Photo-electric Effect

Photon

- Smallest packet of light.
- Energy of smallest packet is $\frac{hc}{\lambda}$
- Packet of energy is known as photon or quantum.
- Packets of energy are known as photons (quanta).
- Total energy contributed by n photons is:
  $E = n\frac{hc}{\lambda} \ldots\ldots (1)$
- Power is:
  $P = \frac{w}{t} = \frac{E}{t} = \frac{nhc}{\lambda t} \ldots\ldots (2)$
- Intensity is:
  $I = \frac{P}{A} = \frac{nhc}{\lambda t A} \ldots\ldots (3)$
  where, $A \rightarrow \text{cross-section area.}$
- At rest mass of photon is zero.
- Dynamic mass of photon is:
  $m = \frac{E}{c^2} = \frac{h\nu}{c^2}$
- Photon is always in motion. It has dynamic character. Therefore, energy of photon according to Einstein's mass energy relation is:
  $E = mc^2$
- When light of frequency f and energy hf get incident on metal surface, if incident frequency is greater than or equal to minimum (threshold) frequency, electrons are emitted out from the metal surface, phenomenon is known as photo-electric effect. So ejected electrons are called photo-electrons.

  i.e. $f \geq f_0$, emission of electrons is possible.

  where, $f \rightarrow$ radiated frequency
  where, $f_0 \rightarrow$ threshold frequency

  For emission of photo-electrons, $\lambda \leq \lambda_0$

  where, $\lambda \rightarrow$ radiated wave length
  where, $\lambda_0 \rightarrow$ threshold wave length

  We have,

  $f \propto \frac{1}{\lambda}$

  $f = \frac{c}{\lambda}$

  $f_{min} = \frac{c}{\lambda_{max}}$

  i. If $f > f_0$, electrons are emitted out as well as accelerated. In this case, electrons carry greatest kinetic energy.

ii. When $f = f_0$, electrons are just emitted out but there is no acceleration. K.E. carried by electrons in this case is zero.

iii. If $f < f_0$, emission of electrons is impossible but electrons are excitated only.

- Incident light energy hf overcome binding energy, electrons are emitted out from the metal surface.
- During the emission, single photon can emit out single electron from the metal surface. (100% chance)
- The emission of no. of photo-electrons from the metal surface depends on intensity of light.
- K.E. carried by emitted electrons depends on frequency of light.

Work Function

- Minimum energy required on metal surface to liberate the electrons.
- Denoted by ϕ_0 or ω_0.
- Equation is :
  $$\phi_0 = hf_0 = hf_{min}$$
  $$\phi_0 = \frac{hc}{\lambda_{max}}$$
  Longest (threshold) wavelength is:
  $$\lambda_{max} = \frac{hc}{\phi_0} \ldots\ldots (1)$$

Stopping (Cut off / Retarding) potential:

- The -ve potential which decelerates the emission of photo-electrons is known as stopping potential.
- Denoted by V_0 or V_s or V_c
- At stopping potential, P.E. gain by e^- balanced its K.E.

$$\mathrm{P.E.} = \mathrm{K.E.}$$

$$eV_S = \mathrm{K.E.}$$

$$V_S = \frac{\mathrm{K.E.}}{e}$$

$$V_s = \frac{\frac{1}{2}mv_{\max}^2}{e} = \frac{v_{\max}^2}{2(e/m)} \ldots\ldots\ldots\ldots (2)$$

Einstein's photo-electric equation

- It deals about the conservation of energy. Energy neither be created nor be destroyed but can be changed one form to another form. Before & after emission of electrons, energy remains conserved.

  Incident Energy = Work function + Kinetic energy

  $$hf = \phi_0 + K.E.$$
  $$hf - hf_0 = \frac{1}{2}mv_{max}^2 \ldots\ldots (1)$$

  We have,

  $$\frac{hc}{\lambda} - \frac{hc}{\lambda_0} = \frac{1}{2}mv_{\max}^2$$

  $$hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) = \frac{1}{2}mv_{\max}^2 \ldots\ldots (2)$$

  Again,

$$hf - hf_0 = P.E.$$
$$hf - hf_0 = eV_0 \ldots\ldots (3)$$
$$\& \ hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) = eV_0 \ldots\ldots (4)$$

These are Einstein's photo-electric equations in different form.

- According to theory of relativity, the rest mass of photon is 0 and its relativistic mass is

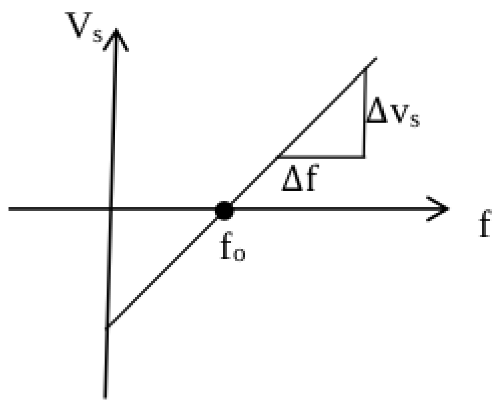
$$m = \frac{hf}{c^2} \ldots\ldots (5)$$

- The momentum of each photon is given by:

$$P = mc = \frac{hf}{c^2}c = \frac{hf}{c} = \frac{h}{\lambda} \ldots\ldots (6)$$

Laws of photo-electric effect

- The kinetic energy of the emitted electron is independent of intensity of incident radiation.
- Photo-electric current increases with the increase in intensity of incident radiation.
- Kinetic energy of the emitted electron depends on the frequency of the incident radiation.
- KE increases with the increase of frequency of incident radiation.
- Incident frequency should be greater than or equal to critical (threshold) frequency.
- There is no time lag between the arrival of light and the emission of photo-electrons.
- K.E. is directly proportional to $(v - v_0)$
- Robert Andrew Millikan's verified Einstein's photo-electric equation experimentally.
- When a graph is plotted in between the incident frequency and stopping potential graph represents a straight line with -ve intercept.



Planck's constant is determined. From Einstein's equation:

$$hf - hf_0 = eV_0$$

$$V_0 = \frac{h}{e}f - \frac{hf_0}{e}$$

$$y = mx + c$$

Einstein's equation also represents a straight line.

Where, slope is $m = h/e$

$$h = m \times e$$

$$h = \tan\theta \times e$$

$$h = \frac{PQ}{QR} \times 1.6 \times 10^{-19}$$

$h = 6.64 \times 10^{-34}\mathrm{JS}$

Work function is to be known.

i.e $\phi_0 = hf_0 = \mathrm{known}$

Photo-cells

- Photo-cells are the devices, used to convert light energy into electrical energy. e.g. solar batteries
- Photo-cells are three types:

  i. Photo-emissive
    a. Vacuum type photo-emissive cells
    b. Gas filled type photo-emissive cells

  ii. Photo-voltaic cells

  iii. Photo-conductive cells

Uses of photo-cells:

- Photo-cells are used in photometry to compare intensity of distinct sources.
- Highly used in counting & switching devices.
- Used in alarm bells.
- Used in one way traffic light.
- Used in T.V. receivers.
- Used in photography.
- Used in industry.
- Photo cells are used for automatic control of signals and detection of speed of the moving objects like vehicles on the roads.

X-rays

- Energetic radiation of short wavelength about $10^{-10}\,m$
- X-rays is high energy photon having energy $\frac{hc}{\lambda}$.
- When fast moving electrons strike a heavy target (having high mass no., high melting & boiling points) after rescattering through the target, electromagnetic wave of short wavelength about $10^{-10}\,m$ are produced, they are naming as X-rays.
- X-rays are discovered by Roentzen.
- X-rays are called Roentzen rays.
- The wavelength of X-rays ranging from $10^{-9}\,m$ to $10^{-12}\,m$
- All X-rays are not of single wavelength.
- Different X-rays have different wavelength but lines within the range.

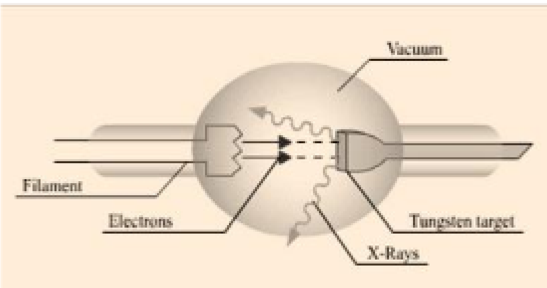
Properties of X-rays

- X-rays are electromagnetic waves.
- X-rays are not deflected by fields (electric & magnetic).
- They move along the straight path with velocity of light in vacuum.
- X-rays can cause photo-electric effect.
- X-rays undergoes reflection, refraction, diffraction, interference & polarization.

- They produce illumination of fluorescent materials on which they fall.
- They ionize the gas through which they pass.
- They can penetrate thin materials like wood, thin sheet etc.
- They do not pass through heavy metals and bones.
- X-rays cast their shadow on screen.
- They affect photo-graphic plates.
- X-rays fall on metal surface having high mass no. secondary X-rays are produced.

Production:

- Filament: Tungsten, it has low work function.

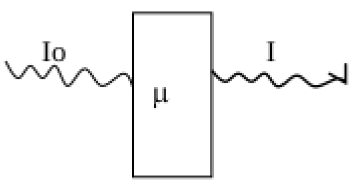


- Target: Molybdenum target is more suitable (Coolidge tube method) which has high mass no., high melting point, high boiling points etc.
- X-rays production is the inverse phenomenon of the photo-electric effect.
- In time of X-rays production, majority percentage of incident power is converted into heat.
- Minority percentage of incident power is converted into X-rays radiations.
- Soft X-rays:
  - having long wavelength
  - low energetic and low penetrating power
- Hard X-rays:
  - having short wavelength more energetic, having high penetrating power
- There is circulation of cold water around the target to maintain heat (temperature).
- The ionization power of X-rays depends on filament current where as penetrating power of X-rays depends on high p.d. provided by H.T.B. in between filament and target.
- Intensity of X-rays is proportional to the number of electrons emitted per second.
- Quality of X-rays implies the penetrating power of X-rays which is controlled by varying the potential difference.

Intensity of X-rays

- Amount of energy radiated per second per unit area is known as intensity denoted by I and expressed as

$$I=\frac{E}{tA}=\frac{P}{A}(\mathrm{watt}/m^2)\ldots\ldots(1)$$



- Dimension of intensity (I) is ML^0T^{-3}

- I_0 = initial intensity before penetrating the thickness of material x.

  I = final intensity after penetrating thickness

  x = thickness of material

  μ = absorption coefficient of a material

  dI = intensity decayed w.r.t. thickenss

  $\frac{dI}{dx}$ = rate of intensity decreases with respect to thickness which is proportional to final intensity

  Therefore,

  $$\frac{dI}{dx} \propto I$$

  $$\frac{dI}{dx} = -\mu I \ldots\ldots\ldots.(2)$$

  -ve sign indicates that intensity decreases.

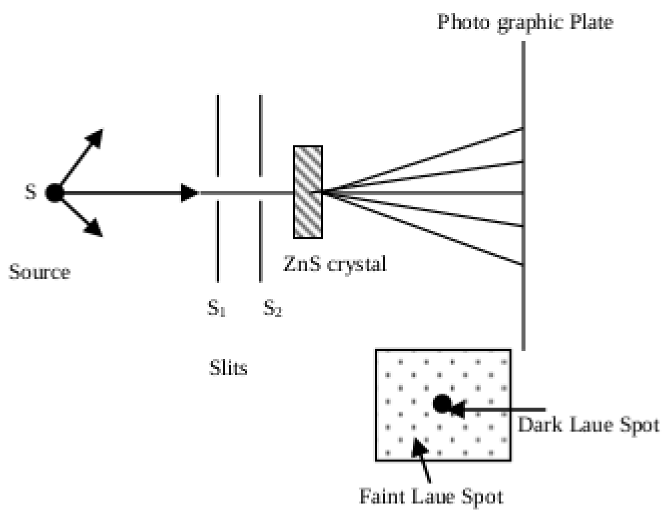
- When X-rays is passed through the material of particular thickness, intensity decreases.
- On integrating, equation of final intensity is:

  $$I = I_0 e^{-\mu x} \ldots\ldots(3)$$

  Final intensity in terms of initial intensity is exponentially decay with respect to thickness. It is due to absorption coefficient (μ) of a material.

Diffraction of X-rays

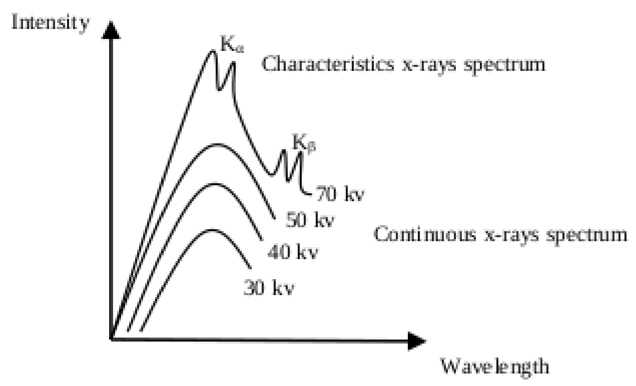
- Von Lane verified wave nature of X-rays.
- Von Lane verified X-rays diffraction by using atomic crystal as diffraction grating.
  Von Lane experiment for X-rays diffraction



- The major role play by ZnS crystal for diffraction of X-rays.
- The bending of X-rays round the corner of an obstacle is known as X-rays diffraction.
- The formation of dark & faint spots, it is due to unequal energy distribution during X-rays diffraction through ZnS crystal.
- Diffraction of X-rays verify its wave nature.

X-rays spectra

X-rays are produced from X-rays tube and they carry different wavelength. At a specified accelerating potential, the intensity of X-rays depends upon its wavelength. The graph between the intensity of X-rays & wavelength of X-rays at specified accelerating potential are called X-rays spectra.



- ### Continuous X-rays spectrum:
  - Continuous X-rays spectrum are produced due to retardation of high speed electrons while passing through the strong electric field.
  - Electron loses its energy in a collision with atom, an X-rays photon of maximum energy hv is emitted.

    At accelerating, potential V volt,

    $\mathrm{P.E.} =$ wave energy

    $$eV = hv_{\max}$$

    $$eV = \frac{hc}{\lambda_{\min}}$$

    $$\lambda_{\min} = \frac{hc}{eV}$$

  - Minimum wavelength of X-rays photon is inversely proportional to accelerating potential.

    i.e. $\lambda_{min} \propto \dfrac{1}{V}$

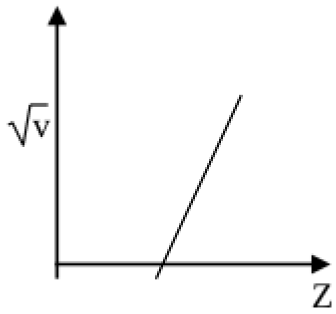
  - Each and every spectrum are abruptly ends at a certain minimum wavelength is known as limiting wavelength.
  - Intensity of continuous X-rays spectrum increases with increase applied voltage.
  - Accelerating potential and maximum frequency of X-rays photon is proportional.
  - Continuous X-rays spectrum depends on accelerating potential.
  - Continuous X-rays spectrum independent with nature of target material.
- ### Characteristics X-rays spectrum:
  - Characteristics spectrum is produced when high energy electron knock out the electrons from the innermost shells $\mathrm{K, L, M}$ etc. A vacancy is created which is filled by jumping of electron from the outermost shell.
  - Different atom emit different characteristics X-rays spectrum.
  - These X-rays have discrete energy.
  - Characteristics spectrum depends on characteristics of the target materials.
  - Transition of electron from 2^{nd} orbit to 1^{st} orbit forms K_α line, from 3^{rd} orbit to 1^{st} orbit forms K_β line, form 4^{th} orbit to 1^{st} orbit forms K_ν)line.
  - Transition of electrons from $3^{rd}, 4^{th}\ \&\ 5^{th}$ orbit to 2^{th} orbit corresponds to $L_\alpha, L_\beta\ \&\ L_\nu$ line.

Moseley's law

- The square root of frequency of the characteristics X-rays spectrum is proportional to atomic number,

$$\sqrt{\nu} = Z \Rightarrow \nu \propto Z^2$$
$$\text{Or, } \sqrt{\nu} = a(Z-b) \quad \text{K series, } b = 1$$
$$\sqrt{nu} = a(Z-1) \Rightarrow \frac{1}{\lambda} \propto (Z-1)^2$$

- Graph plotted between the atomic number (Z) and square root of frequency (ν), graph represents a straight line with +ve intercept.
- Slope of straight line gives the constant a and intercept on x-axis provides value of b.



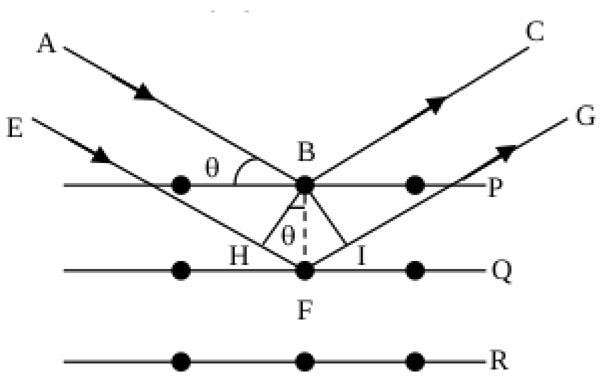
- X-rays spectra cannot be obtained with very light element like hydrogen.
- Moseley law helps to determine the relative position of several elements in periodic table.
- Moseley law helps to predict and discover new elements.

Bragg's law

Bragg's law states that intensity is maximum only when path difference between two successive rays in numerically equal to the integral multiple of its incident wavelength (λ),

i.e, Path difference = $n\lambda \ldots\ldots (1)$

where $n = 1, 2, 3, \cdots$



From fig.

Path difference $= HF + FI$

Path difference $= d\sin\theta + d\sin\theta$

Path difference $= 2d\sin\theta \ldots\ldots\ldots\ldots (2)$

We have,

$2d\sin\theta = n\lambda \ldots\ldots\ldots (3)$

where,

$d =$ lattice space

$\theta =$ glancing angle

$n =$ order of diffraction

$\lambda =$ incident wavelength of X-rays

Glancing angle is, $\theta = \sin^{-1}\left(\frac{n\lambda}{2d}\right) \ldots\ldots\ldots (4)$

Lattice space is, $d = \frac{n\lambda}{2\sin\theta} \ldots\ldots\ldots\ldots (5)$

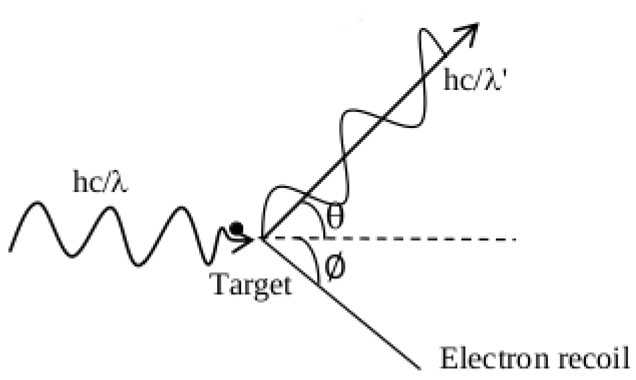
First order glancing angle is,

$\theta_1 = \sin^{-1}\left(\frac{\lambda}{2d}\right) \ldots\ldots\ldots\ldots (6) \quad (n = 1)$

Second order glancing angle is,

$$\theta_2 = \sin^{-1}\left(\frac{\lambda}{d}\right) \ldots\ldots\ldots\ldots (7) \quad (n=2)$$

Compton Scattering



λ = Incident wavelength

λ' = scattered wavelength of X-rays photon

θ = angle of scattering

ϕ = recoil angle of electron

During Compton scattering, the change in wavelength:

$$\Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

where,

$\Delta\lambda$ = change in wavelength

h = Plank's constant

m_0 = rest mass of e^-

c = velocity of light in air

X-rays Doze

- Doze of X-rays are measured in terms of produced ions or free energy through ionization.
- Doze measured in Roentgen.
- Roentgen measures ionization power.
- Safe doze for human being per week is one Roentgen.

Uses of X-rays

1. Highly used in medical fields such as surgery, therapy, cancer treatment, tumor treatment etc.
2. Highly used in engineering field.
3. Used in industrial field.
4. Used in detective field.
5. Used in space exploration.
6. Used in scientific research field.