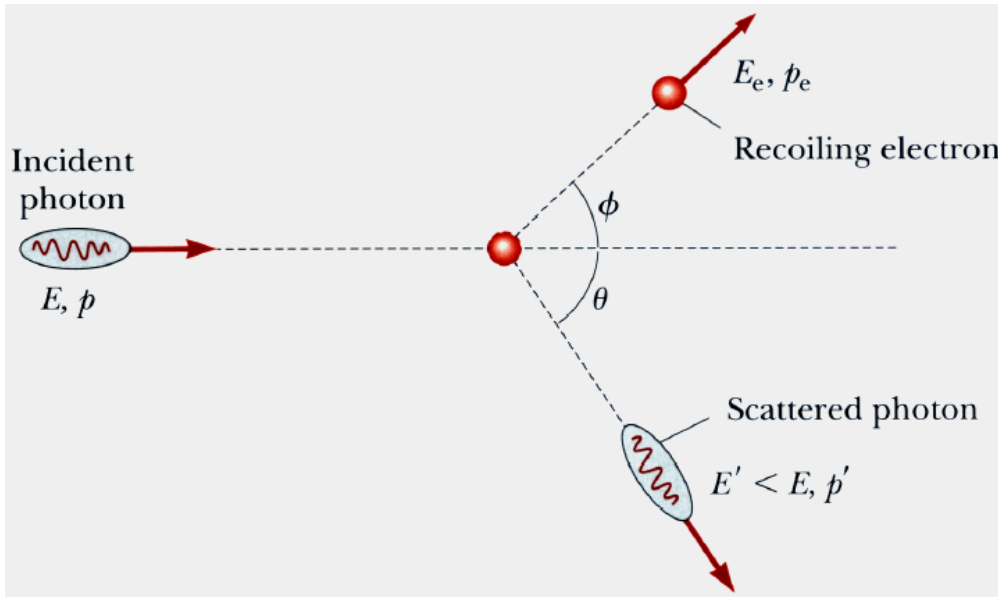
# Compton Effect : Quantum (Relativistic) Pool



(b) Quantum model



# 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

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

$$E_e = (E - E') + m_e c^2$$

**Energy Conservation:**

$$E + m_e c^2 = E' + E_e$$

**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)

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

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

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

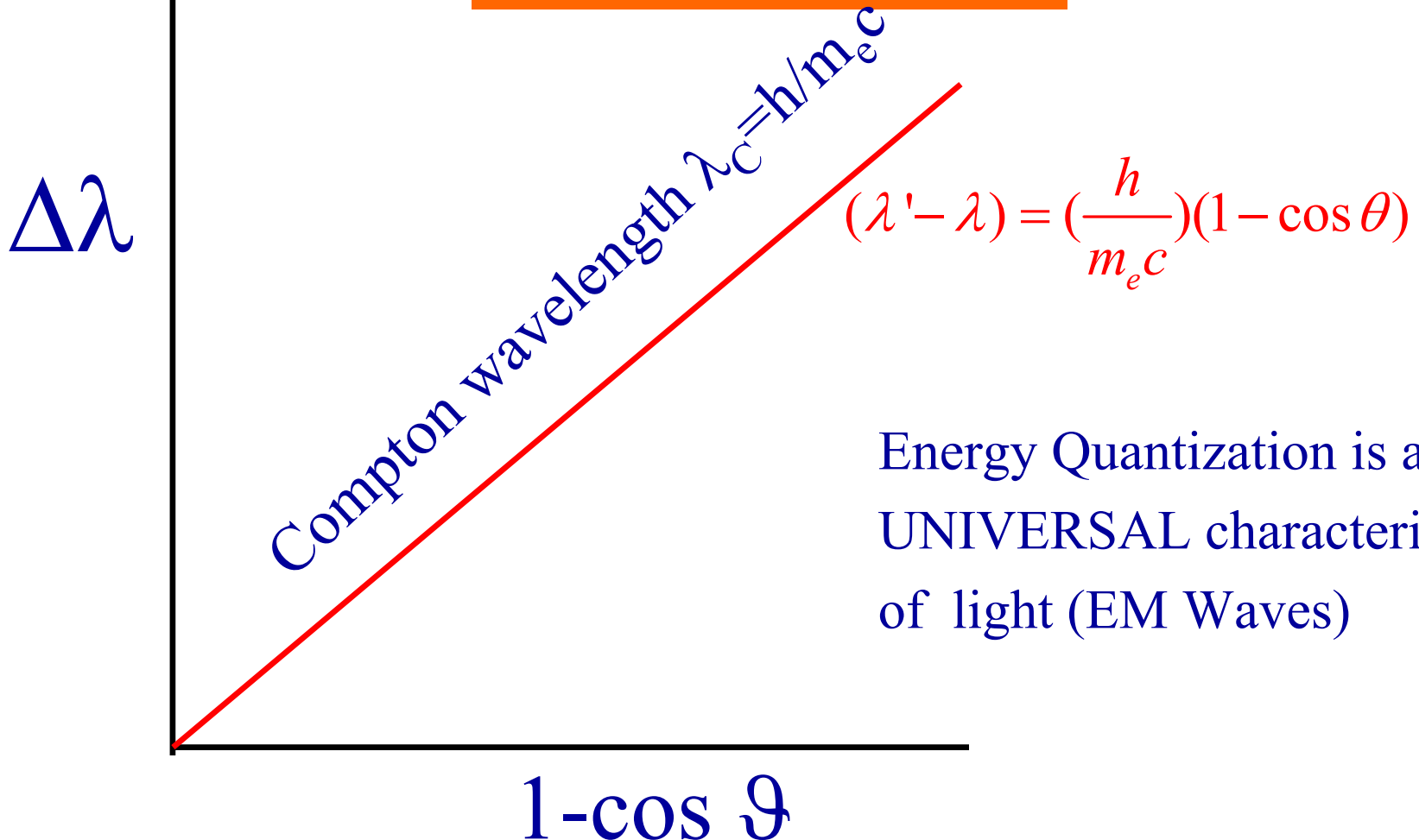
$$\Rightarrow -EE' + (E - E')mc^2 = -EE' \cos \theta$$

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

# Checking for h in Compton Scattering

Plot scattered photon data, calculate slope and measure h

It's the same h !!



# 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**.



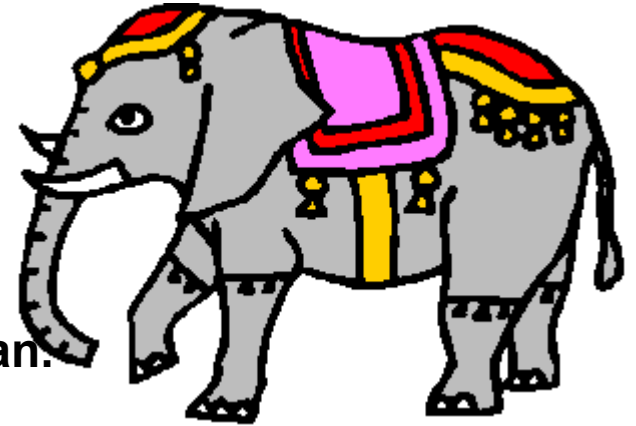
felt a leg of the elephant., elephant was like a **pillar**.



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**

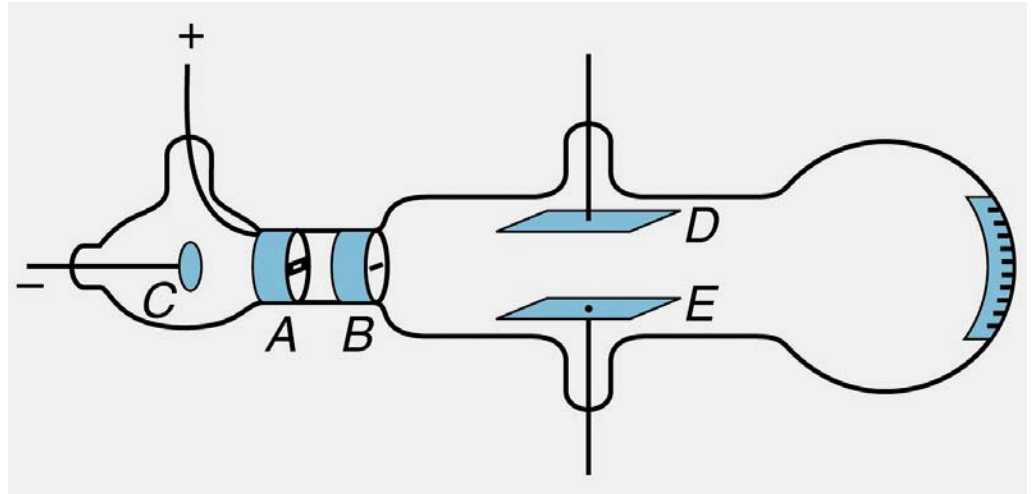


**LIKEWISE WITH LIGHT !**

# Next Question : What is the Nature of Matter

- Fundamental Characteristics of different forms of matter

- Mass
- Charge
- Measure them



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

