Physics 2D Lecture Slides
Lecture 13: Jan 31th 2005

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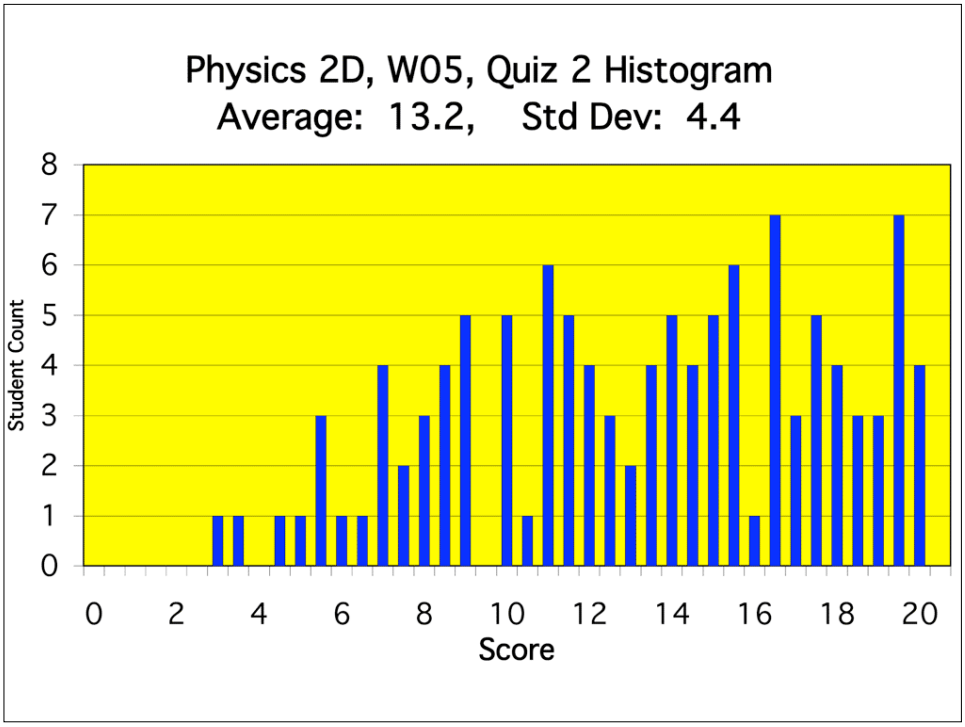
UCSD Physics



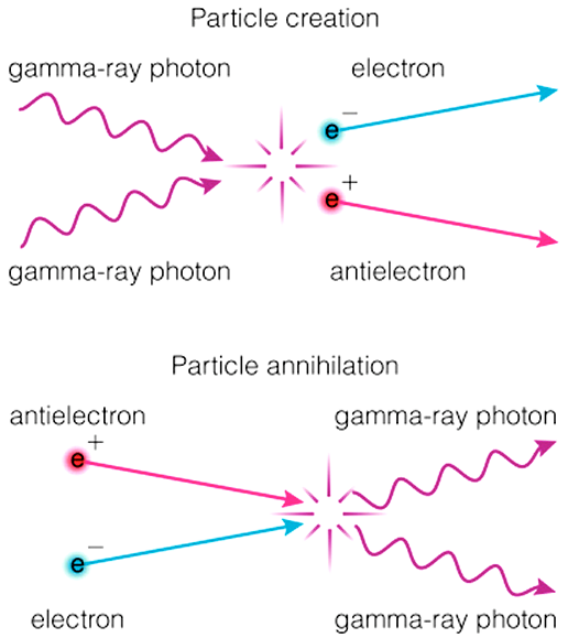
Facts Related to Photoelectric Effect

- The human eye is a sensitive photon detector at visible wavelenghts: Need >5 photons of ≅ 550nm to register on your optical sensor
- The Photographic process :
  - Energy to Dissociate an AgBr molecule = 0.6eV
- Photosynthesis Process : 9 sunlight photon per reaction cycle of converting CO_2 and water to carbohydrate & O_2
  - chlorophyll absorbs best at λ≅ 650-700 nm
- Designing Space Shuttle "skin" : Why Platinum is a good thing
- designing Solar cells : picking your metal cathode

Other forms of Interaction of Energy Exchange between Radiation and Matter

$E \rightleftharpoons mc^2+mc^2$

Always same species of Matter & Antimatter produced or destroyed

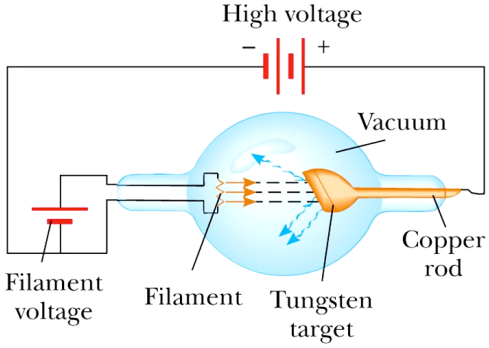


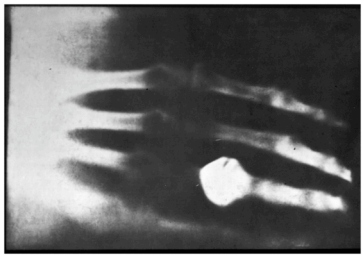
Photon & Relativity: Wave or a Particle ?

- 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": The Braking Radiation

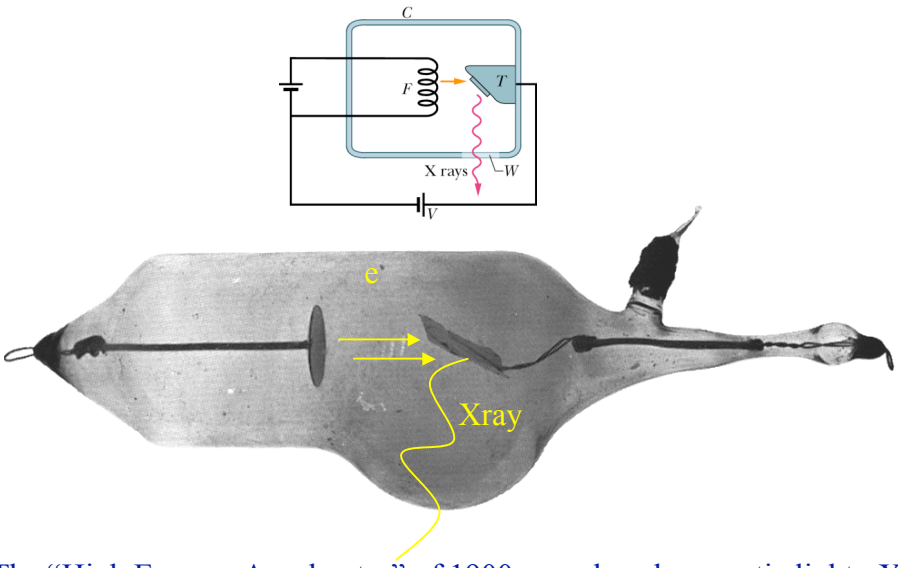
- EM radiation, produced by bombarding a metal target with energetic electrons.
- Produced in general by ALL decelerating charged particles
- X rays : very short $\lambda \cong$ 60-100 pm (10^{-12}m), large frequency f
- Very penetrating because very energetic E = hf !!





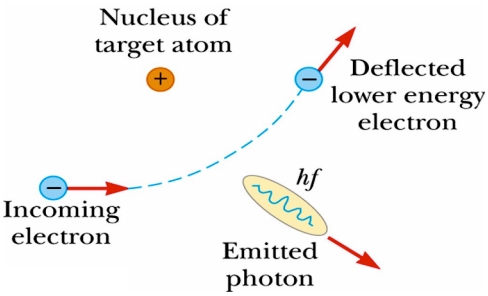
Useful for probing structure of sub-atomic Particles (and your teeth)

An X-ray Tube from early 20th Century



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

X Ray Production Mechanism

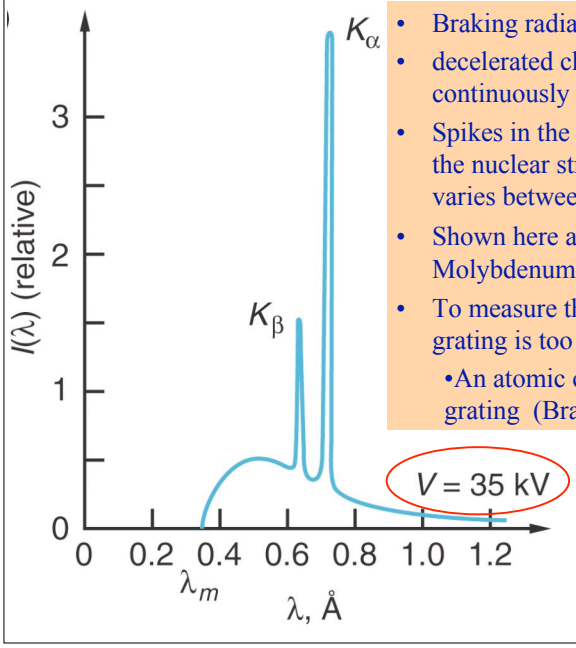


when electron passes near a positively charged target nucleus contained in target material, its deflected from its path because of its electrical attraction , experiences acceleration.

Rules of E&M say that any charged particle will emit radiation when accelerated. This EM radiation "appears" as photons. Since photo carries energy and momentum, the electron must lose same amount. If all of electron's energy is lost in just one single collision then

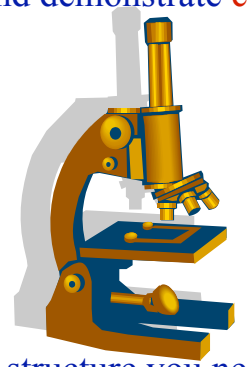
$$e\,\Delta V = \mathrm{hf}_{\max} = \frac{hc}{\lambda_{\min}} \quad \text{or} \quad \boxed{\lambda_{\min} = \frac{hc}{e\,\Delta V}}$$

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)

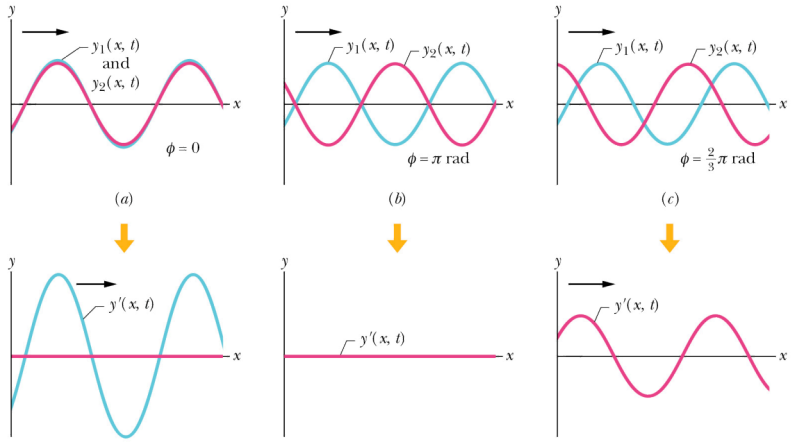
- X rays are EM waves of low wavelength, high frequency (and energy) and demonstrate characteristic features of a wave
  - Interference
  - Diffraction



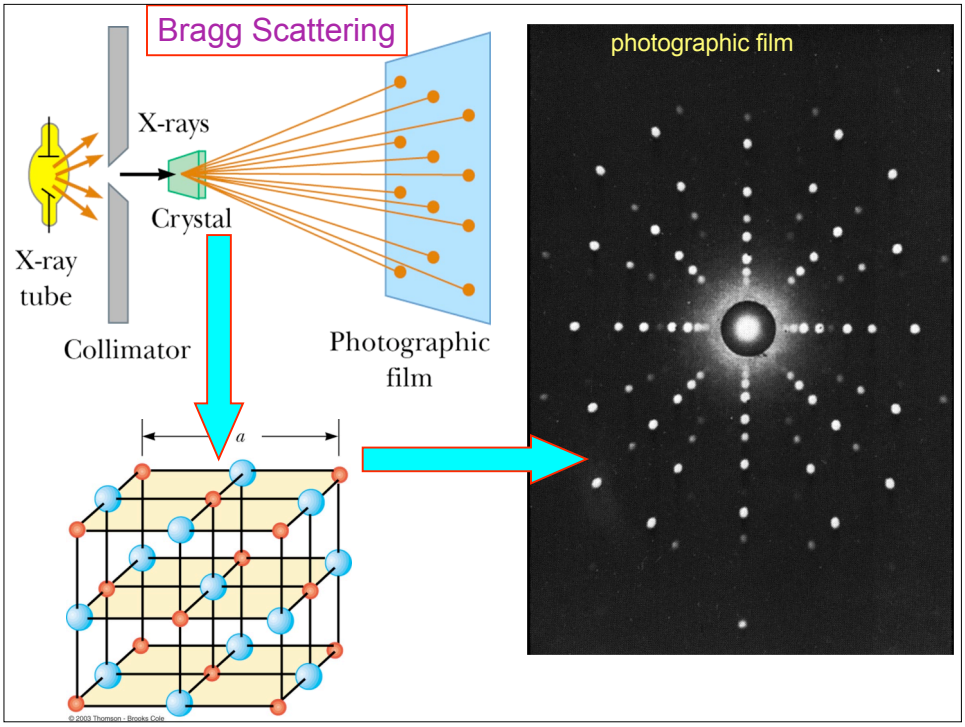
- To probe into a structure you need a light source with wavelength much smaller than the features of the object being probed
  - Good Resolution → $\lambda << \Delta d$
- X rays allows one probe at atomic size (10^{-10})m

Reminder: Constructive Interference of waves depends on relative path length traversed (or corresponding phase difference)

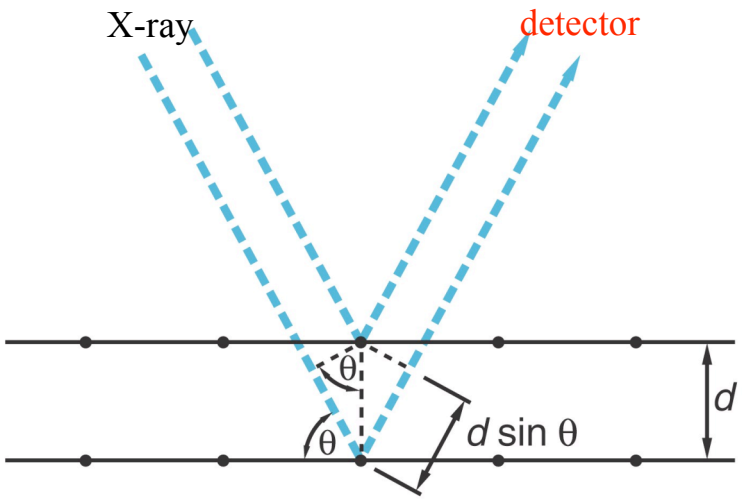
Two Identical waves $y_i(x,t) = y_{\max} \sin(k_i x - \omega_i t + \phi_i)$ travel along +x and interefere to give a resulting wave $y'(x,t)$. The resulting wave form depends on relative phase difference between 2 waves. Shown for $\Delta\phi = 0, \pi, \frac{2}{3}\pi$



Bragg Scattering



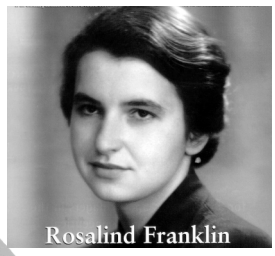
Bragg Scattering: Probing Atoms With X-Rays

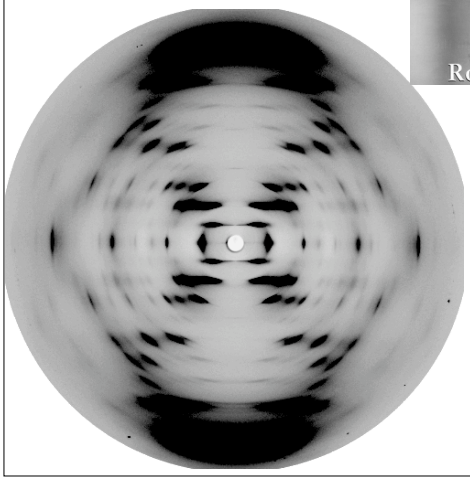


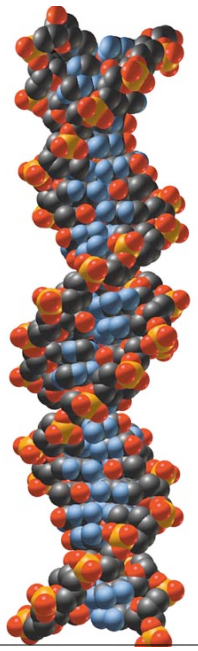
Constructive Interference when net phase difference is 0, 2π etc
This implied path difference traveled by two waves must be integral multiple of wavelength : **$n\lambda=2d\sin\theta$**

Summary : From X Ray (EM Wave) Scattering data, Size of the Atom was known to be about 10^{-10} m

Example : X-Ray Picture of a DNA Crystal and Discovery of DNA Structure !







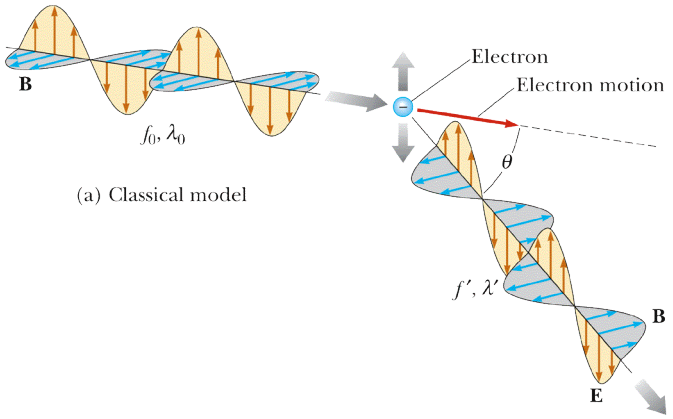
Back to Disasters in Classical Physics

Disaster # 3

Playing Pool with Electrons Using Photon as a Q ball !

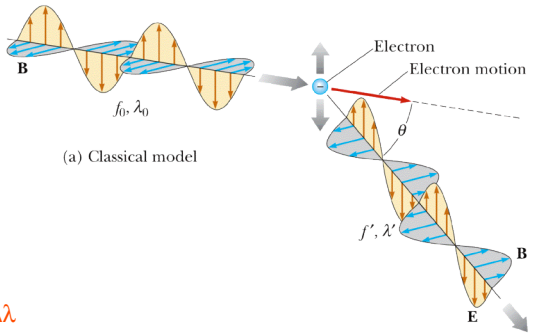
Compton Scattering : Quantum Pool !

- 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

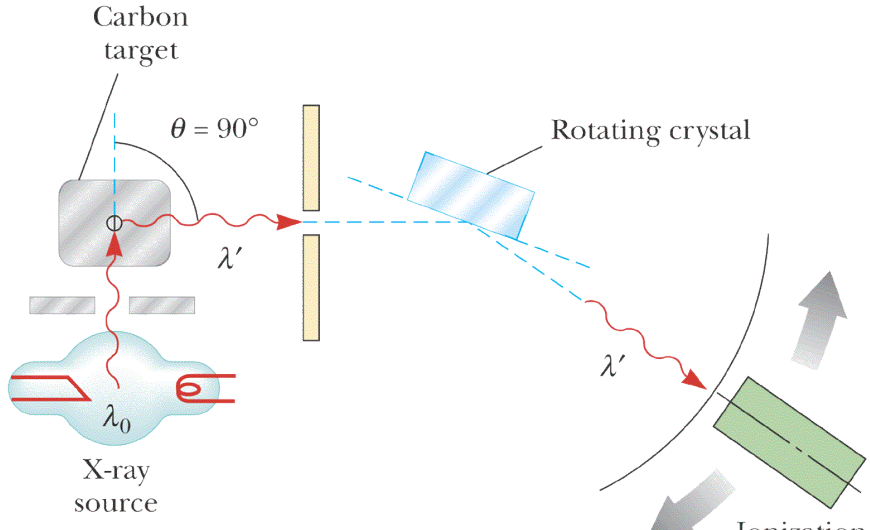


Compton Effect: what should Happen Classically?

- 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



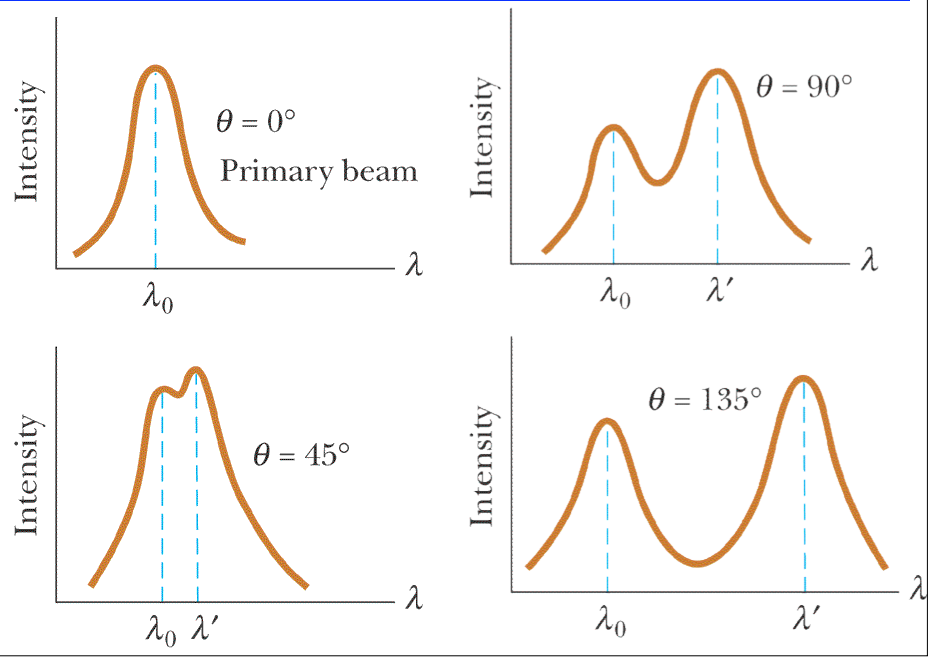
Compton Scattering : Setup & Results



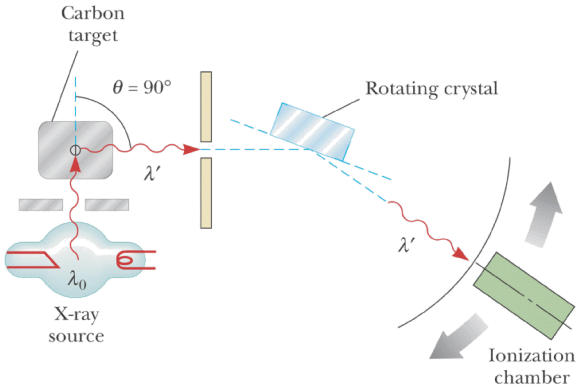
$\Delta\lambda = (\lambda' - \lambda) \propto (1 - \cos\theta)$

Scattered λ' larger than incident

Compton Scattering Observations



Compton Scattering : Summary of Observations

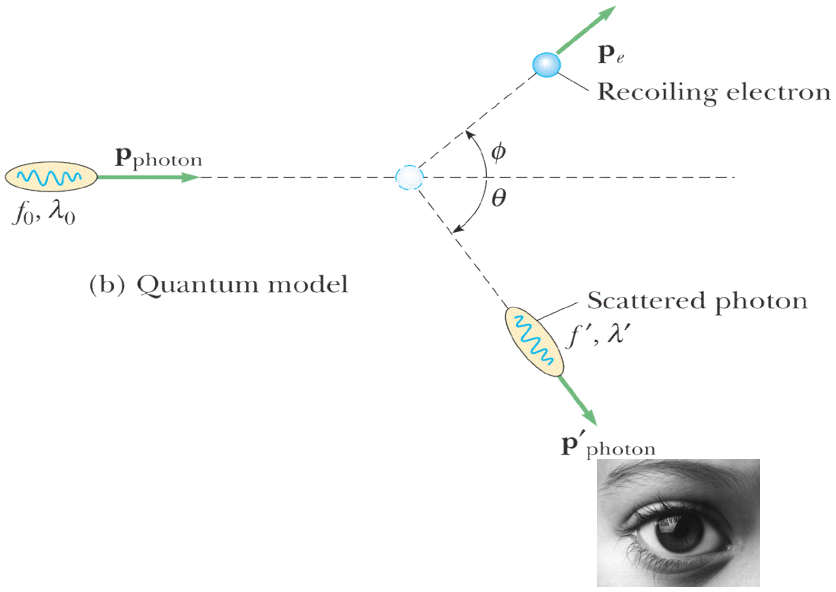


$\Delta\lambda = (\lambda' - \lambda) \propto (1 - \cos\theta)$!

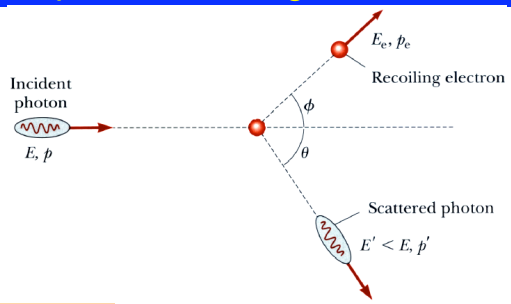
Not isotropy in distribution of scattered radiation

How does one explain this startling anisotropy?

Compton Effect : Quantum (Relativistic) Pool



Compton Scattering: Quantum Picture



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)

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

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

Square and add $\Rightarrow$

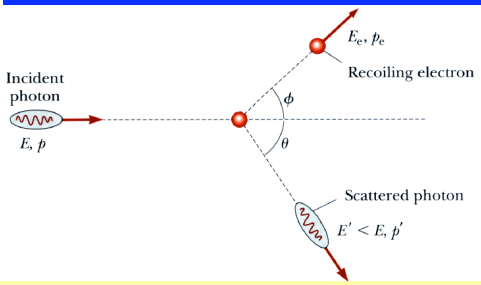
$p_e^2 = p^2 - 2pp'\cos\theta + p'^2$

Eliminate p_e & E_e using

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

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

Compton Scattering: The Quantum Picture



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)

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

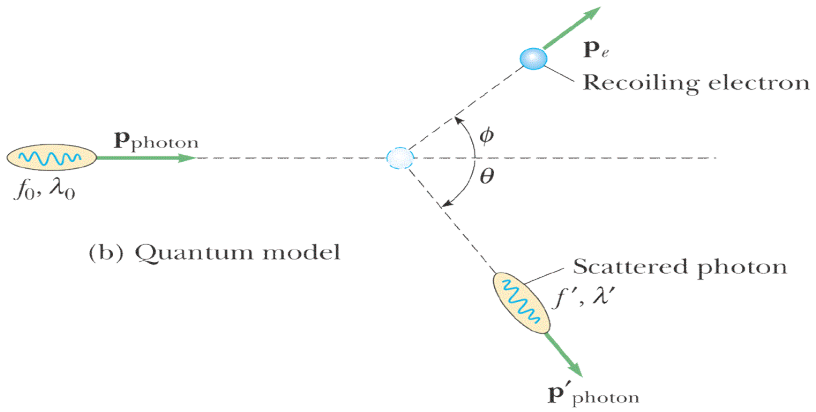
For light $p = \frac{E}{c} \Rightarrow$

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

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

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

Rules of Quantum Pool between Photon and Electron

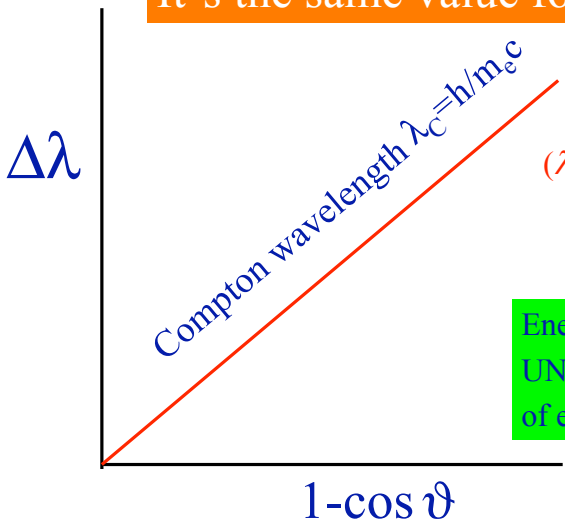


$$(\lambda' - \lambda) = \left(\frac{h}{m_e c}\right)(1 - \cos\theta)$$

Checking for h in Compton Scattering

Plot scattered photon data, calculate slope and measure "h"

It's the same value for h again !!



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

Energy Quantization is a UNIVERSAL characteristic of energy transactions !

Saw what light does, Now examine nature of matter

- Fundamental Characteristics of different forms of matter
  - Rest Mass (m)
  - Electric Charge (q)
    - Measurable
      - using some combination of **E** & **B fields interacting with the particle**

Reading Assignment, one problem from here may be on the quiz

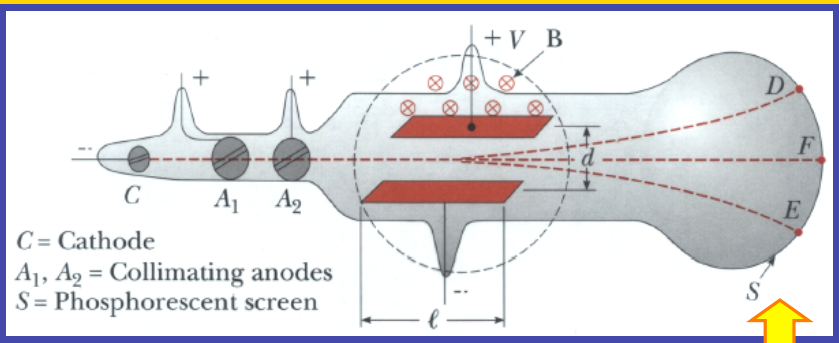
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

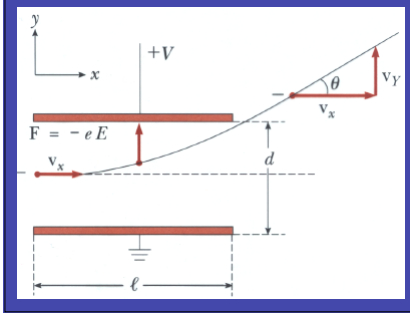
  - **Or E/B or some other macroscopic force**

e.g. Drag Force

The "magic" is that one is measuring tiny tiny numbers using Macroscopic devices

Thomson's Determination of e/m of the Electron

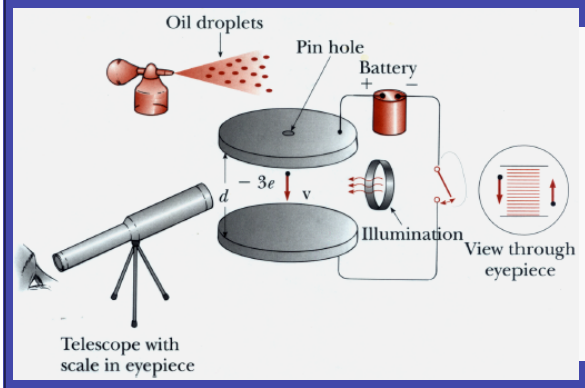


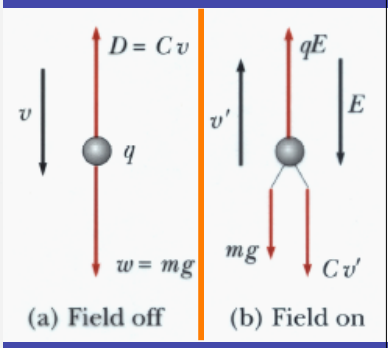


- In E Field alone, electron lands at D
- In B field alone, electron lands at E
- When E and B field adjusted to cancel each other's force → electron lands at F

→ e/m = 1.7588 x 10^{11} C/Kg

Millikan's Measurement of Electron Charge





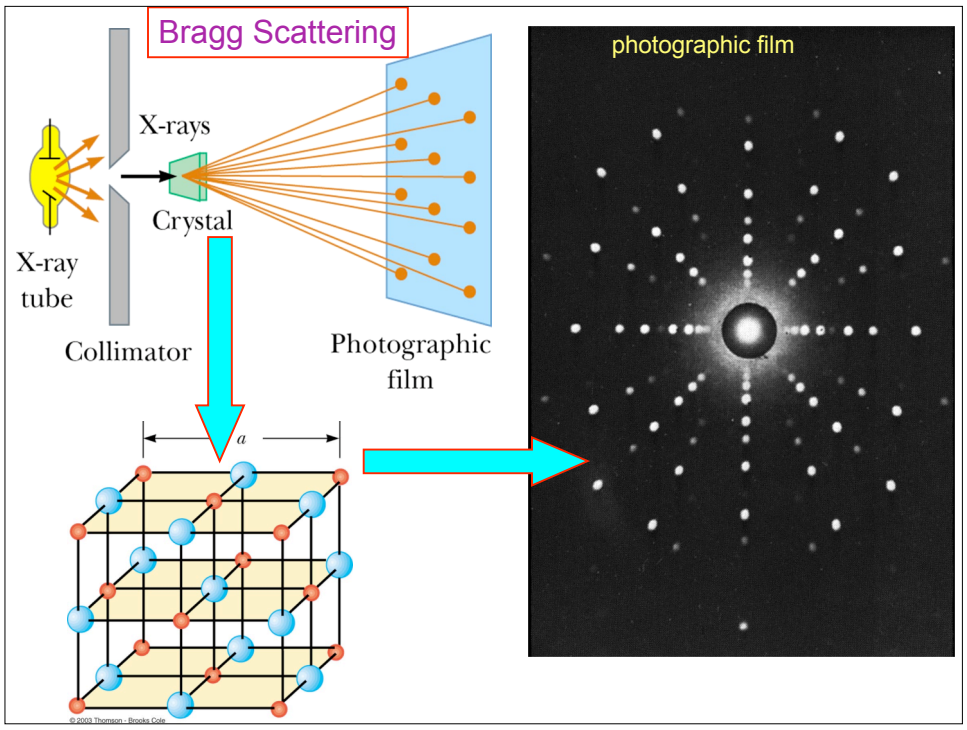
Find charge on oil drop is always in integral multiple of some Q

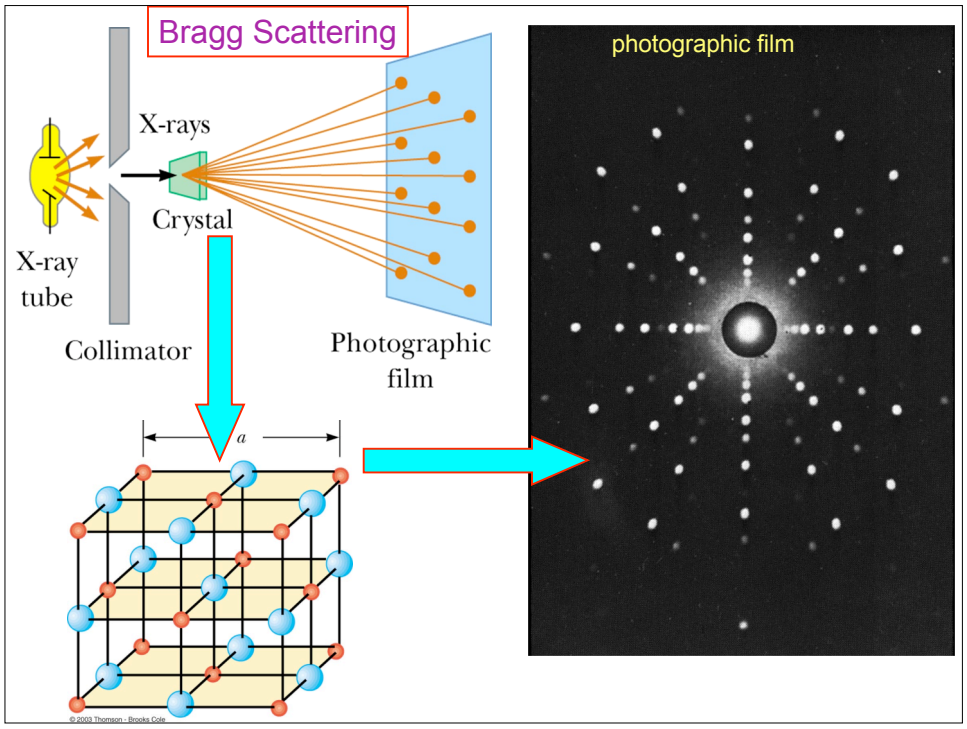
$q_e = 1.688 \times 10^{-19}$ Coulombs

→ $m_e = 9.1093 \times 10^{-31}$ Kg

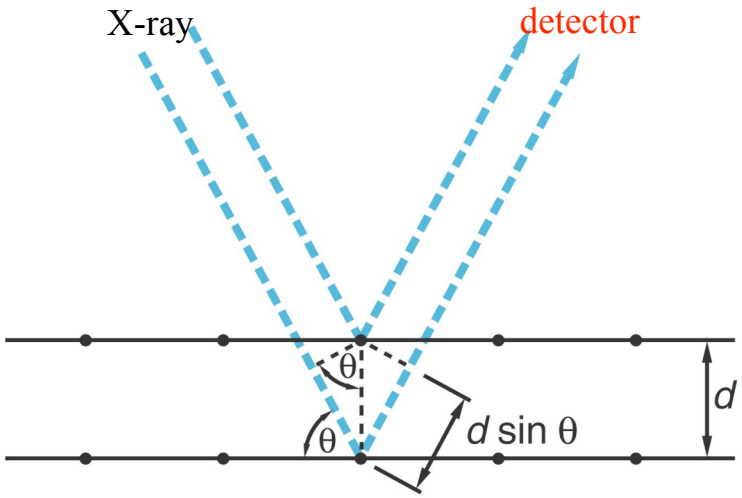
→ Fundamental properties (finger print) of electron

(similarly can measure proton properties etc)





Bragg Scattering: Probing Atoms With X-Rays

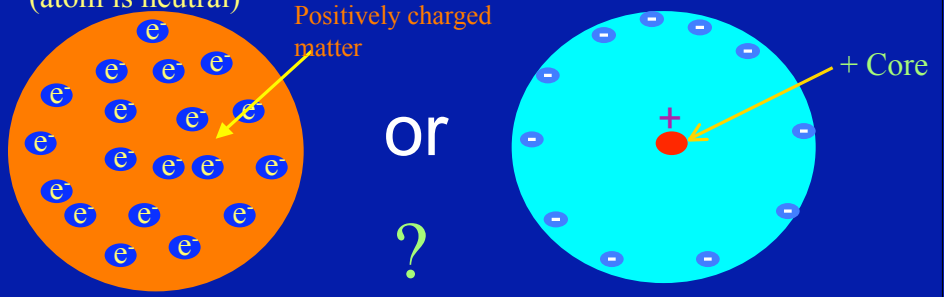


Constructive Interference when net phase difference is 0, 2π etc
This implied path difference traveled by two waves must be integral multiple of wavelength : **nλ=2dsinϑ**

Summary : From X Ray (EM Wave) Scattering data, Size of the Atom was known to be about 10^{-10} m

Where are the electrons inside the atom?

Early Thought: "Plum pudding" model→ Atom has a homogenous distribution of Positive charge with electrons embedded in them (atom is neutral)

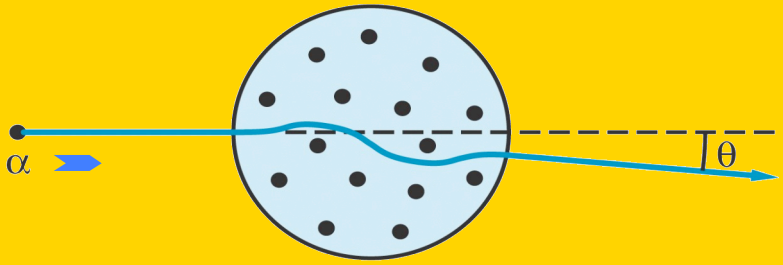


- How to test these hypotheses? → Shoot "bullets" at the atom and watch their trajectory. What Kind of bullets ?
  - •Indestructible charged bullets → Ionized He^{++} atom = α^{++} particles
  - •Q = +2e , Mass M_α=4amu >> m_e , V_α= 2 x 10^7 m/s (non-relavistic)

[charged to probe charge & mass distribution inside atom]

Plum Pudding Model of Atom

- Non-relativistic mechanics ($V_\alpha/c = 0.1$)
- In Plum-pudding model, α-rays hardly scatter because
  - Positive charge distributed over size of atom (10^{-10}m)
  - $M_\alpha >> M_e$ (like moving truck hits a bicycle)
  - → predict α-rays will pass thru array of atoms with little scatter (~1°)



Need to test this hypothesis → Ernest Rutherford