QUANTUM PHYSICS

By Dr. Dhruv Singh

Physics
- Classical
  - Newtonian
  - EM / wave theory
  - Electric field / magnetic
- Modern
- Quantum (majorly belongs to modern but classical is also involved)

Light
- straight lines (rectilinear prop)
- colours (splits into)
- reflection laws by euclid (300 BC)
- refraction (bending) by snell (1621)
- it converges & diverges by Galileo (1610)
- it is a wave / particle
  [Hooke's & Huygens (17th century) on wave theory research]

Wave eq ⇒ $y = A\sin(kx - \omega t)$

where 'y' can be pressure / Amplitude (V), field (E, B)

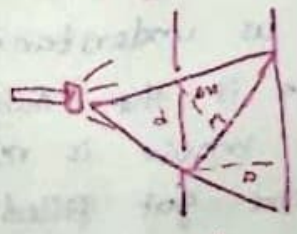
$k = 2\pi/\lambda$, $\omega = 2\pi\nu$

A - max amplitude, $\nu = \frac{1}{T}$

Light when tested with young's double slit experiment, it was proven that light is wave (1801)

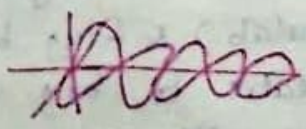
For $D = \left(n + \frac{1}{2}\right)\lambda$ → destructive

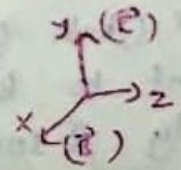
$D = n\lambda$ → constructive



⇒ Maxwell proposed 4 eq on em nature of waves / light in late 19th century.

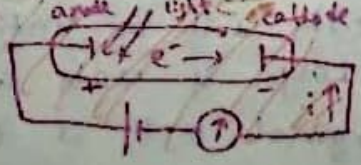
Electro magnetic theory of maxwell





⇒ Photoelectric effect was first performed in the laboratory of Heitz

1926 - photon word was proposed by Lewis



e⁻ emitted are photo e⁻ and current generated is photo current

parameter in this experiment:-

* V (potential diff)
* ν (frequency of e⁻ emitted)
* i (photo current)
* I (Intensity of light incident)

[redacted]

Hertz used em theory and found

Energy $= \frac{1}{2}\varepsilon_0 E_0^2 + \frac{1}{2}\mu_0 B^2$

$B = \frac{E}{c}$, $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

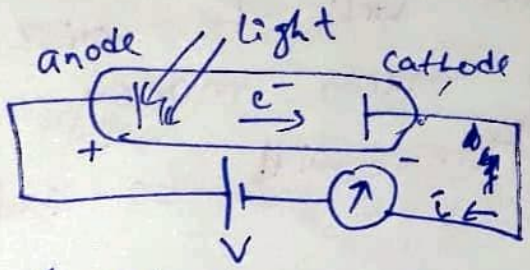
$I = \frac{1}{2} c \varepsilon_0 E^2$

$I \uparrow \Rightarrow$ energy $\uparrow$

Energy is transfered to wave fronts in case of wave which makes delay. But hertz observed that it's an instantaneous process.

How ?

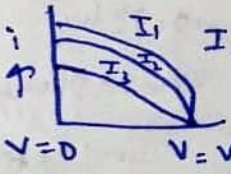
See next lec



ν = const, V & i varies

When $V = 0$, i is max.

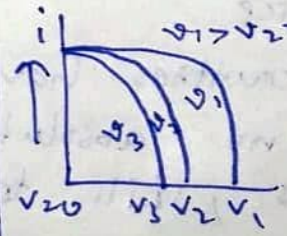
When $V = V_0$, $i = 0 \Rightarrow V_0$ is stopping potential.



$I_1 > I_2 > I_3$

As $I \uparrow$, $i \uparrow$

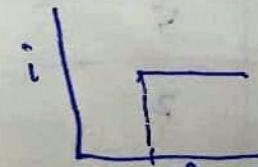
When I is const, ν & i varies



in this stopping potential changed

$\nu \uparrow$ $V \uparrow$

For i & ν



Till some region no current.

ν_0 is threshold frequency.

Quantum Phy Lec-2

⇒ Limitations of EM theory explanation for photo-electric current.

* It cannot explain instant emission of e^- (which indicates that it is a point). According to EM theory there is time lapse which is wrong (wave energy transfers to region)
* EM theory doesn't explain relation btw energy and ν. so we cant explain why we get diff stopping potential for same initial photo current.
* It cannot explain the concept of threshold frequency.

⇒ So later in 1905, Einstein proposed new concepts to overcome the above limitations. (Einstein got Nobel prize in 1922)

* He assumed that light is made of photons (named by Lewis in 1926)
* Each photon has $h\nu$ energy $E = h\nu$
* In this case intensity means no. of photons falling on surface per unit area per unit time.
* He introduced concept of work function.

$E = W + KE$

$h\nu = h\nu_0 + KE$ (ν_0 → threshold frequency)

W ⇒ min energy req to make an e^- to come out of surface.

$\nu = \nu_0 \Rightarrow KE = 0$

$E \propto \nu$, $K.E \propto \nu$, $K.E \uparrow \Rightarrow KE \uparrow \nu \uparrow V \uparrow$

h ⇒ planck's const $= 6.62 \times 10^{-34}$ J.sec

⇒ Application of PEE ⇒ PMT (photo multiplier tubes) (for detecting radiations)
(MVCS, CCD)
(image sensors)

⇒ Compton effect / compton scattering (1923) and got nobel in (1927)

* When we consider elastic collision of photon with anyother body then we should also consider rest mass of photon along with KE while applying energy conservation.

$E' = m_0c^2$ ← rest mass energy. rest mass energy.

$\therefore E = m_0c^2 + KE = \gamma m_0c^2$ ($KE = \frac{1}{2}mv^2$)

$\therefore \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ $\left(\gamma = \frac{m}{m_0}\right)$

γ = Lorentz constant. v = speed of particle, c = speed of light

m_0 => rest mass, m => relativistic mass

momentum $p = mv = \gamma m_0 v$

$E^2 = (m_0c^2)^2 + p^2c^2$ when, $m_0 = 0$

$E = pc \Rightarrow p = E/c$

this is the case of photon.

$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$, $h/2\pi = \hbar$, $\frac{2\pi}{\lambda} = k$

$p = \frac{h}{\lambda} \Rightarrow p = \frac{h}{\lambda}$ $\Rightarrow p = \hbar k$

$E = h\nu = \frac{h\nu}{2\pi} \times 2\pi = \hbar(\omega)$

Lec-3

$E = m_0c^2 + KE \Rightarrow E = m_0c^2 + \frac{p^2}{2m}$

$= m_0c^2 + \frac{\gamma^2 m_0^2 v}{2m}$

After this idk what to do ↙

$= m_0c^2 + \frac{m}{m_0}\left(\frac{m_0^2}{2m}\right)v$

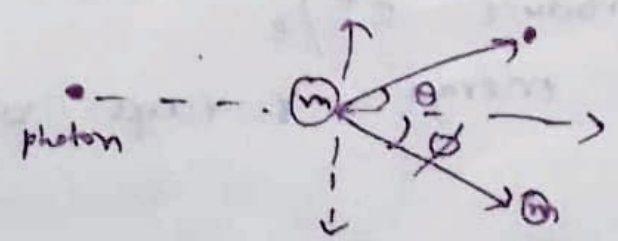
$= m_0c^2 + \frac{m_0 v}{2}$

⇒ Compton effect :-

It explains that there happens an elastic collision btw photon & other massive particle at rest.

Since, the collision is elastic both p & E are conserved.

$P_{1i} = P_{1f} + P_{2f}$, $E_{1i} = E_{1f} + E_{2f}$ [assume massive particle at rest]



along x-axis , $\frac{h}{\lambda} = \frac{h}{\lambda'}\cos\theta + P\cos\phi \rightarrow (1)$

y-axis , $0 = \frac{h}{\lambda'}\sin\theta - P\sin\phi \rightarrow (2)$

Similarly for energy,

$\frac{hc}{\lambda} + m_0c^2 = \frac{hc}{\lambda'} + \sqrt{(m_0c^2)^2 + (pc)^2} \rightarrow (3)$

From ①, ② & ③, $\underbrace{\Delta\lambda}_{\text{compton wave length}} = \lambda - \lambda' = \frac{h}{mc}(1-\cos\theta)$

* This is independent of λ.
* λ is wave property. But the change in wavelength is independent of λ which indicates that wave theory couldn't explain this. Hence it was finally concluded that it has both particle & wave nature (duality).
* It is observed for X-rays or other waves of the higher frequency.

For $\Delta\lambda$ to be max, $\theta = 90°$

$\Delta\lambda = \frac{h}{m_0c^2} = 0.1$ nm for X-rays range

But for visible light,

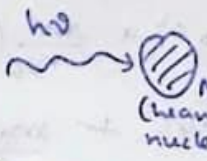
$\Delta\lambda = 10^{\frac{1}{2}}$nm which is not a suitable range for compton effect.

[which is suitable for compton effect]

Hence visible light is not suitable.

=> Pair production:-

* Light can be converted into matter



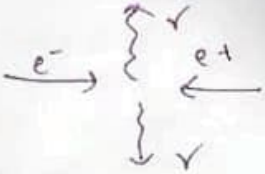
* similarly matter can be converted into light. which indicates that there exists relation btw energy and matter.
* Energy of e^- & e^+ together is 1.02 Mev (0.51 + 0.51).
* Hence any radition with energy greater than or eq to 1.02 mev can produce e^+/e^-.
* To produce such energy, γ rays will be suitable.

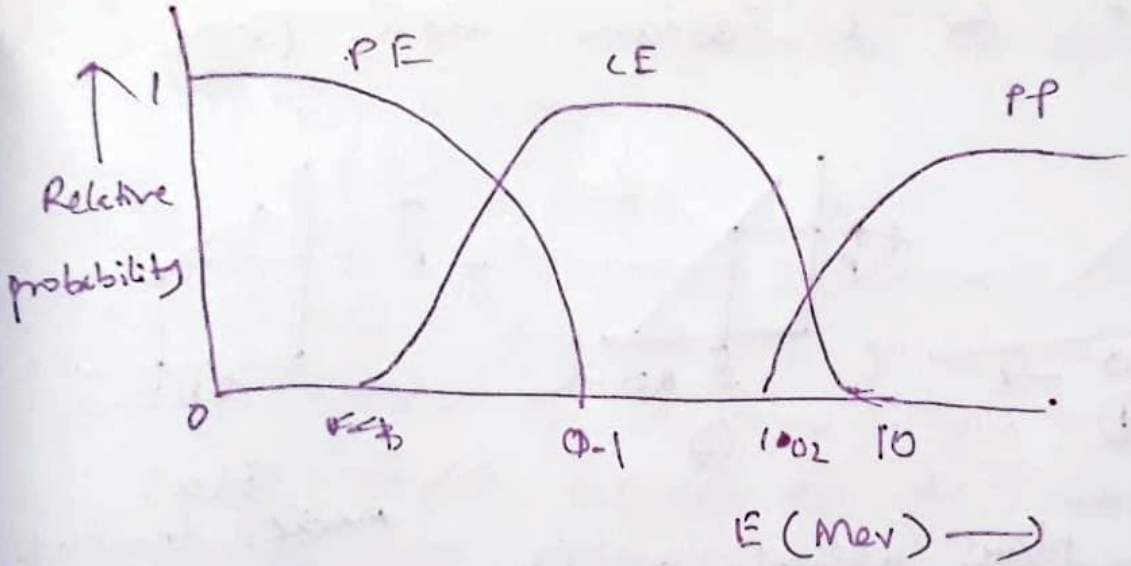
[rest mass of e^- and e^+ rest mass energy of e^- & e^+ is 0.51 Mev]

=> Pair annihilation:-

When 1 e^- & 1 e^+ collide then 2 γ rays are produced.

This is know as pair annihilation, here 0.51 Mev of each 2 particles converts into γ radiation.





Energy inc then there is more chance of occurance of PP. If it's less then PE happens mostly.

⇒ Gravitational red shift (Black hole):-

Prove $\Rightarrow E^2 = (m_0c^2)^2 + (pc)^2$

Sol. $p = \gamma m_0 v = \dfrac{m_0 v}{\sqrt{1-\frac{v^2}{c^2}}} \Rightarrow p^2c^2 = \dfrac{m_0^2 v^2 c^2}{1-\frac{v^2}{c^2}} \rightarrow (1)$

$E = \gamma m_0 c^2 \Rightarrow E^2 = m_0^2 c^4 / \left(1-\frac{v^2}{c^2}\right) \rightarrow (2)$

$(2) - (1) \Rightarrow E^2 - p^2c^2 = \dfrac{m_0^2c^4\left(1-\frac{v^2}{c^2}\right)}{\left(1-\frac{v^2}{c^2}\right)} = m_0^2c^4 = (m_0c^2)^2$

$\Rightarrow E^2 = (m_0c^2)^2 + (pc)^2$

GRAVITATIONAL RED SHIFT :- (Idea abt black hole given)

mass of moving photon $m = P/c$.

$(1) \leftarrow m = \dfrac{h\nu}{c^2}$ $\left[\because P = \dfrac{E}{c} \Rightarrow P = \dfrac{h\nu}{c}\right]$

For mass m (particle / photon) and (planet or star) of mass M

$$PE = -\frac{GMm}{R} \rightarrow (2)$$

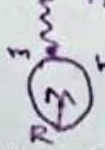
Sub (1) in (2)

$$PE = -\frac{GMh\nu}{c^2R} \rightarrow (3)$$

Total energy (TE) of mass (M, m) is

$$E = h\nu - \frac{GMh\nu}{c^2R}$$

$$h\nu' = h\nu - \frac{GMh\nu}{c^2R}$$



[ν' is frequency of light after emission which comes out of planet]

Here $\frac{GM}{c^2R} > 0$ $\quad \nu' = \nu\left(1-\frac{GM}{c^2R}\right)$

$\Rightarrow \left(1-\frac{GM}{c^2R}\right) < 0 \Rightarrow \nu' < \nu$

$\Rightarrow \underbrace{\lambda' > \lambda}_{\text{red shift}}$

[ν - freq at source
ν' - freq after coming out of star fro observed by observer]

Hence observe finds freq to be decreased.

If for some planet, $\frac{GM}{c^2R} = 1$ then, $\nu' = 0$

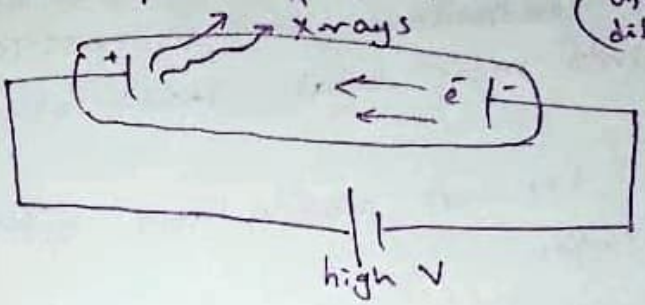
then observer will not observe any light.

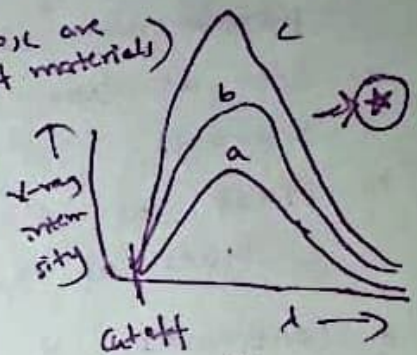
This is the case of black hole

* for $\theta = 2\pi$, we get max $\Delta\lambda$ in compton effect.

X-RAYS (discovered by WK Roentgen 1895 & got Nobel prize in 1902 which was first nobel prize in physics)

* It is also called inverse of photo electric effect.
* we use vaccum tube, to reduce & increase the mean free path of e^-.

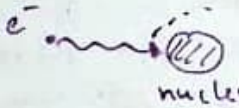




* e^- are emitted by thermoionic emission and then reach the opposite side. and due to that hitting of e^-, x-rays are emitted
* Duane & Hunt & gave equation

$$\lambda_{min} = \frac{1.24 \times 10^{-6}}{V}$$

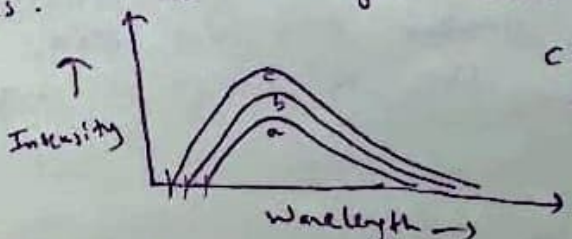
c > b > a are energies of e^-



$$eV = h\nu_{max} = \frac{hc}{\lambda_{min}}$$

$$\lambda_{min} = \frac{1.24 \times 10^{-6}}{V}$$

* Cutoff wavelength:- Minimum wavelength below which no x-ray was observed.
* Even if we change the materials used, cutoff wavelength will not change. refer (*)
* But if energy changes then cutoff wavelength changes.

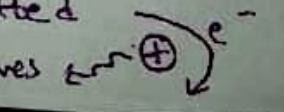


c > b > a
here a, b, c are energies of e^-
Intensity ∝ energy

* It was explained that when e^- (charged particle) passes through a medium, if there is change in acceleration then, EM waves are emitted

(electrostatic repulsion & attraction) ← reason

This phenomenon is Brems Strahlung radiation.



Extra info to understand about X-rays

There are two types of X-rays.

* Continuous X-rays (which we discussed in today's class)
* Characteristic X-rays (which sir explained at the end)

=> We already gathered info and understood the phenomenon of continuous X-ray emission.

=> Let us look into more detail about characteristic X-rays.

=> First of all let us understand difference btw 2 types of X-rays.

* Continuous X-rays are emitted when free moving e^- electromagnetically interact with nuclei, whereas characteristic X-rays are emitted when e^- jumps from higher level to lower level to occupy an empty space.
* Characteristic X-rays are produced when element is bombarded with high energy particles, photons, e^-, p^+, electrons get emitted from inner shell and there will be a vacancy. When, outer shell e^- fall into inner shell then they release energy in form of X-rays.
* For a vacancy in K shell when can denotes emissions as K_α from L to K, K_β from M to K, K_γ from N to K. Similarly for vacancy in L shell, L_α, denotes X-rays emission from M to L.
* Instead of emitting X-rays, the energy can be transferred to another e^- and then, that e^- gets ejected. This is known as auger effect.