Physics 2D Lecture Slides
Oct 20

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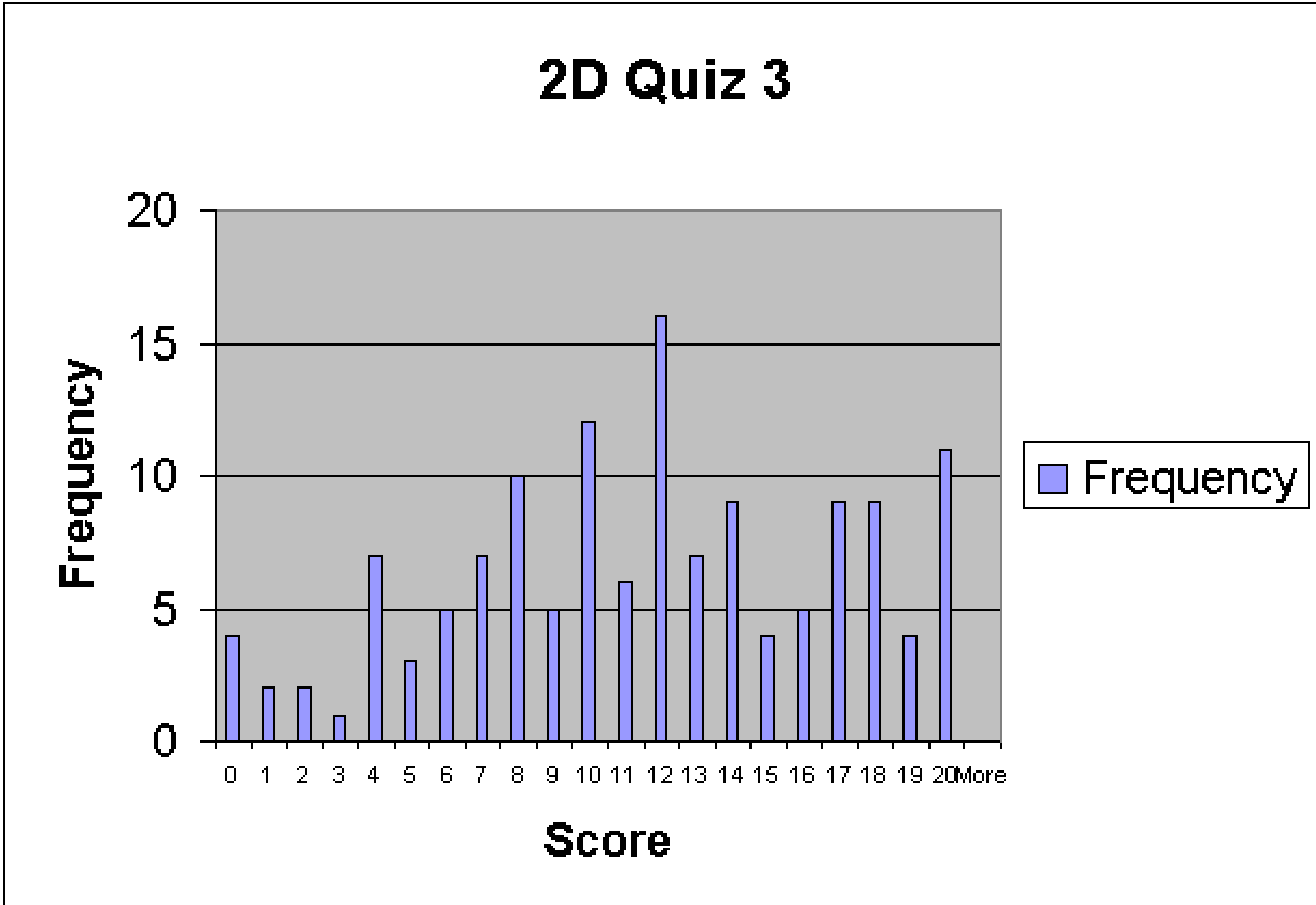

2D Quiz 3
Frequency
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 More
Score
Frequency

The Beginning of The End ! How BBQ Broke Physics

Classical Calculation

of standing waves between Wavelengths λ and λ+dλ are

$$N(\lambda)d\lambda = \frac{8\pi V}{\lambda^4} \bullet d\lambda \ ; \ V = \text{Volume of box} = L^3$$

Each standing wave contributes energy $E = kT$ to radiation in Box

Energy density $u(\lambda)$= [# of standing waves/volume]× Energy/Standing Wave

$$= \frac{8\pi V}{\lambda^4} \times \frac{1}{V} \times kT = \frac{8\pi}{\lambda^4} kT$$

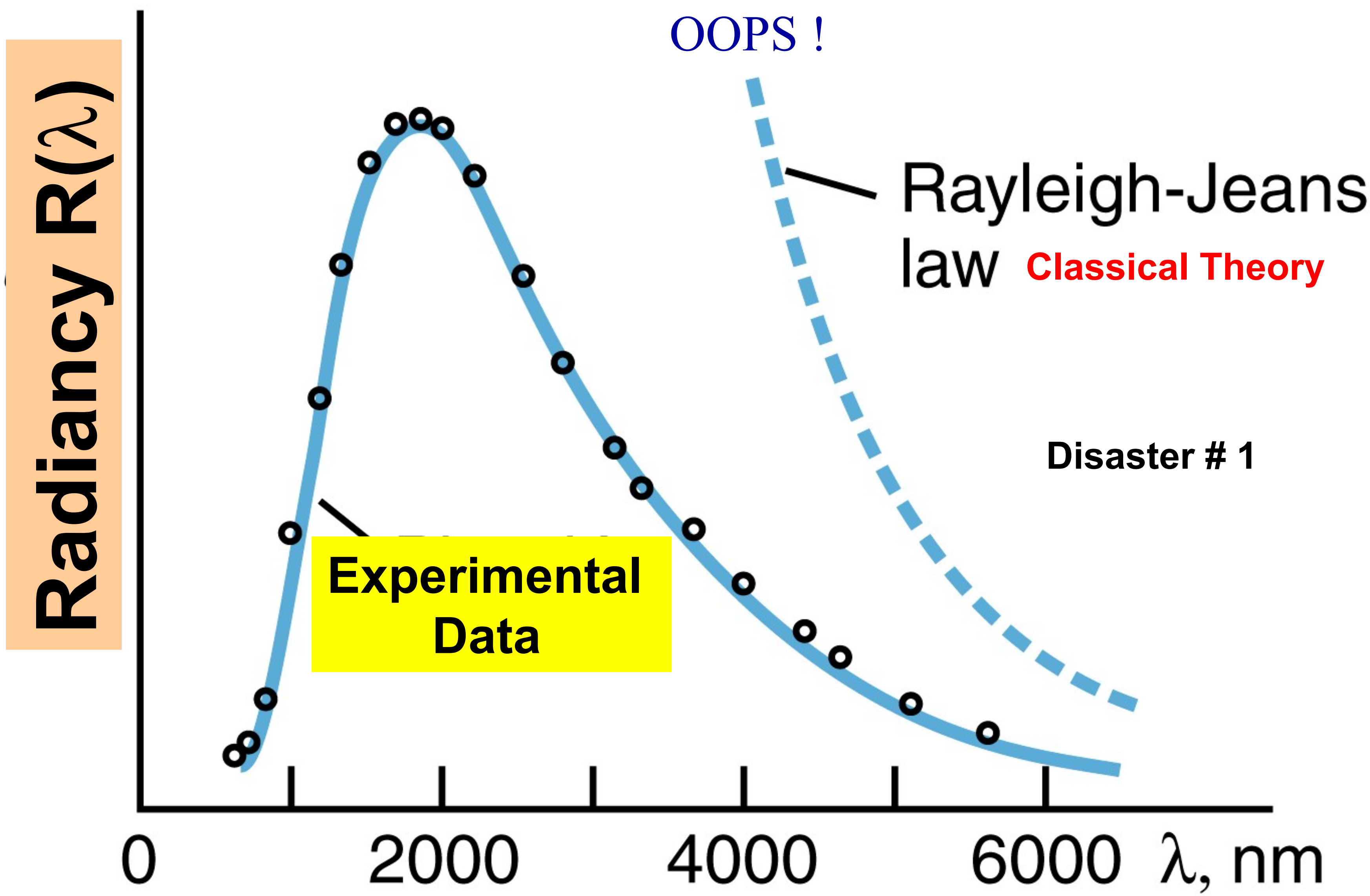
$$\text{Radiancy } R(\lambda) = \frac{c}{4} u(\lambda) = \frac{c}{4} \frac{8\pi}{\lambda^4} kT = \frac{2\pi c}{\lambda^4} kT$$

Radiancy is Radiation intensity per unit λ interval: Lets plot it

Prediction : as $\lambda \rightarrow 0$ (high frequency) $\Rightarrow$ R(λ) $\rightarrow$ Infinity !

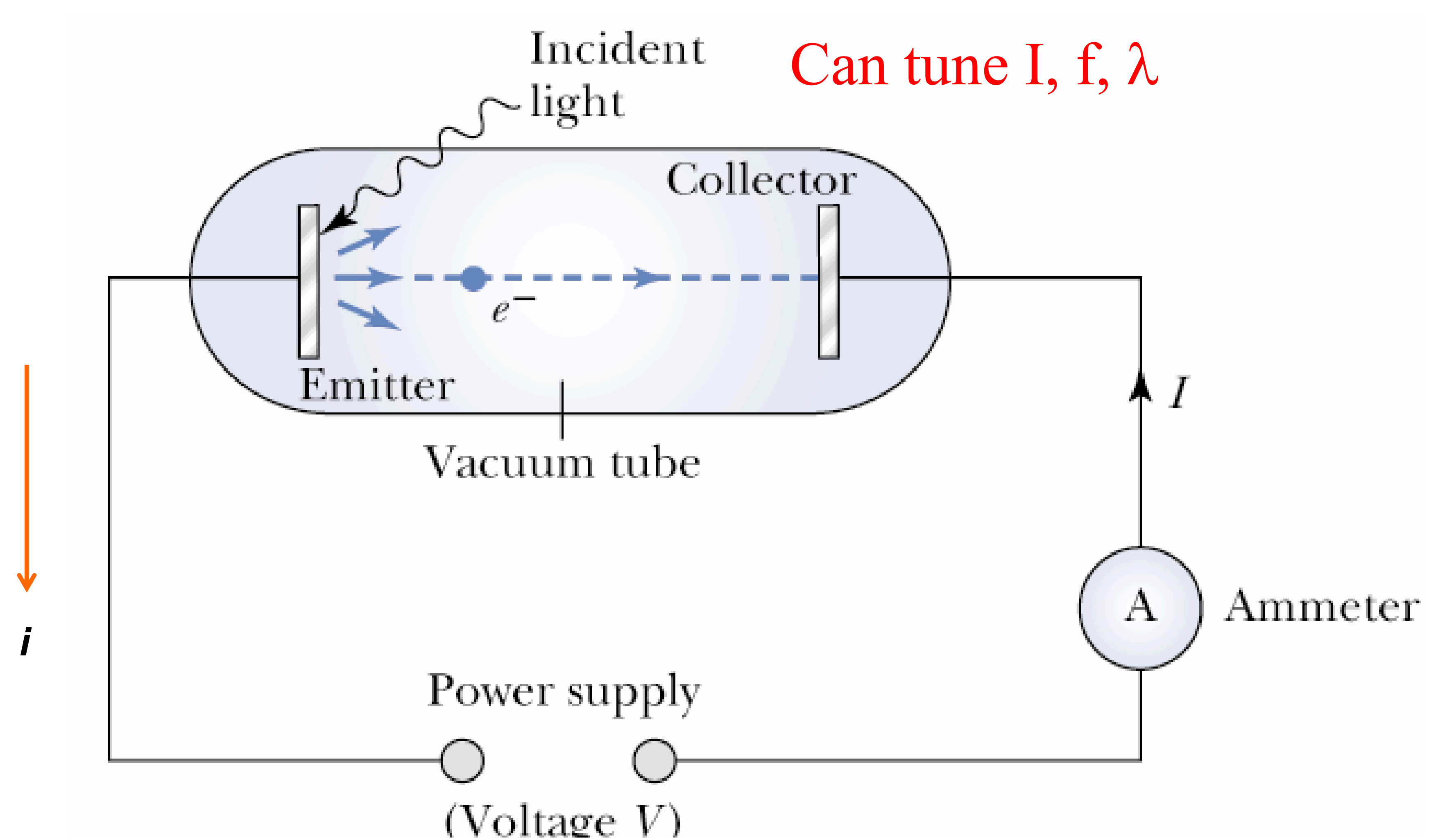
Oops !

Ultra Violet (Frequency) Catastrophe



Disaster # 2 : Photo-Electric Effect

Light of intensity I, wavelength λ and frequency ν incident on a photo-cathode



Measure characteristics of current in the circuit as a fn of I, f, λ

Conclusions from the Experimental Observation

- Max Kinetic energy K_{MAX} independent of Intensity I for light of same frequency
- No photoelectric effect occurs if light frequency f is below a threshold no matter how high the intensity of light
- For a particular metal, light with $f > f_0$ causes photoelectric effect IRRESPECTIVE of light intensity.
  - f_0 is characteristic of that metal
- Photoelectric effect is instantaneous !...not time delay

Can one Explain all this Classically !

Max Planck & Birth of Quantum Physics

Back to Blackbody Radiation Discrepancy

Planck noted the UltraViolet Catastrophe at high frequency

"Cooked" calculation with new "ideas" so as bring:

$R(\lambda) \rightarrow 0$ as $\lambda \rightarrow 0$

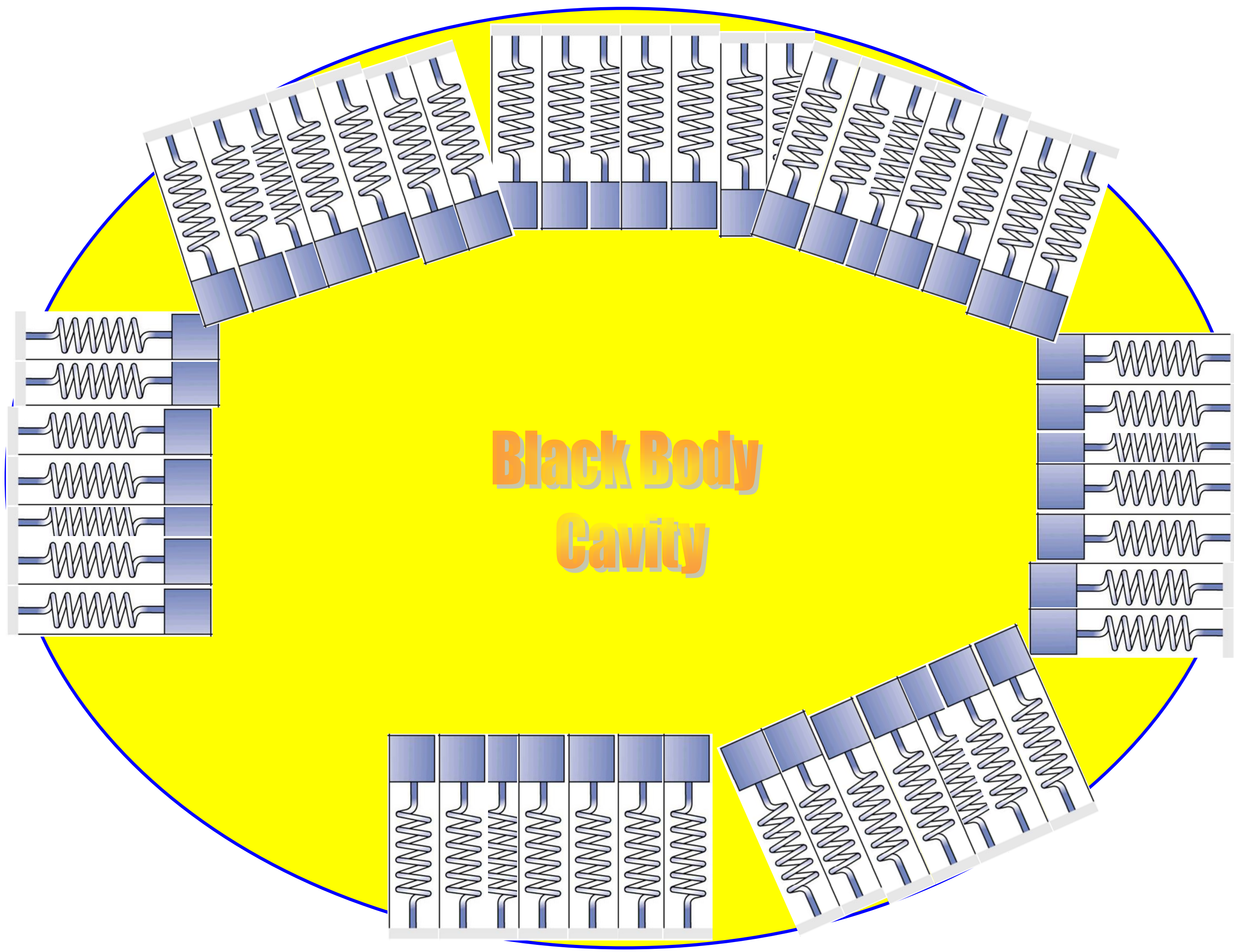
$f \rightarrow \infty$

- Cavity radiation as equilibrium exchange of energy between EM radiation & "atomic" oscillators present on walls of cavity
- Oscillators can have any frequency f
- But the Energy exchange between radiation and oscillator NOT continuous and arbitarary…it is discrete …in packets of same amount
- $E = n\,hf$, with $n = 1, 2\ 3 \ldots \infty$

  h = constant he invented, a very small number he made up

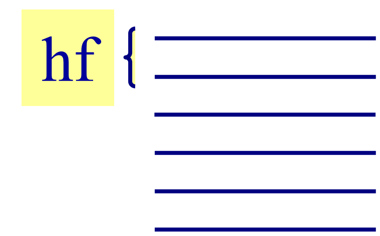
Planck's "Charged Oscillators" in a Black Body Cavity

Planck did not know about electrons, Nucleus etc

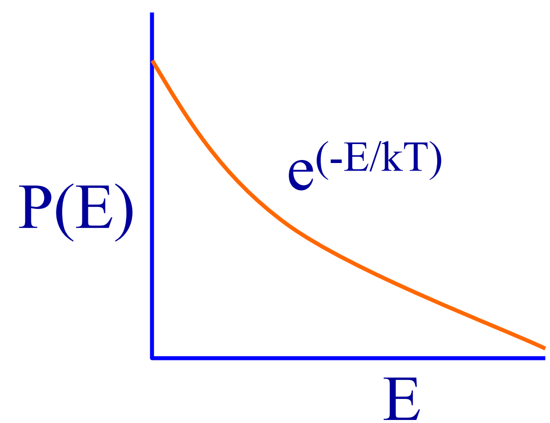


Planck, Quantization of Energy & BB Radiation

- Keep the rule of counting how many waves fit in a BB Volume
- Radiation Energy in cavity is quantized
- EM standing waves of frequency f have energy
  - $E = n\,hf$ ($n = 1,2,3 \ldots 10 \ldots 1000 \ldots$)



- Probability Distribution: At an equilibrium temp T, possible Energy of wave is distributed over a spectrum of states: $P(E) = e^{(-E/kT)}$
- Modes of Oscillation with :
  - Less energy E=hf = favored
  - More energy E=hf = disfavored



By this statistics, large energy, high f modes of EM disfavored

Planck's Calculation

$$R(\lambda) = \left(\frac{c}{4}\right)\left(\frac{8\pi}{\lambda^4}\right)\left[\frac{hc}{\lambda}\left(\frac{1}{e^{\frac{hc}{\lambda kT}} - 1}\right)\right]$$

Odd looking form

When $\lambda \rightarrow$ large $\Rightarrow \frac{hc}{\lambda kT} \rightarrow$ small

Recall $e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ...$

$$\Rightarrow e^{\frac{hc}{\lambda kT}} - 1 = (1 + \frac{hc}{\lambda kT} + \frac{1}{2}\left(\frac{hc}{\lambda kT}\right)^2 + ...] - 1$$

$$= \frac{hc}{\lambda kT}$$ plugging this in $R(\lambda)$ eq:

$$R(\lambda) = \left(\frac{c}{4}\right)\left(\frac{8\pi}{\lambda^4}\right)\frac{hc}{\lambda kT}$$

Graph & Compare
With BBQ data

Planck's Formula and Small λ

When λ is small (large f)

$$\frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \cong \frac{1}{e^{\frac{hc}{\lambda kT}}} = e^{-\frac{hc}{\lambda kT}}$$

Substituting in R(λ) eqn:

$$R(\lambda) = \left(\frac{c}{4}\right)\left(\frac{8\pi}{\lambda^4}\right) e^{-\frac{hc}{\lambda kT}}$$

As $\lambda \to 0$, $e^{-\frac{hc}{\lambda kT}} \to 0$

$\Rightarrow R(\lambda) \to 0$

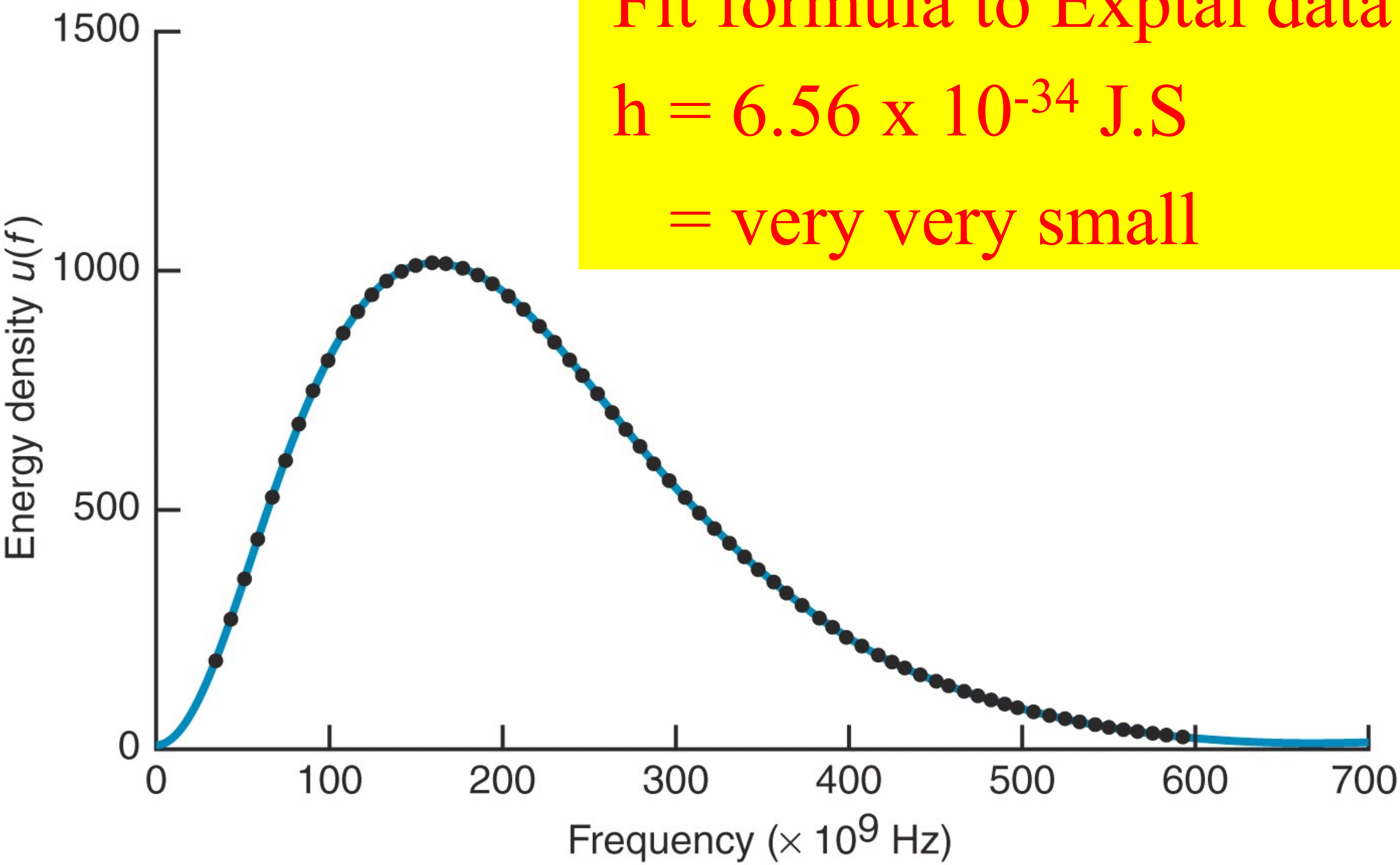
Just as seen in the experimental data

Planck's Explanation of BB Radiation

Fit formula to Exptal data

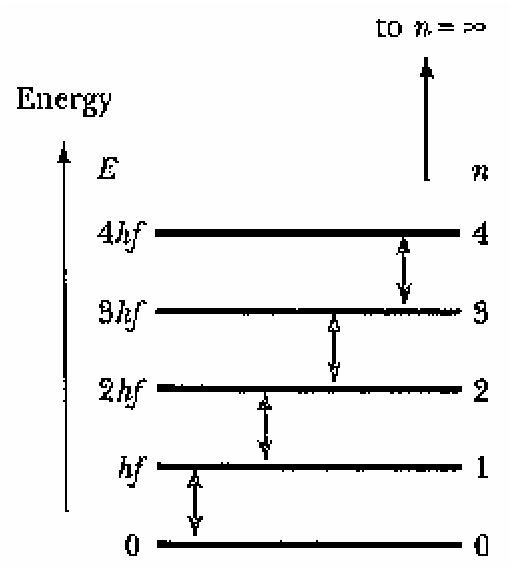
$h = 6.56 \times 10^{-34}$ J.S

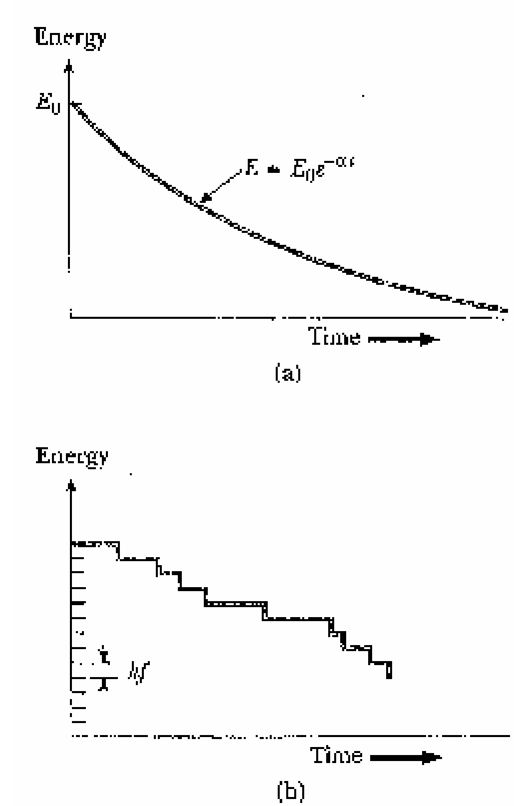
= very very small



Consequence of Planck's Formula

Quantization of Energy !

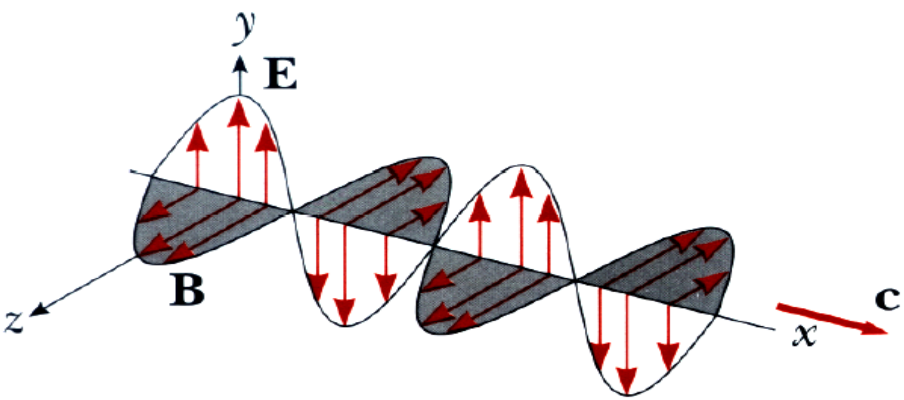


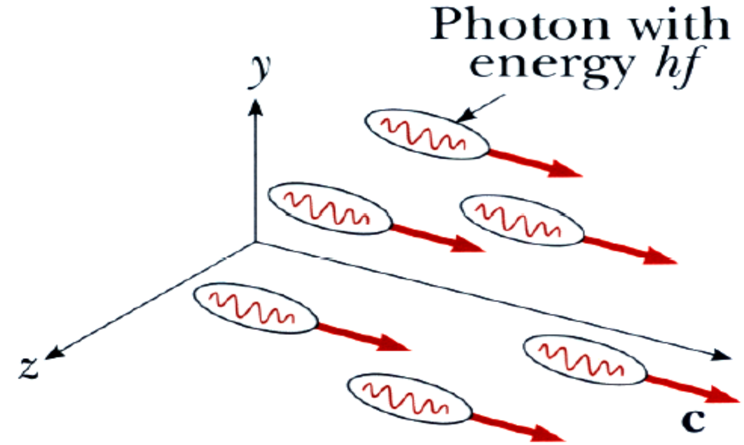


Einstein's Explanation of Photoelectric Effect

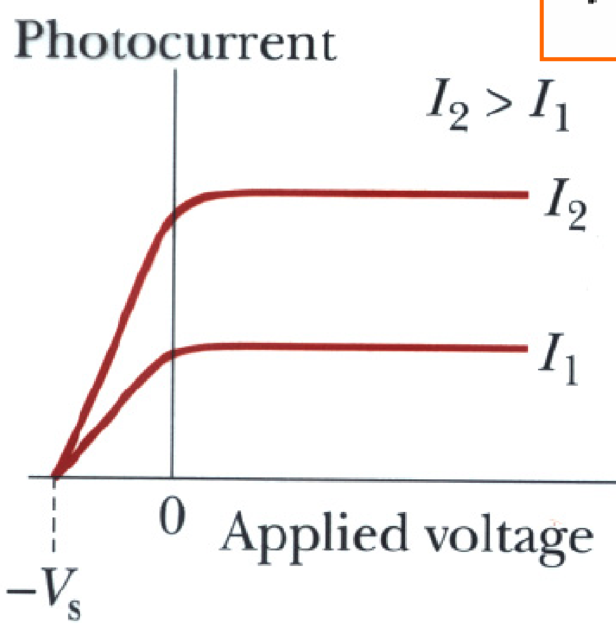
- Energy associated with EM waves in not uniformly distributed over wave-front, rather is contained in packets of "stuff" $\Rightarrow$ PHOTON
- $E = hf = hc/\lambda$ [but is it the same h as in Planck's th.?]
- Light shining on metal emitter/cathode is a stream of photons of energy which depends on frequency f
- Photons knock off electron from metal instantaneously
  - Transfer all energy to electron
  - Energy gets used up to pay for Work Function Φ (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 → more photons incident
- Low frequency light f → not energetic enough to overcome work function of electron in atom

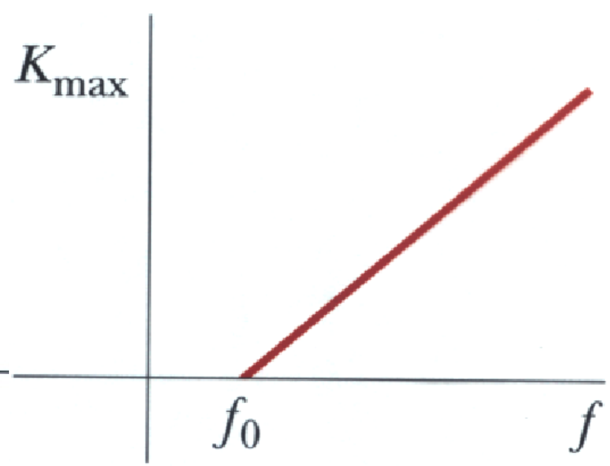
Einstein's Explanation of PhotoElectric Effect





$$V_s e = hf - \phi$$





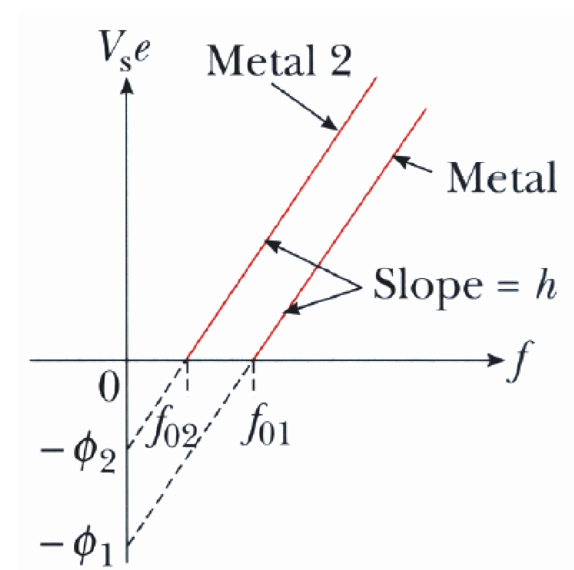


Photo Electric & Einstein (Nobel Prize 1915)

Light shining on metal cathode is made of photons

Each of the same energy E, depends on frequency f

$$E = hf = h\,(c/\lambda)$$

This QUANTA used to knock off electron & give KE

$$E = hf = KE + \varphi \quad \Rightarrow KE = hf - \varphi$$

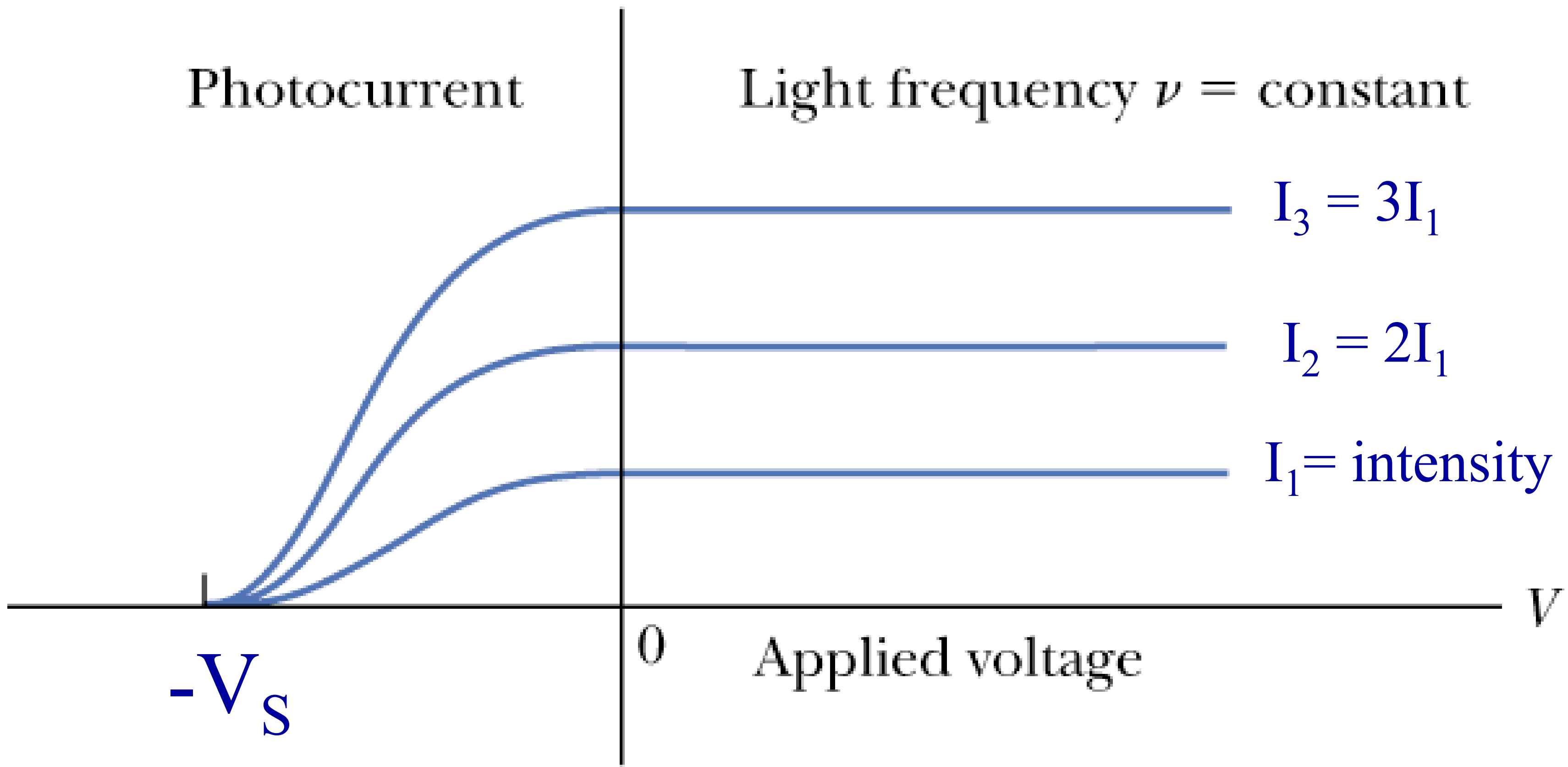
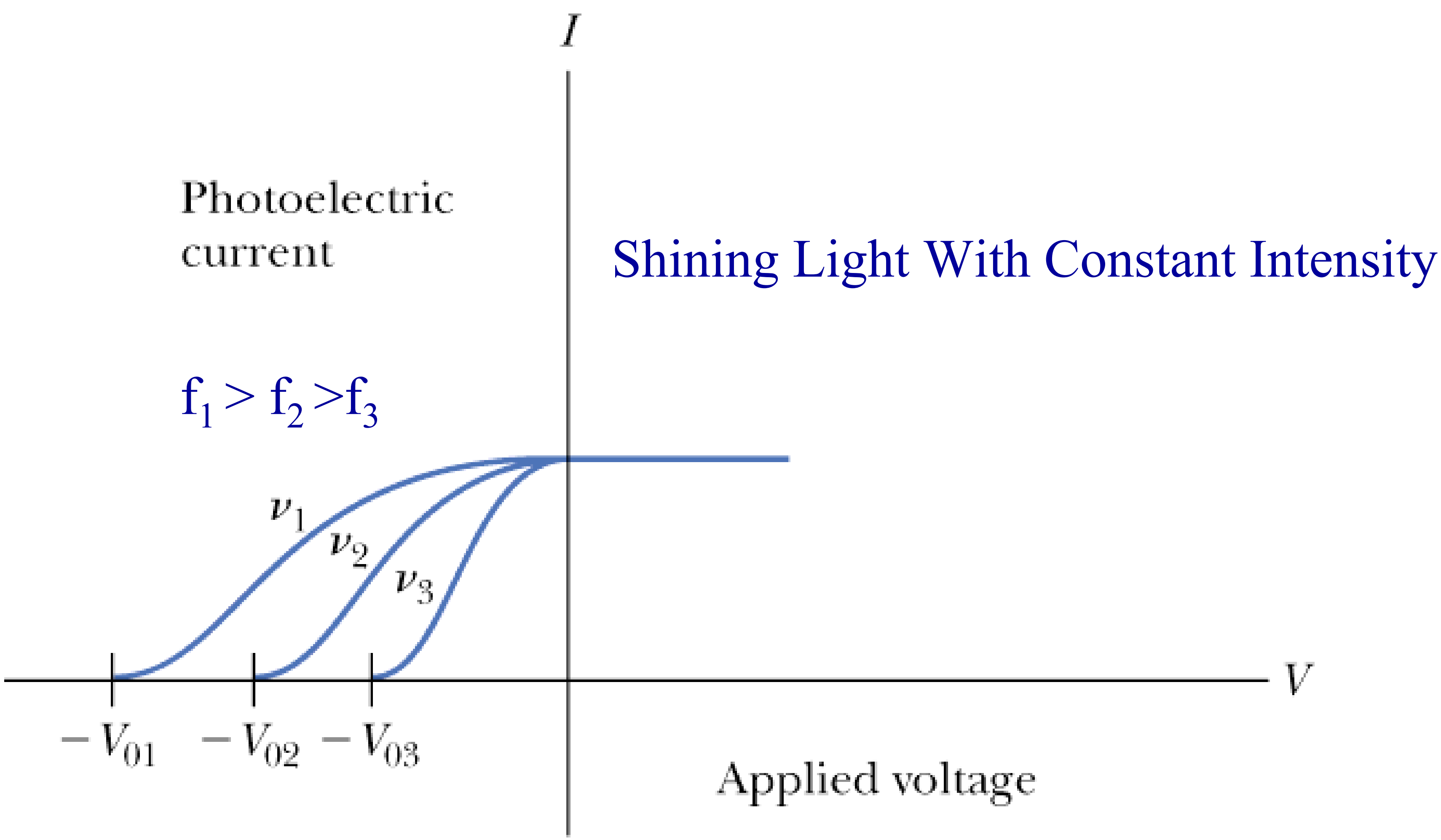


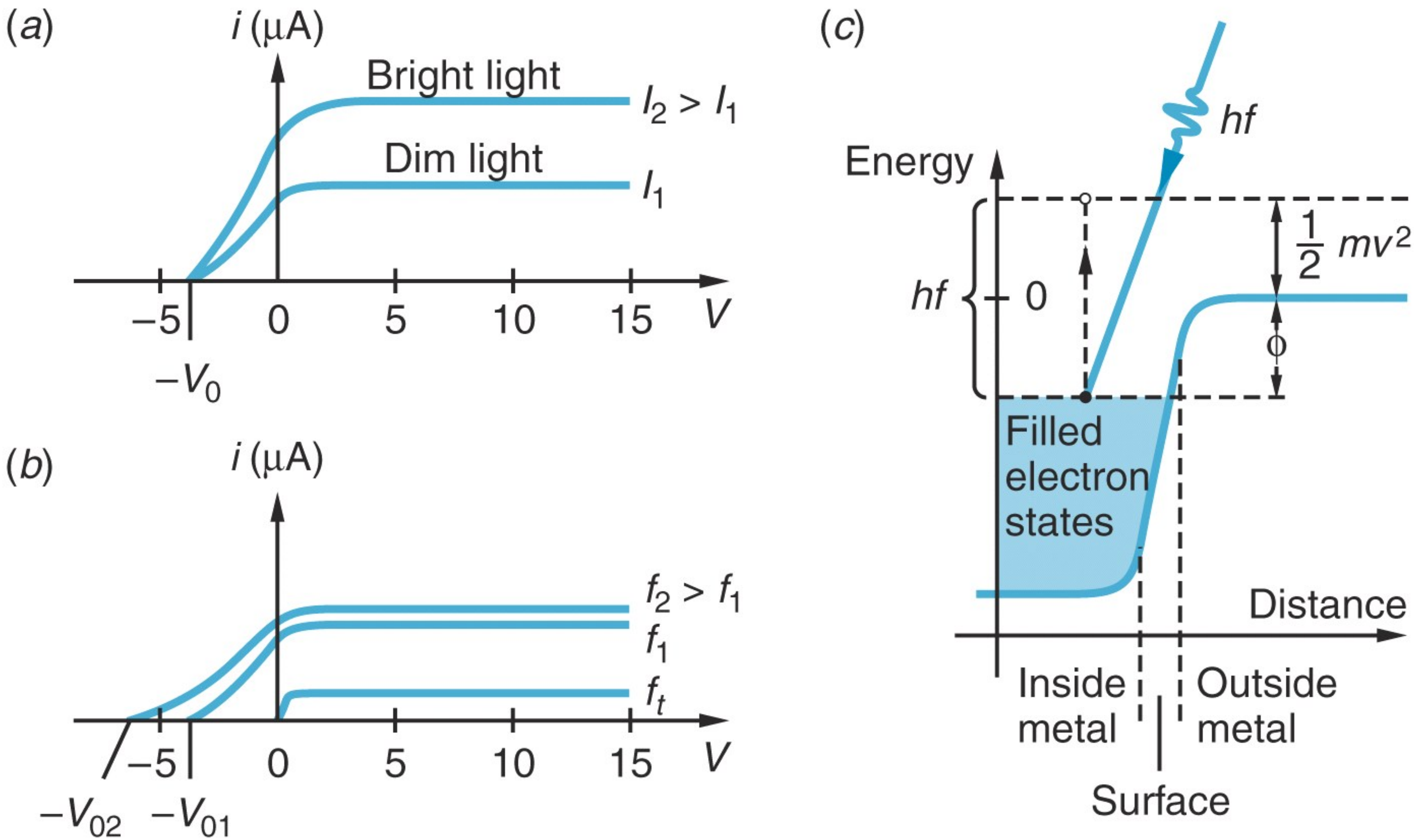
Photo Electric & Einstein (Nobel Prize 1915)

Light shining on metal cathode is made of photons

Quantum of Energy $E = hf = KE + \varphi \Rightarrow KE = hf - \varphi$



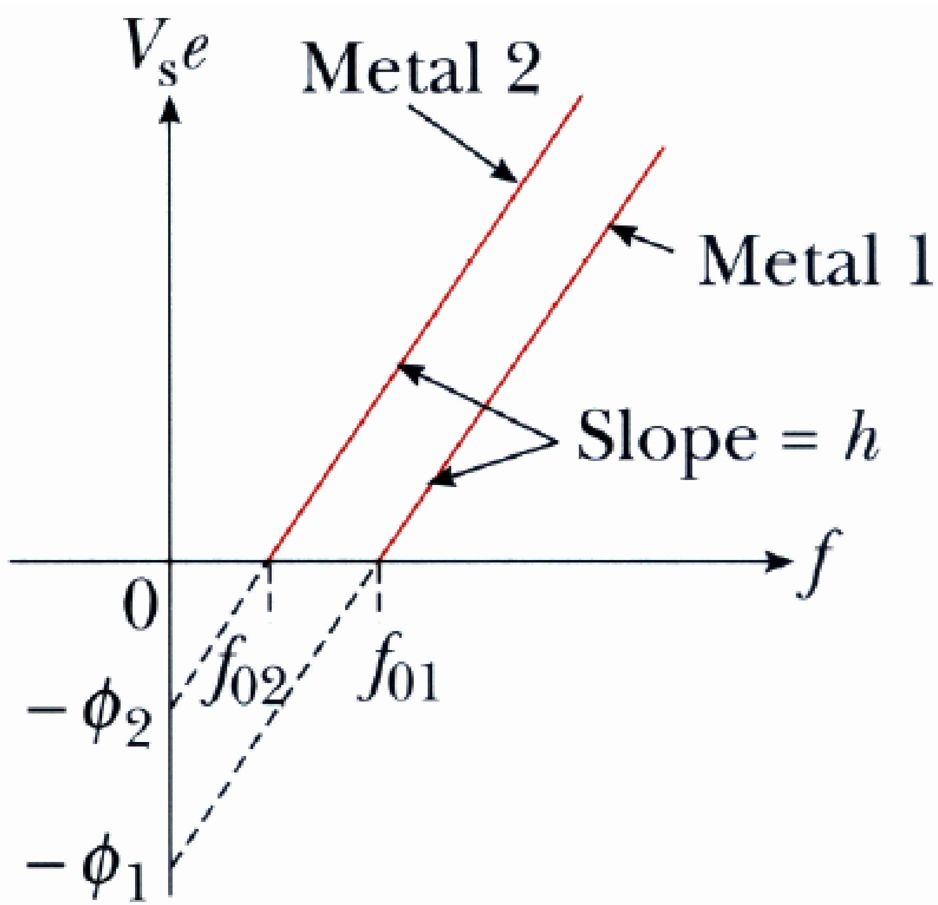
Modern View of Photoelectric Effect



Is "h" same in Photoelectric Effect as BB Radiation?

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

Einstein → 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	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 $I = 1.0\ \mu W/cm^2$ incident on $1.0 cm^2$ surface of Fe

Assume Fe reflects 96% of light

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

barely above threshold frequency for Ph. El effect

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

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

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

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

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

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

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

$$= 4.5\ eV$$

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 : $hc/\lambda = pc$
  - $\Rightarrow \quad p = h/\lambda$
  - 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

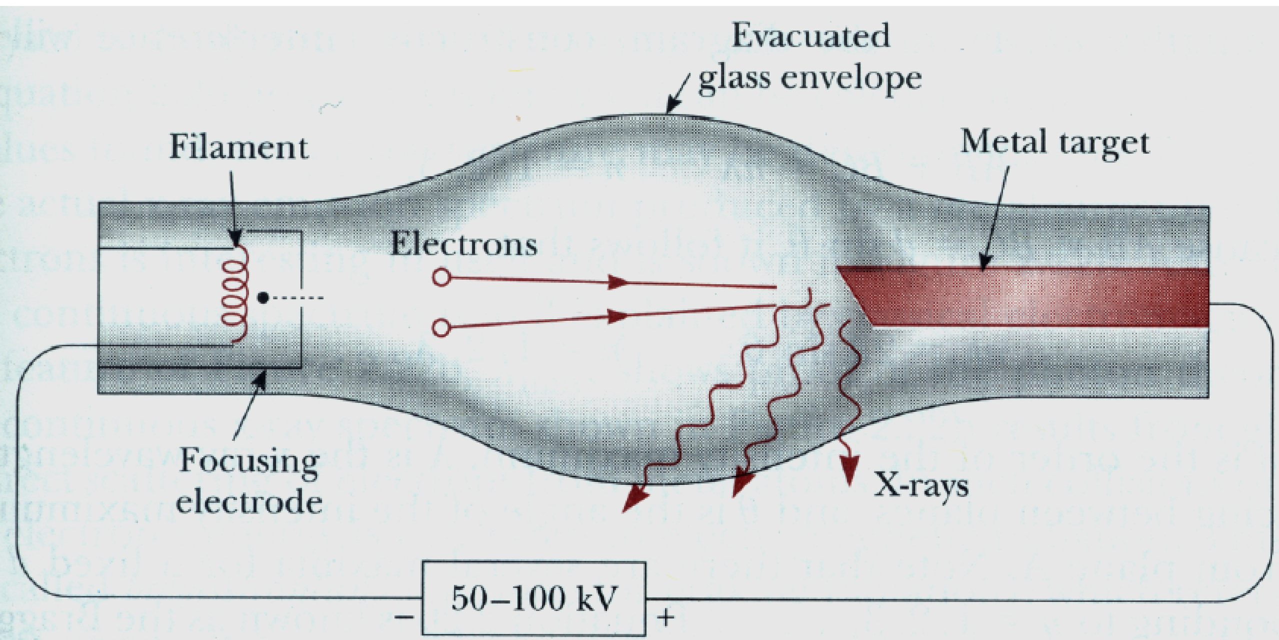
X Rays : “Bremsstrahlung”: Braking Radiation

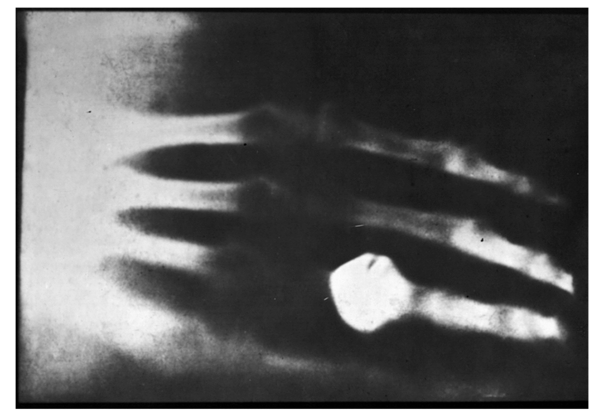
Produced by bombarding a metal target with energetic electrons

Produced in general by ALL accelerating charged particles

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

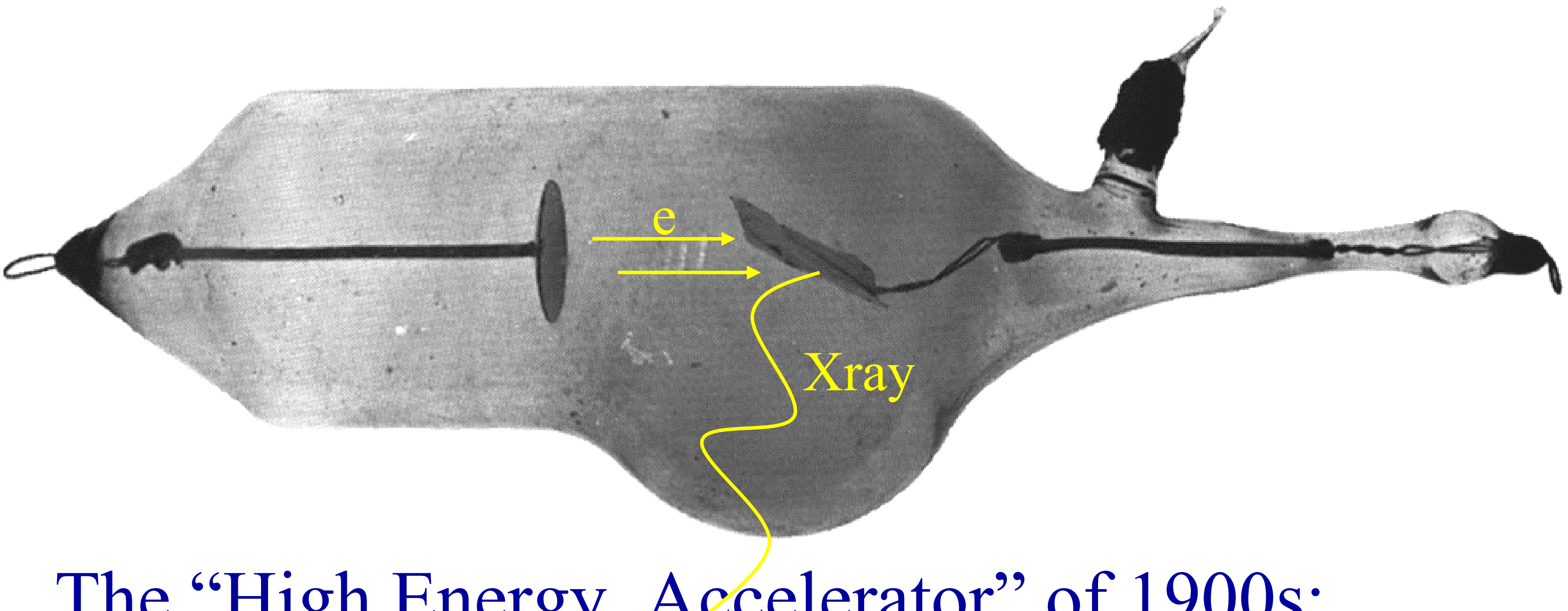
Very penetrating because energetic





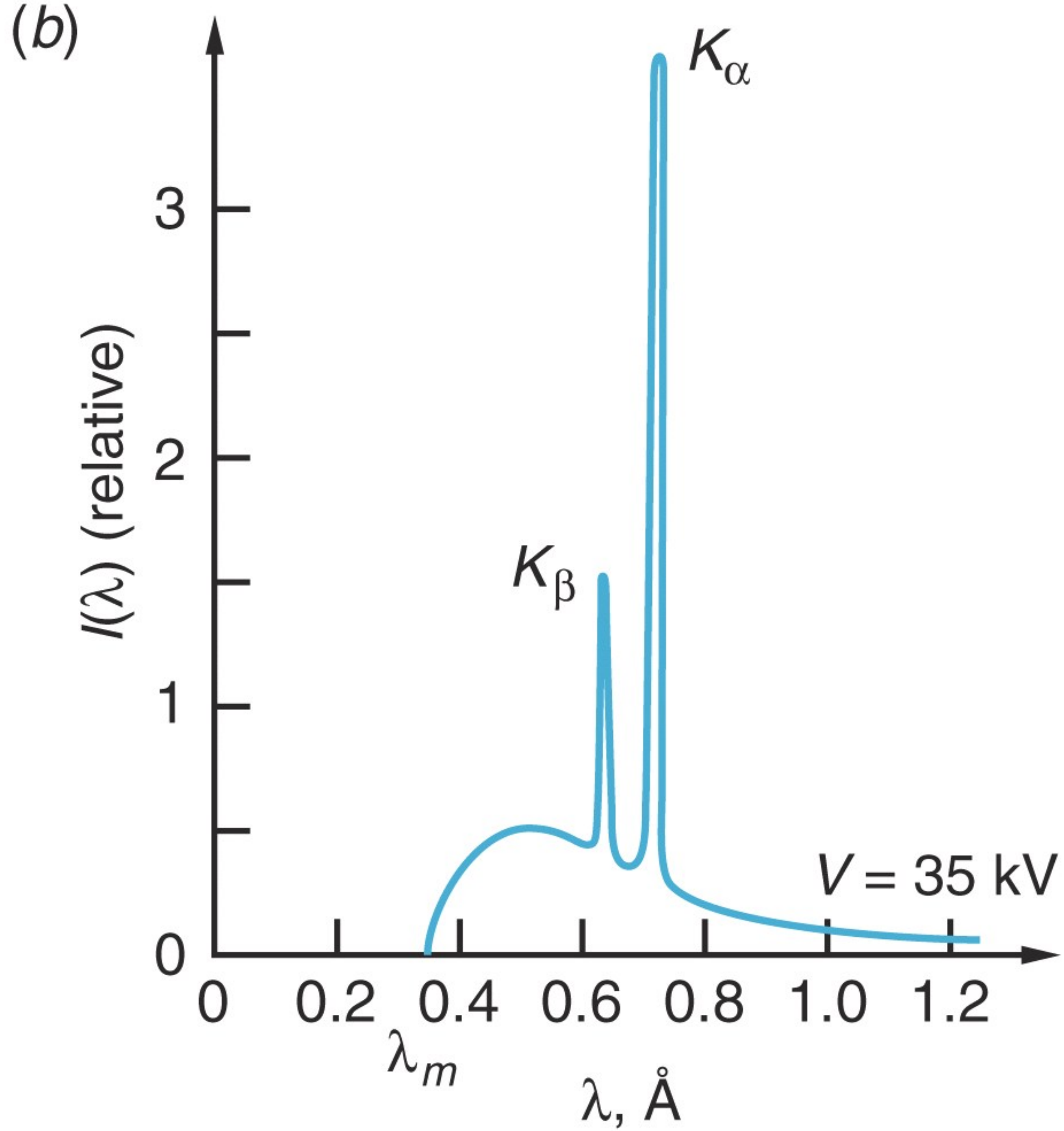
Useful for probing structure of sub-atomic Particles

An X-ray Tube from 20th Century



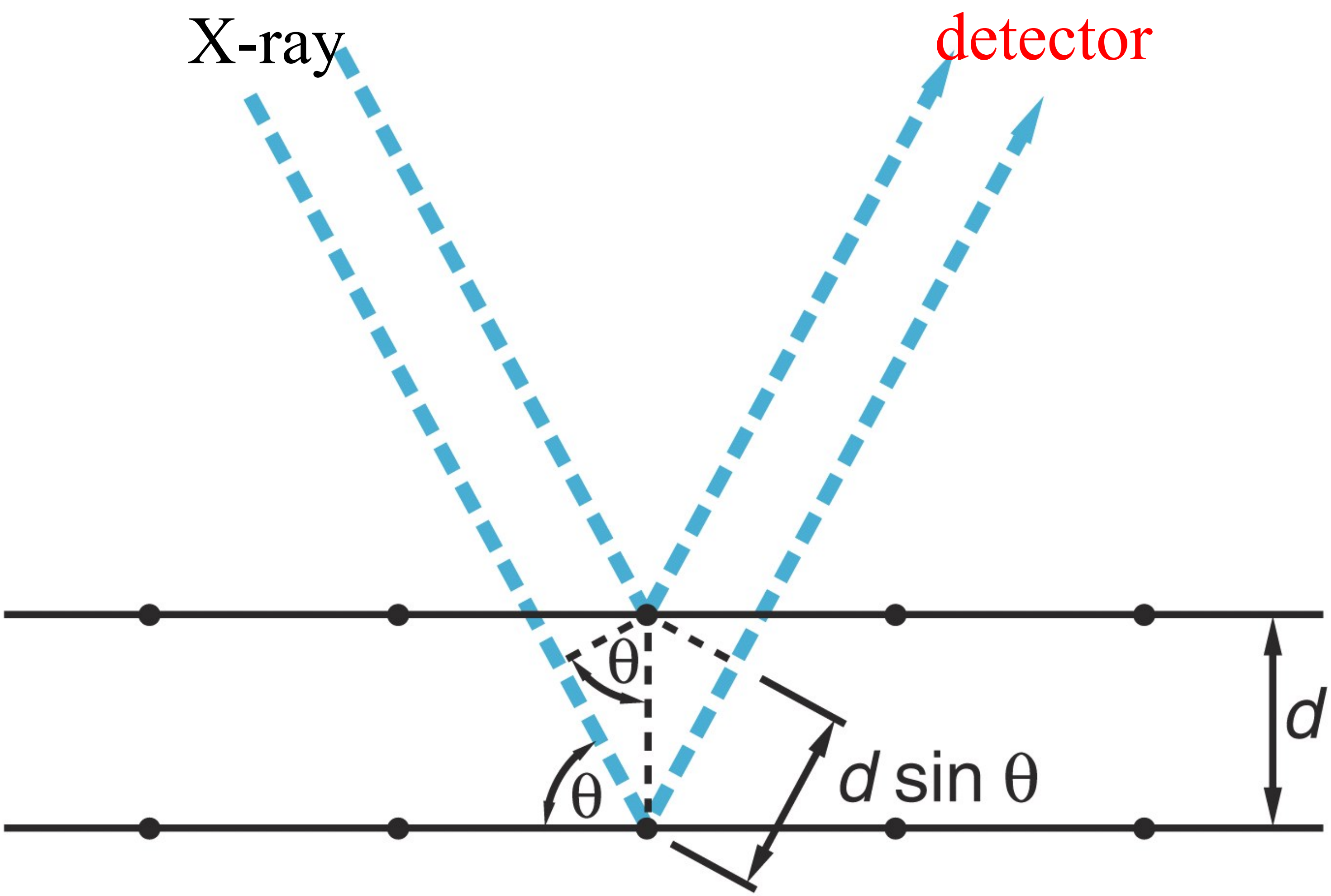
The "High Energy Accelerator" of 1900s: produced energetic light : X –Ray , gave new optic to subatomic phenomena

X Ray Spectrum in Molybdenum (Mo)



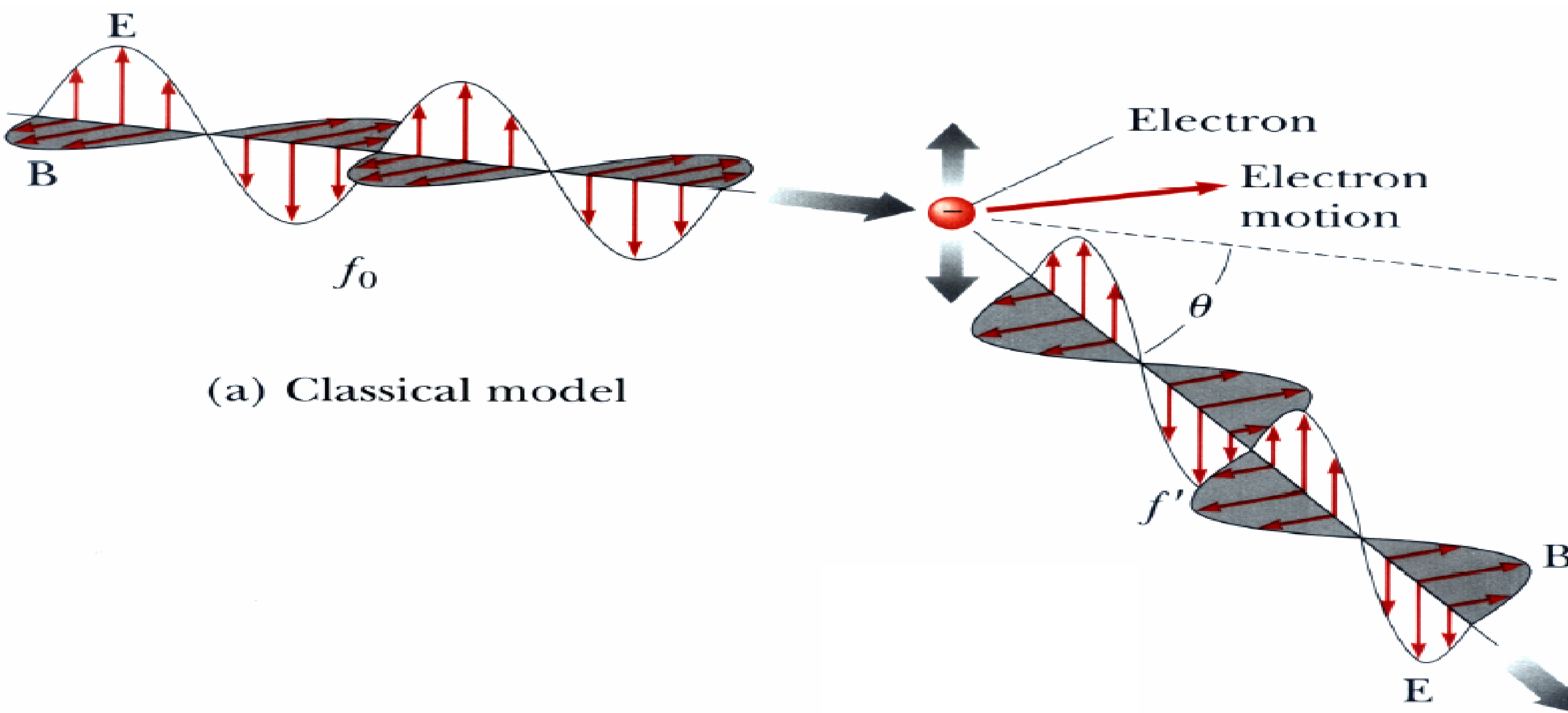
Bragg Scattering: Probing Atoms With X-Rays

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



Compton Scattering : Quantum Pool !

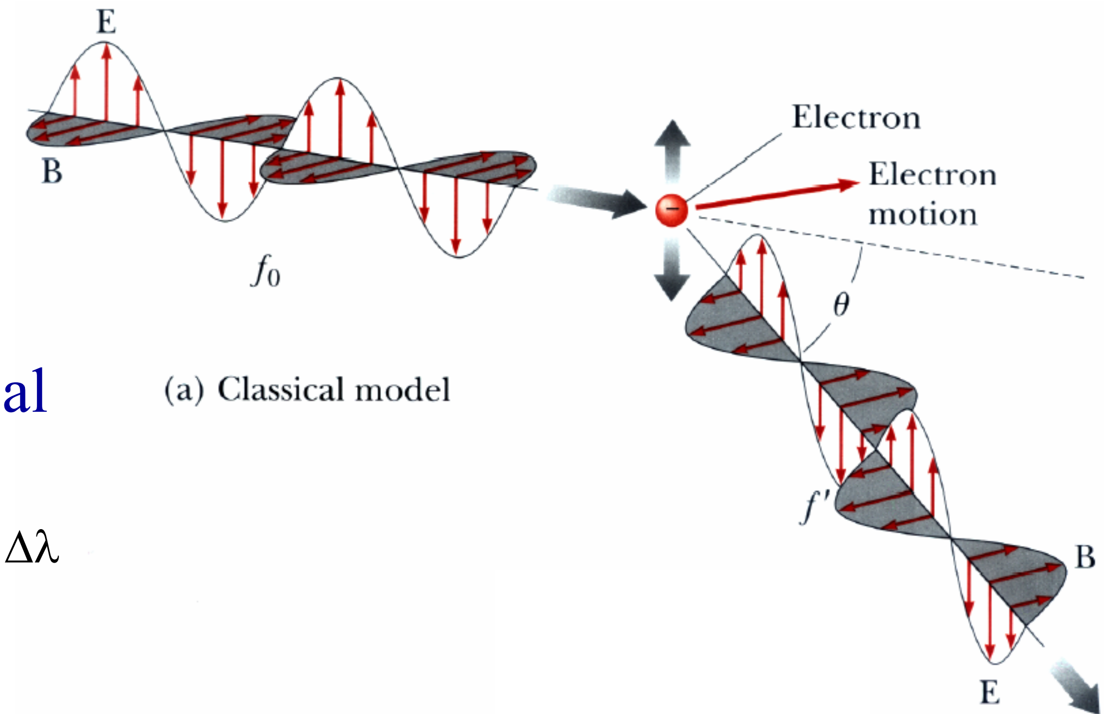
- 1922: Arthur Compton (USA) proves that X-rays (EM Waves) have particle like properties (acts like photons)
  - Showed that classical theory failed to explain the scattering effect of
    - X rays on to free (not bound, barely bound electrons)
- Experiment : shine X ray EM waves on to a surface with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



(a) Classical model

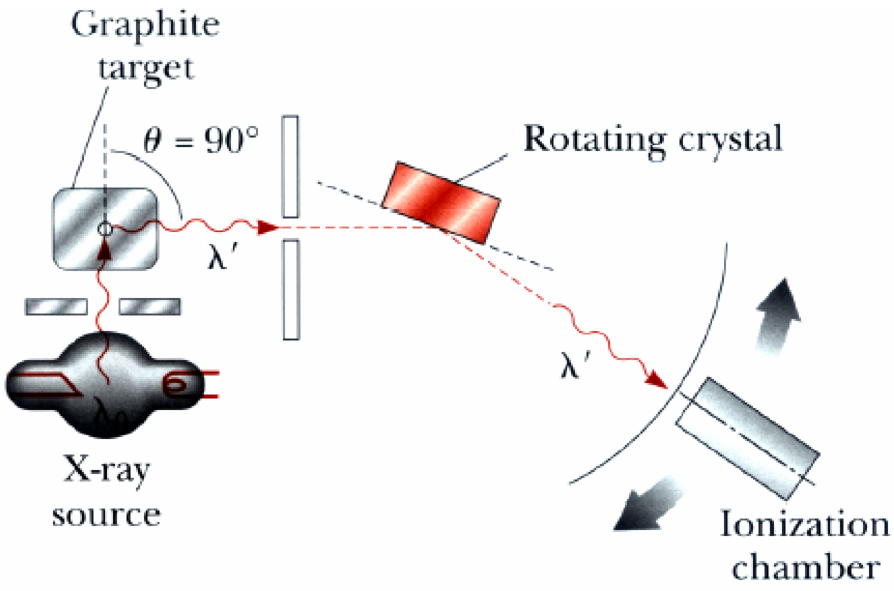
Compton Effect: what should Happen Classically?

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



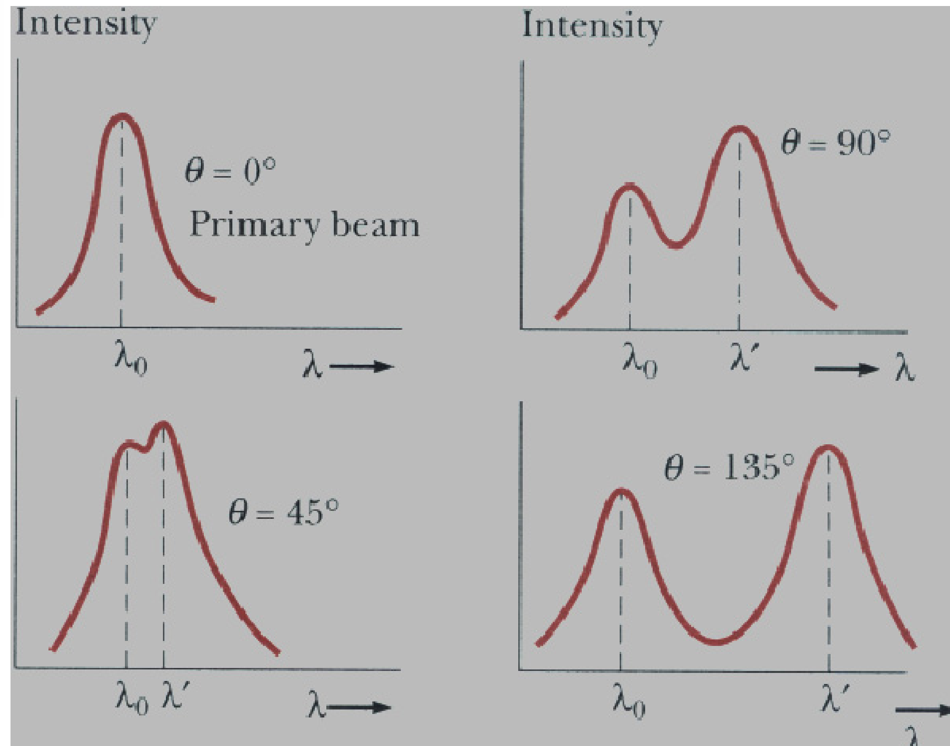
(a) Classical model

Compton Scattering : Setup & Results



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

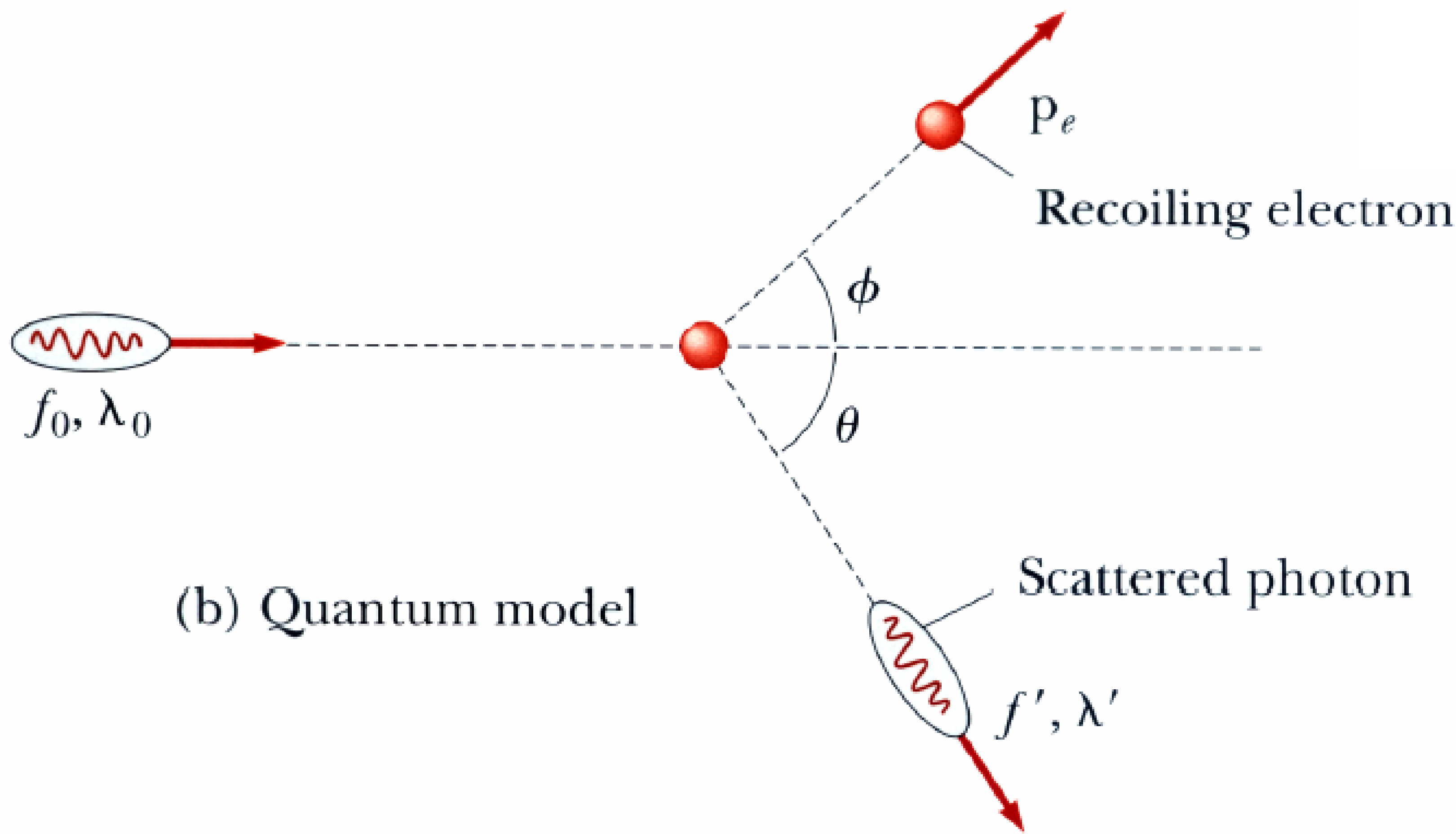
Scattered λ' larger than incident



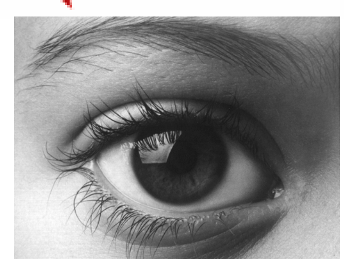
$$\Delta\lambda = \left(\frac{h}{m_e c}\right)(1-\cos\theta)$$

How does one explain this startling anisotropy?

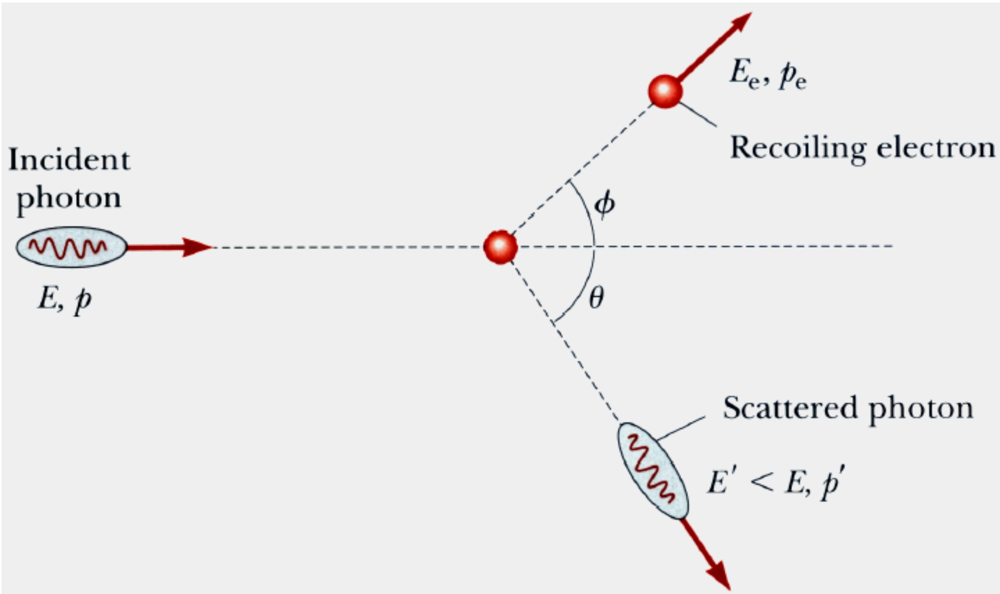
Compton Effect : Quantum (Relativistic) Pool



(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

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

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

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

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

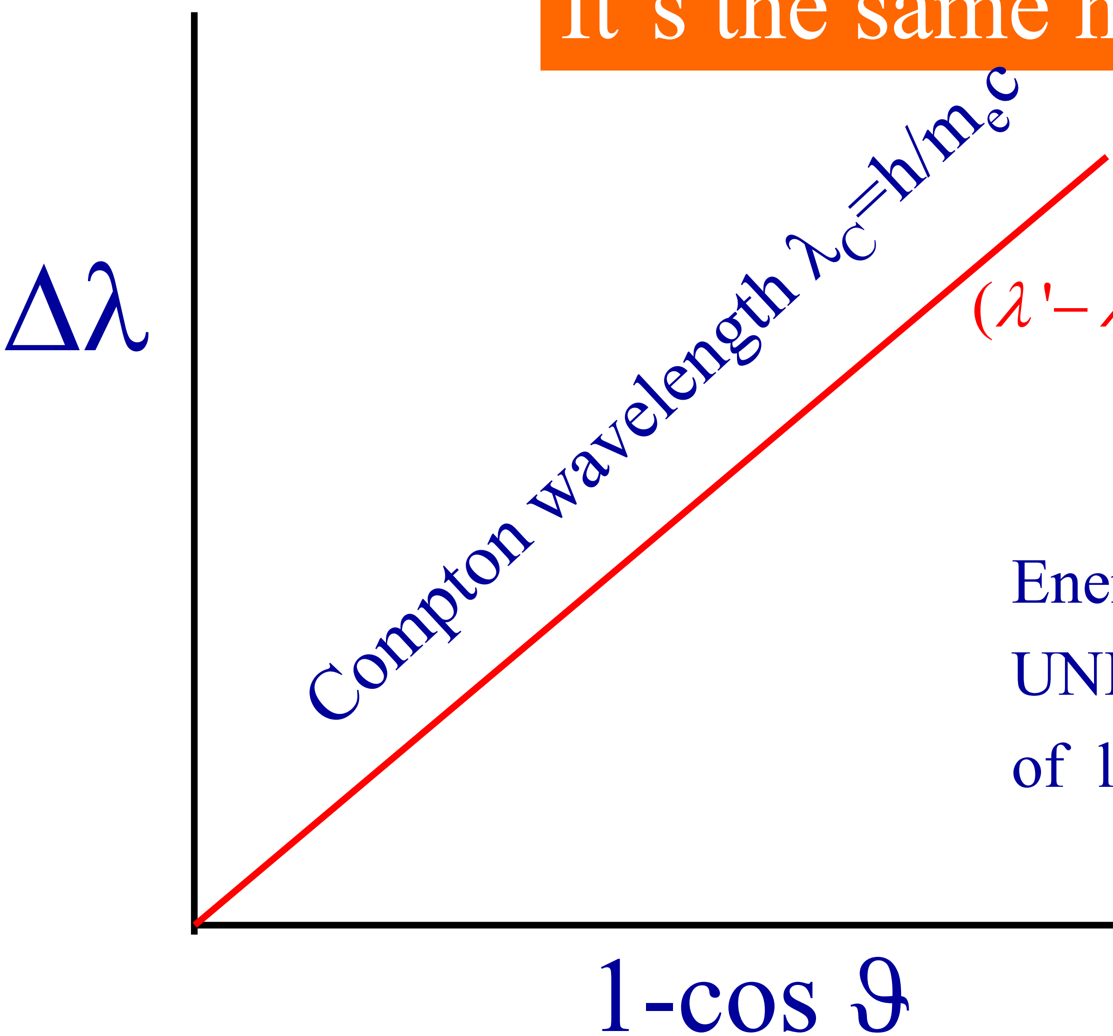
$$\Rightarrow -EE' + (E - E')mc^2 = -EE'\cos\theta$$

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

Checking for h in Compton Scattering

Plot scattered photon data, calculate slope and measure h

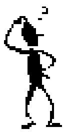
It's the same h !!



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

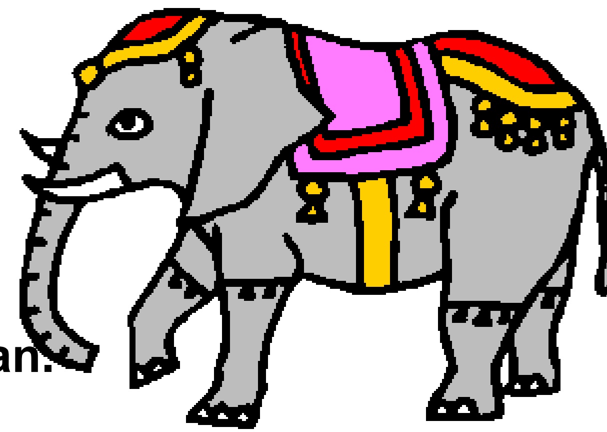
Energy Quantization is a UNIVERSAL characteristic of light (EM Waves)

Blindmen & an Elephant



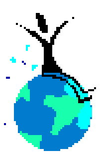
touched the trunk of the elephant, said elephant was like a **branch of a tree**.

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 !