Welcome to

Aakash + BYJU'S NOTES

Dual Nature of Radiation and Matter

$E = H + \nu$

$E = \varphi + KEmax$

$P = \frac{F}{A}$

History of Scientific Developments of the Nature of Light

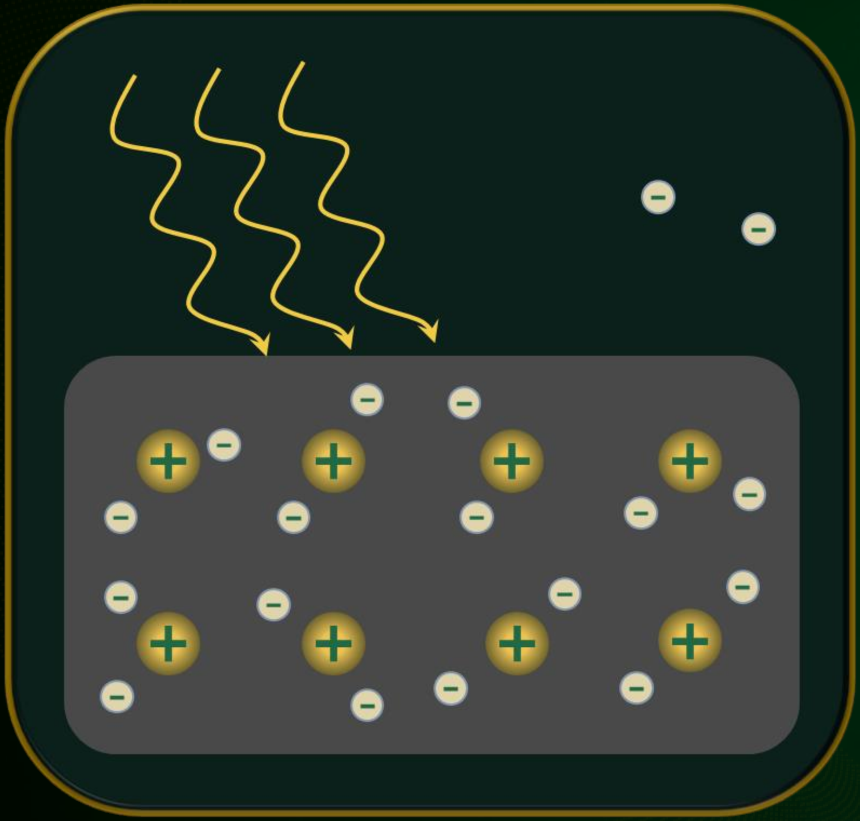
1660	Newton's Corpuscular Theory
1678	Huygens' Wave Theory
1801	Young's Double Slit Experiment
1809	Discovery of Polarization
1860	Maxwell's Equations of Electromagnetism
1887	Hertz' Observation - **?**

$E = \varphi + KE_{max}$

$P = \frac{}{A}$

$E = H + \nu$

Hertz Observation

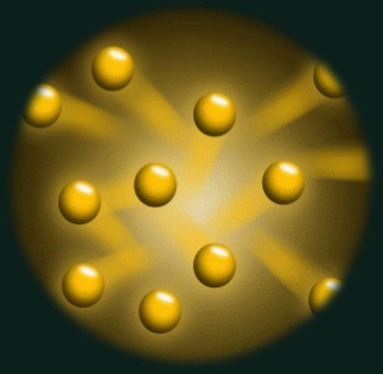


- If light is considered as a wave, then there should be sufficient time gap between light incident on a material and electron getting emitted from that surface.

- However, experimentally it is observed that the electron ejection process is instantaneous.

- Experimentally, it is also observed that above a particular wavelength or below a particular frequency of light, no electron is ejected even when the intensity of the light is high.

Photon Theory of Light



Photon

Max Planck's quantum theory of light:

- All the electromagnetic radiation is quantized in the form of wave packets or quanta. In case of light, the quantum of energy is known as photon.

Properties of photons:

- Rest mass of photon is zero.
- Photons always travel with the speed of light $\left(c = 3 \times 10^8 \frac{m}{s}\right)$ in vacuum.
- Photon has definite energy and momentum.

- Energy of photon:

$$E = \frac{hc}{\lambda} = h\nu$$

- Momentum of photon:

$$p = \frac{E}{c} = \frac{h}{\lambda}$$

- In general, the energy of a photon is represented in eV.

- $1\ eV$ is defined as the energy gained by an electron when accelerated by a potential difference of $1\ V$.

$$1\ eV = 1.6 \times 10^{-19}\ J$$

$$E = \frac{12400}{\lambda(in\ \text{Å})}\ eV$$

- Energy and momentum of a photon are always conserved.

- Number of photons may not be conserved.

The momentum of a photon of energy 1 MeV in SI unit is:

A 0.33×10^{6}

B 7×10^{-24}

C 1.33×10^{-22}

D 5.33×10^{-22}

Solution:

Momentum of a photon (p) is,

$$p = \frac{E}{c} = \frac{1 \times 10^{6} \times 1.6 \times 10^{-19}}{3 \times 10^{8}}$$

$$\Rightarrow \quad p = 5.33 \times 10^{-22}\ kgms^{-1}$$

There are n_1 photons of frequency ν_1 in a beam of light. In an equally energetic beam, there are n_2 photons of frequency ν_2. Then, the correct relation is:

A $\frac{n_1}{n_2} = 1$

B $\frac{n_1}{n_2} = \frac{\nu_1}{\nu_2}$

C $\frac{n_1}{n_2} = \frac{\nu_2}{\nu_1}$

D $\frac{n_1}{n_2} = \frac{\nu_1^2}{\nu_2^2}$

Solution:

Energy of each photon, $E = h\nu$

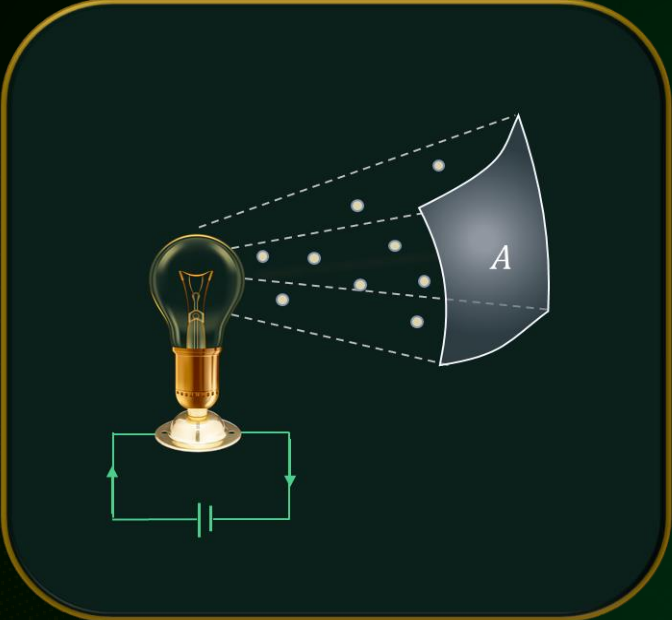
Energy of each beam of light, $E = nh\nu$

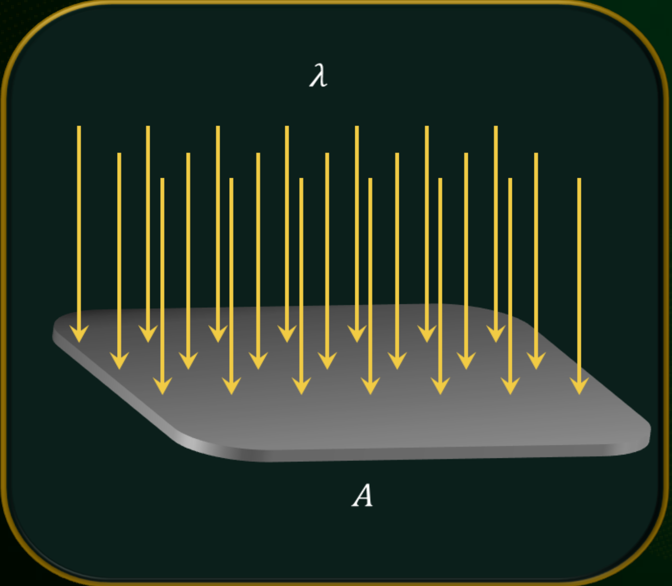
Given that, $E_1 = E_2$

$$\Rightarrow n_1 h\nu_1 = n_2 h\nu_2$$

$$\boxed{\Rightarrow \frac{n_1}{n_2} = \frac{\nu_2}{\nu_1}}$$

Intensity of Light Beam





- The intensity of light is defined as the amount of energy crossing per unit area per unit time perpendicular to the direction of propagation.
- The intensity of light is associated with number of photons.
- Photon count (n) is defined as the number of photons emitted per second by a source.
- If N is the total number of photons, then, $n = \frac{N}{t}$.
- Power, $P = \frac{NE}{t} = nE = nh\nu = \frac{nhc}{\lambda}$
- Intensity, $I = \frac{NE}{At} = \frac{P}{A} = \frac{nE}{A}$
- Photon flux (ϕ): Number of photons incident normally on a surface per second per unit area.
- If A be the area of the surface and photons are incident normally on the surface, then,

$$\phi = \frac{n}{A} \quad , n = \frac{P}{E} = \frac{P\lambda}{hc}$$

$$\boxed{\Rightarrow \phi = \frac{P\lambda}{Ahc} = \frac{I\lambda}{hc}}$$

Monochromatic light of frequency $6.0 \times 10^{14}\ Hz$ is produced by a laser. The power emitted is $2 \times 10^{-3}\ W$. The number of photons emitted by the source per second is:

A 5×10^{14}

B 5×10^{15}

C 5×10^{16}

D 5×10^{17}

Solution:

Power, $P = \frac{NE}{t} = \frac{Nh\nu}{t} = nh\nu$

$$\Rightarrow n = \frac{P}{h\nu} = \frac{2 \times 10^{-3}}{6.626 \times 10^{-34} \times 6 \times 10^{14}}$$

$$\boxed{\Rightarrow\ n = 5 \times 10^{15}}$$

10^{20} photons of wavelength 660 nm are emitted per second from a lamp. What is the wattage of the lamp?

A. $30\ W$

B. $60\ W$

C. $100\ W$

D. $500\ W$

Solution:

Power, $P = \frac{NE}{t} = \frac{Nh\nu}{t} = \frac{nhc}{\lambda}$

$$\Rightarrow P = \frac{10^{20} \times 6.6 \times 10^{-34} \times 3 \times 10^{8}}{660 \times 10^{-9}}$$

$$\boxed{\Rightarrow P = 30\ W}$$

A source S_1 is producing 10^{15} photons per second of wavelength $5000\ \dot{A}$.
Another source S_2 is producing 1.02×10^{15} photons per second of wavelength $5100\ \dot{A}$.
Find the ratio of power emitted by S_1 and S_2.

A 0.98

B 1

C 1.02

D 1.02

Solution:

Power, $P = \frac{NE}{t} = \frac{Nhv}{t} = \frac{nhc}{\lambda}$

$$\Rightarrow \frac{P_1}{P_2} = \frac{n_1}{n_2} \times \frac{\lambda_2}{\lambda_1} = \frac{10^{15}}{1.02 \times 10^{15}} \times \frac{5100\ \dot{A}}{5000\ \dot{A}}$$

$$\boxed{\Rightarrow \frac{P_1}{P_2} = 1}$$

The intensity of sunlight reaching the Earth's surface is $1.65 \times 10^3 \frac{W}{m^2}$. How many photons per square metre are incident on the Earth per second? Assume that the photons in the sunlight have an average wavelength of $540\ nm$.

A 4.5×10^{21}

B 5.4×10^{21}

C 4.5×10^{20}

D 4.5×10^{22}

Solution:

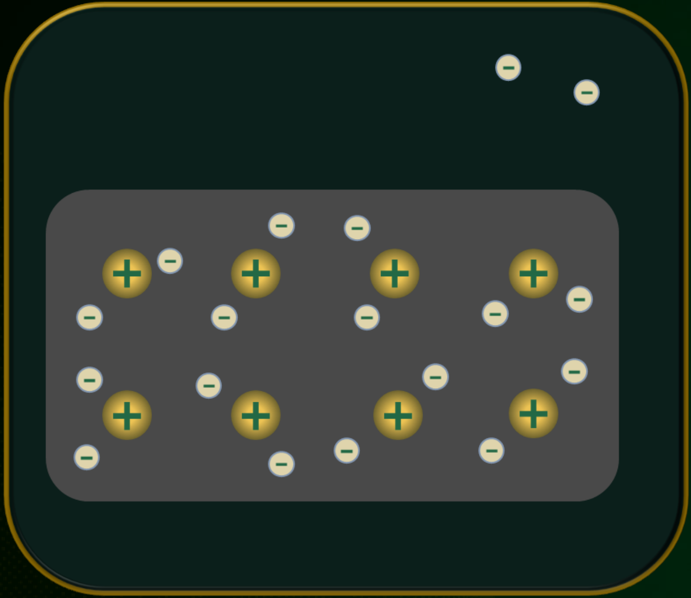
If N is the number of photons, then, $n_A = \frac{N}{At}$.

Intensity, $I = \frac{NE}{At} = \frac{Nh\nu}{At} = \frac{n_A hc}{\lambda}$

$$\Rightarrow n_A = \frac{I\lambda}{hc} = \frac{1.65 \times 10^3 \times 540 \times 10^{-9}}{6.6 \times 10^{-34} \times 3 \times 10^8}$$

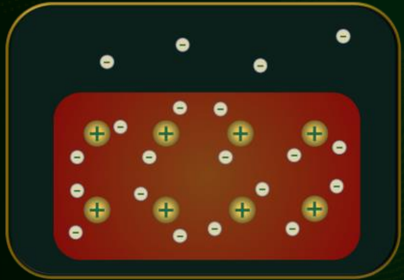
$$\boxed{\Rightarrow \quad n_A = 4.5 \times 10^{21}}$$

Electron Emission



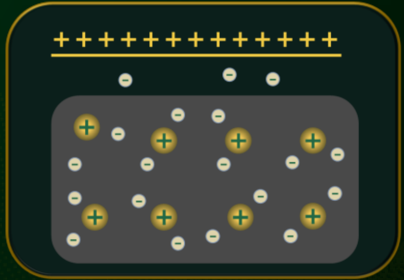
- The free electrons are free to move anywhere inside the material but self-ejection of electron from any material is not possible.
- If an electron comes out because of its own energy, then the material acquires a net positive charge owing to charge neutrality. Thus, the emitted electron will be attracted back into the material.
- The minimum amount of energy required to remove an electron from a metal surface is called work function (ϕ).
- The work function depends on the nature of the metal surface.
- The phenomenon of emission of electrons from the surface of a metal is called electron emission.

Thermionic Emission



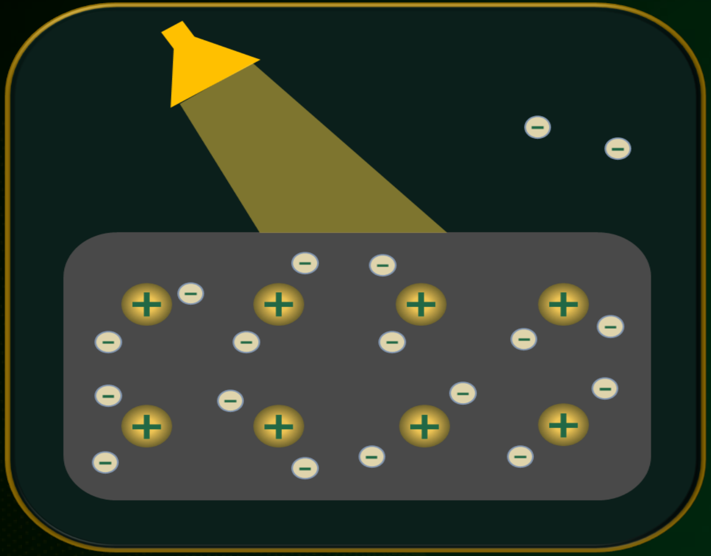
By suitably heating, sufficient thermal energy can be imparted to the free electrons to enable them to come out of the metal.

Field Emission

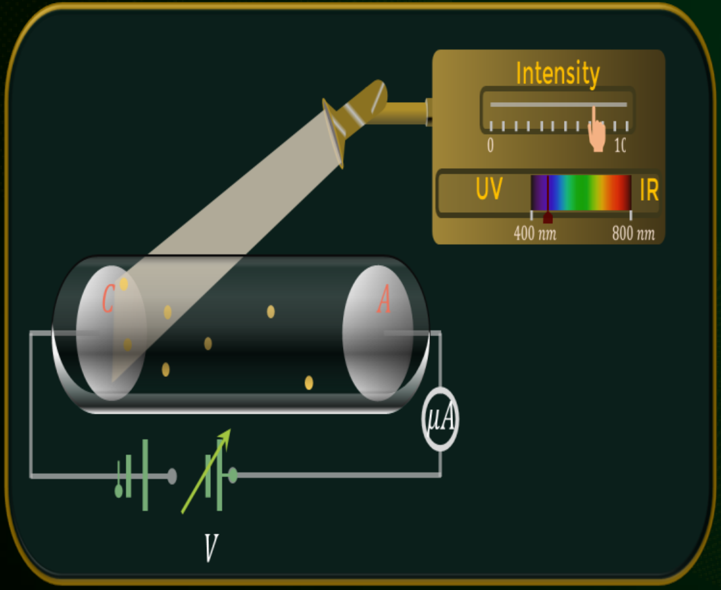


By applying a very strong electric field (of the order of $10^8\ V/m$) to a metal, electrons can be pulled out of the metal.

Photoelectric Effect



- When light of suitable frequency illuminates a metal surface, free electrons are emitted from the metal surface.
- These photo (light) generated electrons are called photoelectrons.
- Emission of photoelectrons from a metal surface when light of suitable frequency falls on it is called photoelectric effect.



- When light of suitable frequency falls on the photosensitive plate C (emitter), the photoelectrons are emitted from it which get accelerated towards the anode A (collector). These electrons flow in the outer circuit resulting in photoelectric current.
- No photocurrent is produced below a particular frequency or above
  a particular wavelength, even at higher intensity.
- Photocurrent is produced even at lower intensity, above a particular frequency.

When ultraviolet rays are incident on a metal plate, the photoelectric effect does not take place. Then, the photoelectric effect might take place by the incidence of:

A Infrared rays

B $X-$ Rays

C Radio Waves

D Yellow light

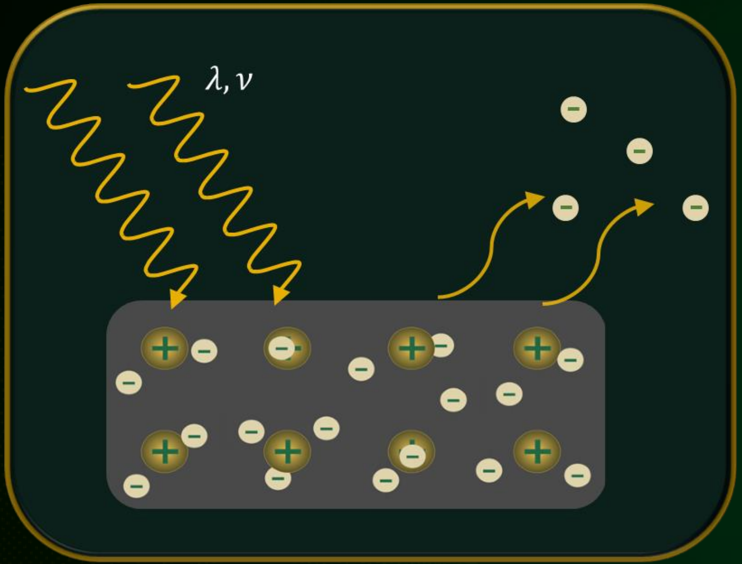
Solution:

The Photoelectric effect takes place only when the incident frequency is greater than a certain value for a given metal.

The photoelectric effect might take place for the incident frequency greater than the frequency of the ultraviolet rays.

Hence, in the given options, only $X-$ rays have frequency which is greater than the frequency of ultraviolet light.

Einstein's Observation



- Threshold frequency (ν_0): The minimum frequency below which no emission of photoelectrons take place.
- Photocurrent was observed only if the frequency of incident radiation (ν) was more than threshold frequency (ν_0).
- There is no time lag between the incidence of light and emission of electrons.
- The maximum kinetic energy (KE_{max}) of the ejected electrons is given by:

$$\boxed{KE_{max} = E - \phi}$$ (Where, ϕ = Work function)

Threshold Wavelength

Threshold wavelength: The maximum wavelength of the incident radiation above which photoelectric emission is not possible.

$$KE_{max} = h\nu - \phi = \frac{hc}{\lambda} - \phi$$

For $\lambda > \lambda_0$, emission will not take place, so KE_{max} of photoelectrons is zero.

$$0 = \frac{hc}{\lambda_0} - \phi \qquad \boxed{\lambda_0 = \frac{hc}{\phi}}$$

Threshold Frequency

Threshold frequency: The minimum frequency of the incident radiation below which photoelectric emission is not possible.

$$\lambda_0 = \frac{hc}{\phi} \quad \Rightarrow \frac{\lambda_0}{c} = \frac{h}{\phi} \quad \boxed{\Rightarrow \nu_0 = \frac{\phi}{h}}$$

Note: For the photoelectric effect to occur, the frequency of incident light:

$$\boxed{\nu \geq \nu_0}$$

When light of frequency $2v_0$ (where v_0 is threshold frequency) is incident on a metal plate, the maximum velocity of electrons emitted is v_1. When the frequency of the incident radiations is increased to $5v_0$, the maximum velocity of electrons emitted from the same plate is v_2. The ratio of v_1 and v_2 is:

A $1 : 2$

B $4 : 1$

C $1 : 4$

D $2 : 1$

Solution:

The maximum kinetic energy of photoelectrons emitted is given by:

$$KE_{max} = E - \phi$$

$$\frac{1}{2}mv^2 = hv - hv_0$$

Case I:

$$\frac{1}{2}mv_1^2 = h(2v_0) - hv_0$$

$$\Rightarrow \boxed{\frac{1}{2}mv_1^2 = hv_0}$$

Case II:

$$\frac{1}{2}mv_2^2 = h(5v_0) - hv_0$$

$$\Rightarrow \boxed{\frac{1}{2}mv_2^2 = 4hv_0}$$

$$\boxed{\frac{v_1}{v_2} = \frac{1}{2}}$$

Photoelectric emission is observed from a metallic surface for frequencies ν_1 and ν_2 of the incident light rays ($\nu_1 > \nu_2$). If the maximum values of kinetic energy of the photoelectrons emitted in the two cases are in the ratio of $1 : K$, then the threshold frequency of the metallic surface is:

A. $\dfrac{\nu_1 - \nu_2}{K - 1}$

B. $\dfrac{K\nu_2 - \nu_1}{K - 1}$

C. $\dfrac{K\nu_1 - \nu_2}{K - 1}$

D. $\dfrac{\nu_2 - \nu_1}{K}$

Solution:

The maximum kinetic energy of the photoelectrons emitted is given by:

$$KE_{max} = h\nu - h\nu_0$$

Case 1: For frequency ν_1, kinetic energy is $(KE_{max})_1$

$$(KE_{max})_1 = h\nu_1 - h\nu_0 \quad \text{.............}(1)$$

Case 2: For frequency ν_2, kinetic energy is$(KE_{max})_2$

$$(KE_{max})_2 = h\nu_2 - h\nu_0 \quad \text{..........}(2)$$

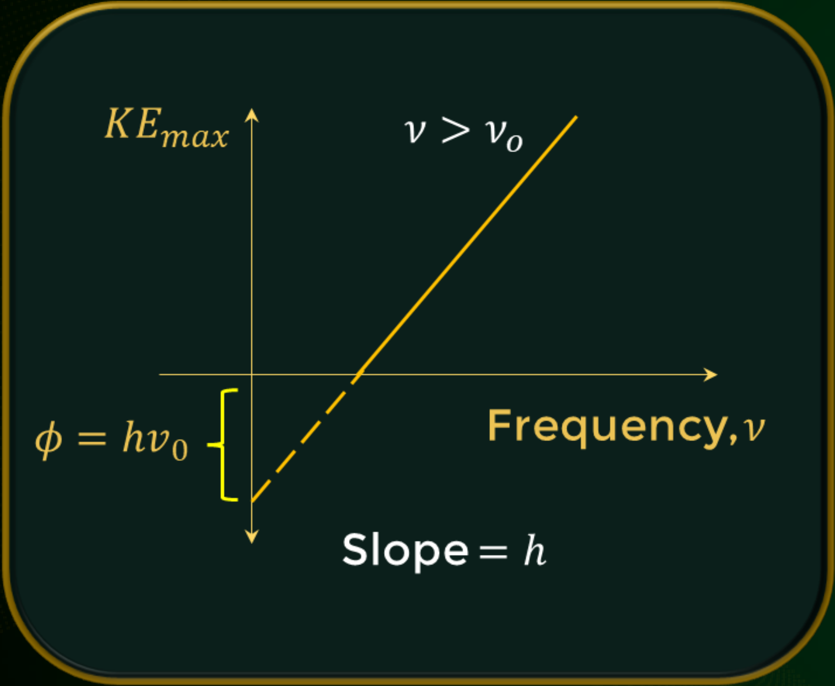
Dividing equation (1) by (2), we get,

$$\frac{(KE_{max})_1}{(KE_{max})_2} = \frac{h\nu_1 - h\nu_0}{h\nu_2 - h\nu_0} \Rightarrow \frac{1}{K} = \frac{\nu_1 - \nu_0}{\nu_2 - \nu_0}$$

$$\boxed{\nu_0 = \frac{K\nu_1 - \nu_2}{K - 1}}$$

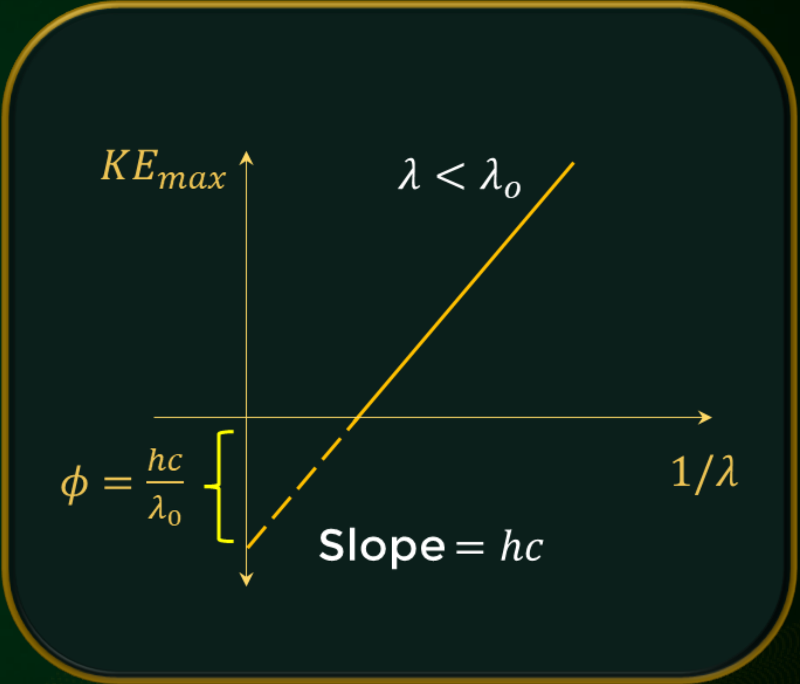
Graphs

KE_{max} vs Frequency (ν)



$$KE_{max} = h\nu - h\nu_0$$

KE_{max} vs Wavelength (λ)



$$KE_{max} = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

A graph regarding photoelectric effect is drawn between the maximum kinetic energy of emitted electrons and the frequency of the incident light.
Based on this graph, calculate the work function:

A $4\ eV$

B $2\ eV$

C $4.2\ eV$

D $2.5\ eV$

Solution:

From the graph, threshold frequency$(\nu_0) = 10 \times 10^{14}\ Hz$

Slope $= h = \frac{\Delta KE_{max}}{\Delta \nu} = \frac{8 \times 1.6 \times 10^{-19}}{20 \times 10^{14}}$

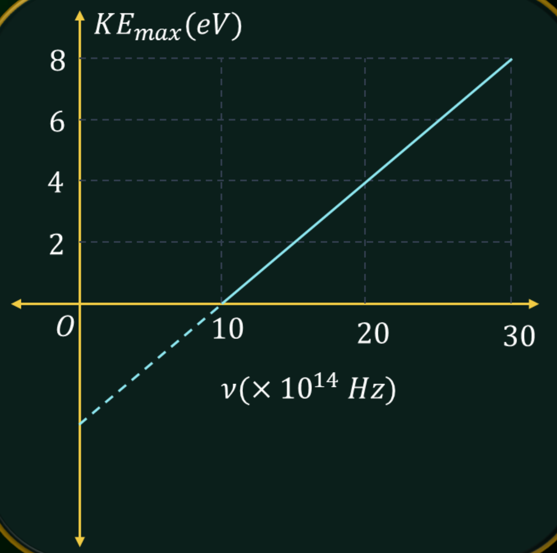
$\Rightarrow h = 6.4 \times 10^{-34}\ J$

Work function is given by,

$\phi = h\nu_0$

$\Rightarrow \phi = 6.4 \times 10^{-34} \times 10 \times 10^{14} = 6.4 \times 10^{-19} J$

$\boxed{\Rightarrow \phi = 4\ eV}$



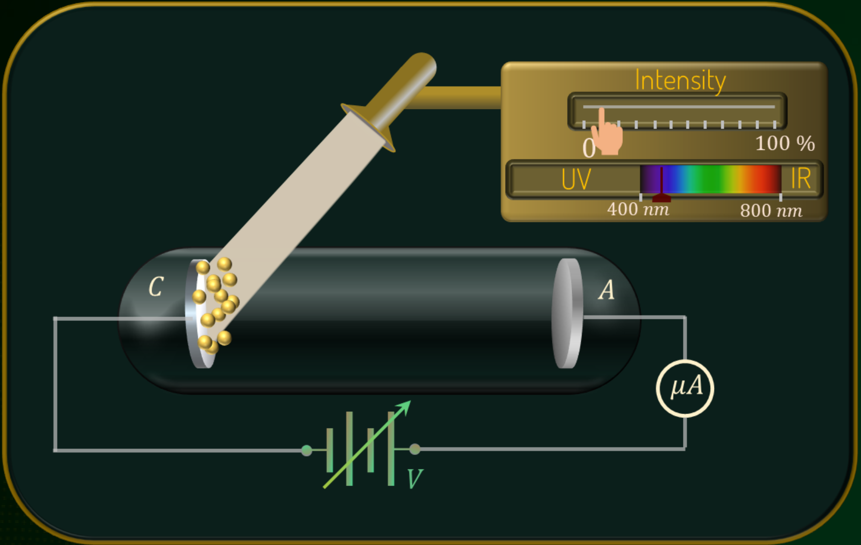
Failure of Wave Theory

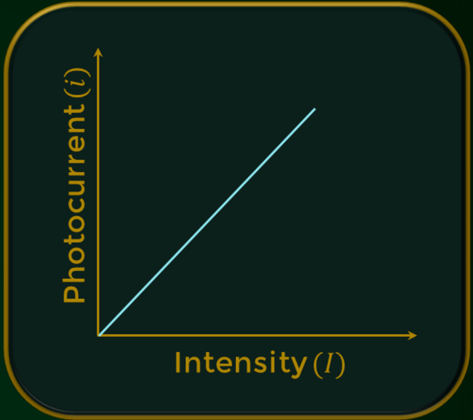
	Wave Theory	Particle Theory
Intensity Problem	According to wave theory, light of greater intensity should impart greater kinetic energy to the liberated electrons. This does not happen.	The experiments show that the maximum kinetic energy of the photoelectrons does not depend on the intensity of the incident light.
Frequency Problem	The photoelectric effect should occur for any frequency of the light, provided that the light is intense enough to eject the photoelectrons.	The photoelectrons will eject only when frequency is more than threshold value.
Time Delay Problem	The electron will take some time to accumulate enough energy to escape from the metal surface. Hence, there should be a time lag.	Whole of the energy associated with a photon is absorbed by a free electron. Hence, emission is instantaneous.

Wave Particle Duality

Phenomenon	Wave nature	Particle nature
Reflection	✓	✓
Refraction	✓	✓
Interference	✓	
Diffraction	✓	
Polarization	✓	
Photoelectric effect		✓

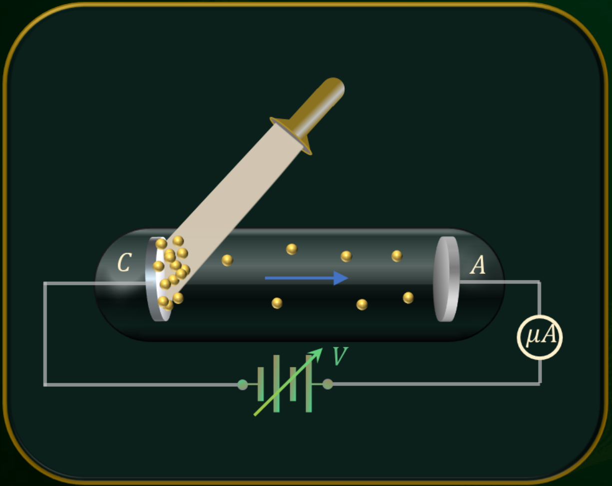
Effect of Intensity of Light on Photocurrent

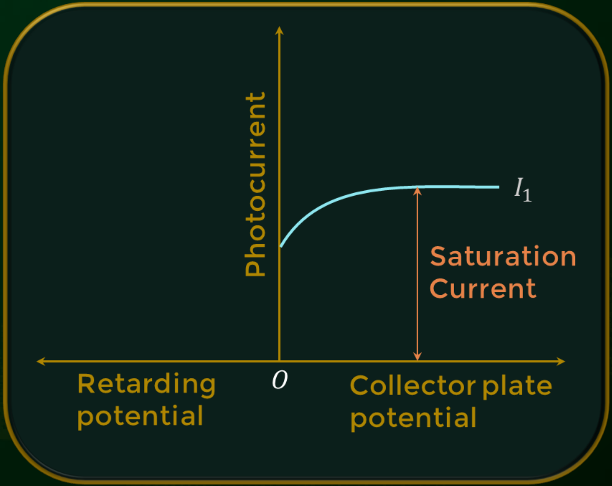




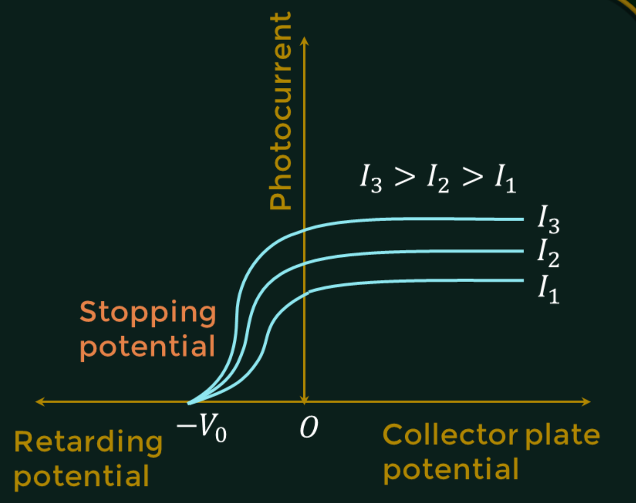
Photocurrent ∝ Intensity of light

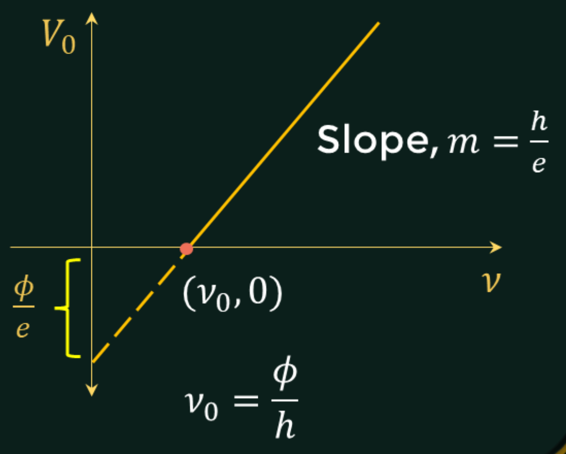
When all the photoelectrons reach plate A, the current reaches its maximum value which is called saturation current.





Stopping Potential





- Stopping potential: The minimum retarding (negative) potential of the anode(collector plate) of a photoelectric tube for which photoelectric current stops or becomes zero.
- Saturation current increases with increase in intensity.
- Number of photoelectrons emitted is proportional to the intensity.
- At a given frequency of incident radiation, the stopping potential is independent of its intensity.

$$KE_{max} = eV_0 \text{ and } KE_{max} = E - \phi$$

$$\Rightarrow eV_0 = E - \phi \quad \Rightarrow eV_0 = h\nu - h\nu_0$$

$$\Rightarrow V_0 = \frac{h\nu}{e} - \frac{h\nu_0}{e} \quad \Rightarrow V_0 = \frac{h\nu}{e} - \frac{\phi}{e}$$

Comparing above equation with $y = mx + c$, we get,

$\boxed{\text{Slope, } m = \frac{h}{e}}$ $\boxed{y - \text{intercept, } c = -\frac{\phi}{e}}$

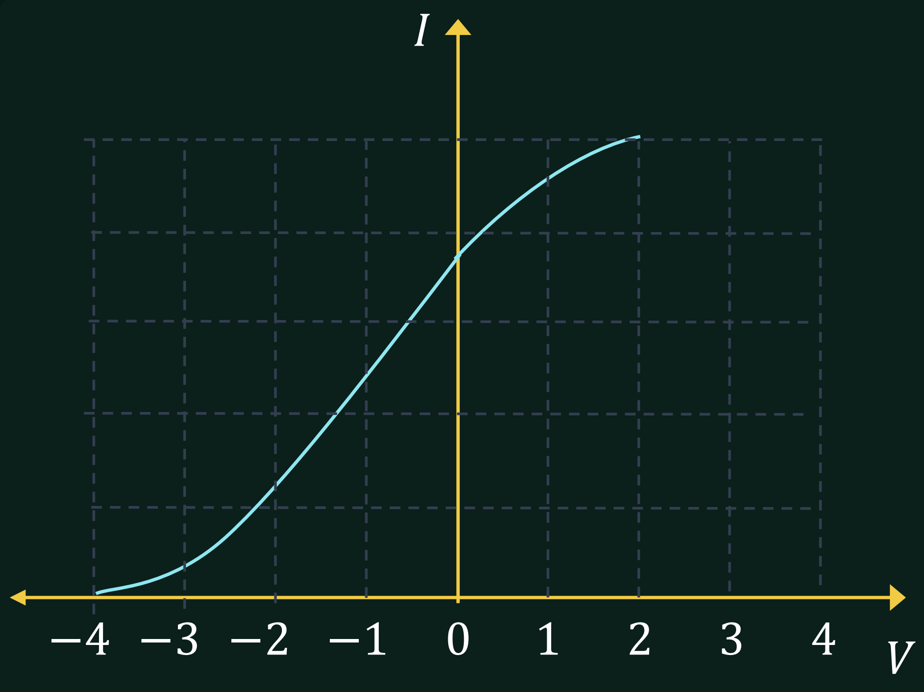
Figure represents the graph of photo current (I) versus applied voltage (V). The maximum energy of the emitted photoelectrons is:

A. $2\ eV$

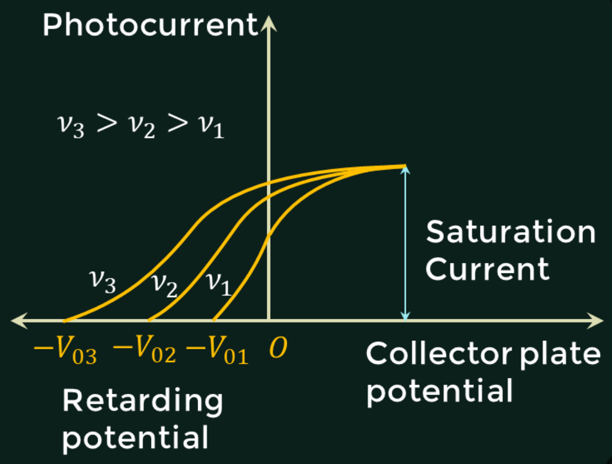
B. $4\ eV$

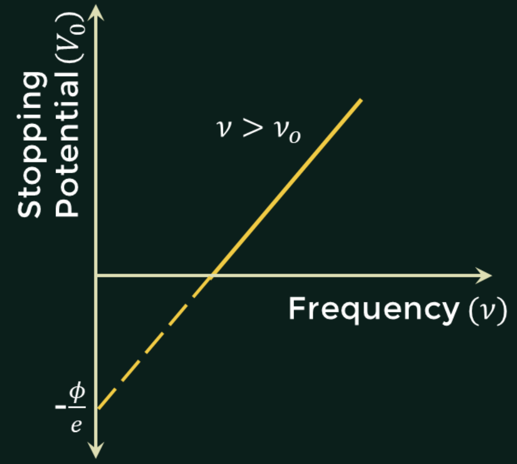
C. $0\ eV$

D. $4\ J$



Effect of Frequency on Stopping Potential





- Maximum kinetic energy of emitted photoelectrons vary linearly with frequency when intensity is constant.

$$V_0 = \frac{h}{e}\nu - \frac{\phi}{e} \Rightarrow V_0 \propto \nu$$

- Stopping potential is more negative for higher frequencies.

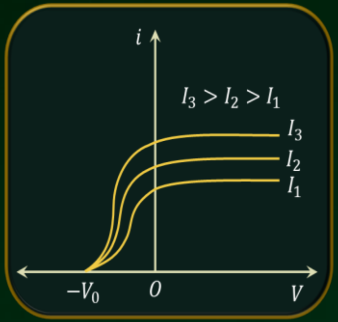
$$\nu_3 > \nu_2 > \nu_1 \Rightarrow |-V_{03}| > |-V_{02}| > |-V_{01}|$$

$$\boxed{V_0 = \frac{h}{e}\nu - \frac{\phi}{e}}$$

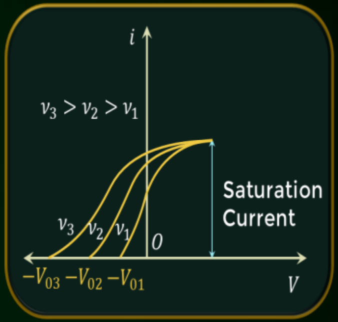
- Comparing the above equation with the equation of straight line $(y = mx + c)$, we get,
- Slope $(m) = \frac{h}{e}$ (constant for all metals)
- y - intercept $= -\frac{\phi}{e}$

Summary of Graphs

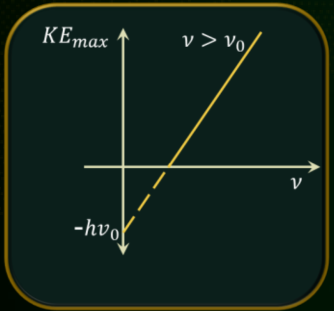
- Photocurrent is directly proportional to intensity.



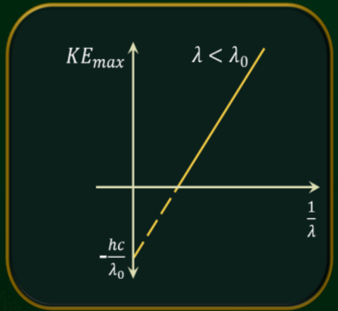
- Saturation current increases with increase in intensity.
- At a given frequency of incident radiation, the stopping potential is independent of its intensity.



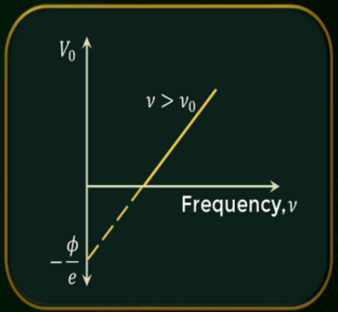
- Stopping Potential is more negative for higher frequencies when intensity is kept constant.



- $KE_{max} = h\nu - h\nu_0$
- Slope $= h$
- y – intercept $= (-)h\nu_0$



- $KE_{max} = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$
- Slope $= hc$
- y – intercept $= (-)\frac{hc}{\lambda_0}$



- $V_0 = \frac{h}{e}\nu - \frac{\phi}{e}$
- Slope $(m) = \frac{h}{e}$
- y – intercept $= (-)\frac{\phi}{e}$

The photoelectric threshold wavelength of silver is $3250 \times 10^{-10}\ m$. The maximum velocity of the electron ejected from a silver surface by ultraviolet light of wavelength $2536 \times 10^{-10}\ m$ is approximately:

A $0.6 \times 10^{5}\ ms^{-1}$

B $6 \times 10^{6}\ ms^{-1}$

C $0.3 \times 10^{6}\ ms^{-1}$

D $6 \times 10^{5}\ ms^{-1}$

Solution:

$$KE_{max} = h\nu - \phi = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

$$\frac{1}{2}mv_{max}^2 = hc\left[\frac{1}{\lambda} - \frac{1}{\lambda_0}\right]$$

$$\frac{1}{2}mv_{max}^2 = 12400\left[\frac{1}{2536} - \frac{1}{3250}\right] = 1.074\ eV$$

$$v^2 = 2 \times \frac{1.074\ eV}{m} = \frac{2.148 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}$$

$$\boxed{v \approx 6 \times 10^{5}\ ms^{-1}}$$

In photoelectric emission process from a metal of work function $1.8\ eV$, the kinetic energy of most energetic electrons is $0.5\ eV$. The corresponding stopping potential is:

A $1.8\ V$

B $1.3\ V$

C $2.3\ V$

D $0.5\ V$

Solution:

Stopping potential is the minimum retarding potential, that stops the most energetic electron in reaching the collector (anode) plate.

By the Conservation of energy, $eV_0 = K.E_{max}$

$$\Rightarrow eV_0 = 0.5\ eV$$

$$\boxed{\Rightarrow V_0 = \frac{0.5eV}{e} = 0.5\ V}$$

A metal of work function $3.3\ eV$ is illuminated by light of wavelength $300\ nm$. Find the stopping potential. (Take $h = 6.6 \times 10^{-34}\ Js$)

A $2.00\ V$

B $3.33\ V$

C $0.83\ V$

D No electron is emitted

Solution:

According to Einstein's photoelectric equation,

$$KE_{max} = E - \phi \implies eV_0 = \frac{hc}{\lambda} - \phi$$

$$\implies eV_0 = \frac{12400}{3000} - 3.3\ eV = 0.83\ eV$$

$$\boxed{\implies V_0 = 0.83\ V}$$

Ultraviolet light of wavelength $250\ nm$ falls on a metal surface. If the stopping potential is $1.2\ V$, find the work function of the metal.

A $1.2\ eV$

B $6.16\ eV$

C $4.76\ eV$

D $3.76\ eV$

Solution:

According to Einstein's photoelectric equation,

$$eV_0 = E - \phi \Rightarrow \phi = \frac{hc}{\lambda} - eV_0$$

$$\Rightarrow \phi = \frac{12400}{2500} - e(1.2\ V) = 4.96\ eV - 1.2\ eV$$

$$\boxed{\Rightarrow \quad \phi = 3.76\ eV}$$

The stopping potential of a metal is $3\ V$, when it is illuminated by light of wavelength $500\ nm$. What will be the stopping potential of the metal when the wavelength is $600\ nm$? (Photoelectric emission takes place in both the cases)

A $2.58\ V$

B $3.42\ V$

C $1.76\ V$

D $0.76\ V$

Solution:

According to Einstein's photoelectric equation,

$$eV_0 = \frac{hc}{\lambda} - \phi$$

Case 1: $$eV_{0_1} = \frac{hc}{\lambda_1} - \phi \quad \text{... (1)}$$

Case 2: $$eV_{0_2} = \frac{hc}{\lambda_2} - \phi \quad \text{... (2)}$$

$$eV_{0_2} - e(3\ V) = \frac{12400}{6000} - \frac{12400}{5000}$$

$$eV_{0_2} - 3\ eV = 2.06\ eV - 2.48\ eV$$

$$\Longrightarrow eV_{0_2} = 2.58\ eV$$

$$\boxed{\Longrightarrow V_{0_2} = 2.58\ V}$$

When a certain photosensitive surface is illuminated by a monochromatic light of frequency ν, the stopping potential for photoelectric current is V_0. When the same surface is illuminated by a monochromatic light of frequency $\frac{\nu}{2}$, the stopping potential is $\frac{V_0}{3}$. The threshold frequency for photoelectric emission is:

A $\frac{\nu}{3}$

B $\frac{\nu}{2}$

C $\frac{\nu}{4}$

D 2ν

Solution:

According to Einstein's photoelectric equation,

$$KE_{max} = E - \phi \Rightarrow eV_0 = h\nu - h\nu_0$$

Case 1: $eV_0 = h(\nu - \nu_0)$ ... (1)

Case 2: $\frac{eV_0}{3} = h\left(\frac{\nu}{2} - \nu_0\right)$ ... (2)

$$\frac{(1)}{(2)} \Rightarrow 3 = \frac{\nu - \nu_0}{\left(\frac{\nu - 2\nu_0}{2}\right)}$$

$$\Rightarrow 3\nu - 6\nu_0 = 2\nu - 2\nu_0$$

$$\boxed{\Rightarrow \nu_0 = \frac{\nu}{4}}$$

The threshold frequency for a certain photosensitive metal is ν_0. When it is illuminated by light of frequency $\nu = 2\nu_0$, the maximum velocity of photoelectrons is v_m. What will be the maximum velocity of the photoelectrons when the same metal is illuminated by light of frequency $\nu = 5\nu_0$?

A $\sqrt{2}v_m$

B $2v_m$

C $2\sqrt{2}v_m$

D $4v_m$

Solution:

According to Einstein's photoelectric equation,

$$KE_{max} = E - \phi \implies \frac{1}{2}mv_{max}^2 = h\nu - h\nu_0$$

Case 1: $$\frac{1}{2}mv_m^2 = h(2\nu_0 - \nu_0) \quad \text{... (1)}$$

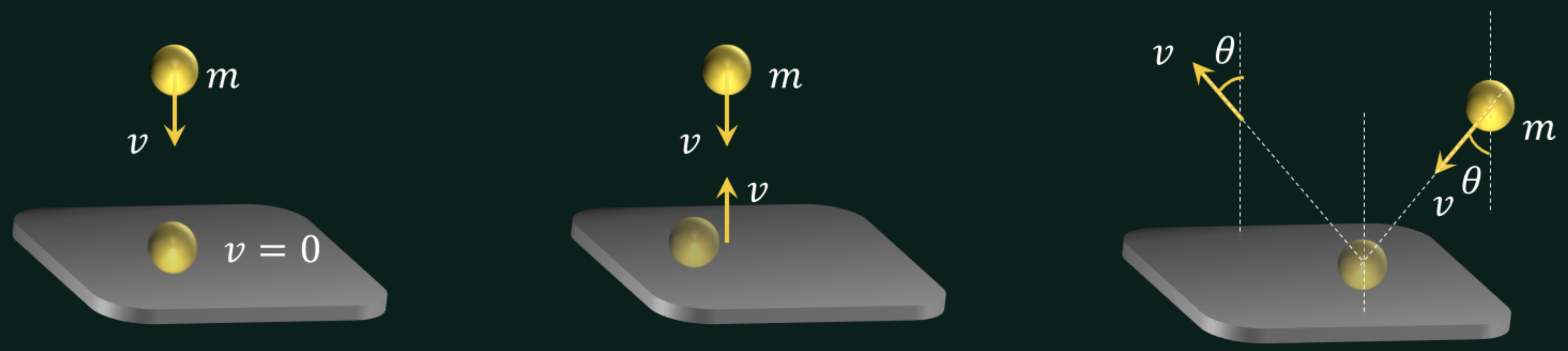
Case 2: $$\frac{1}{2}m\left((v_{max})_2\right)^2 = h(5\nu_0 - \nu_0) \quad \text{... (2)}$$

$$\frac{(2)}{(1)} \implies \frac{\left((v_{max})_2\right)^2}{v_m^2} = \frac{4\nu_0}{\nu_0}$$

$$\implies \left((v_{max})_2\right)^2 = 4v_m^2$$

$$\boxed{\implies (v_{max})_2 = 2v_m}$$

Radiation Pressure - Introduction



$|\Delta p| = mv$

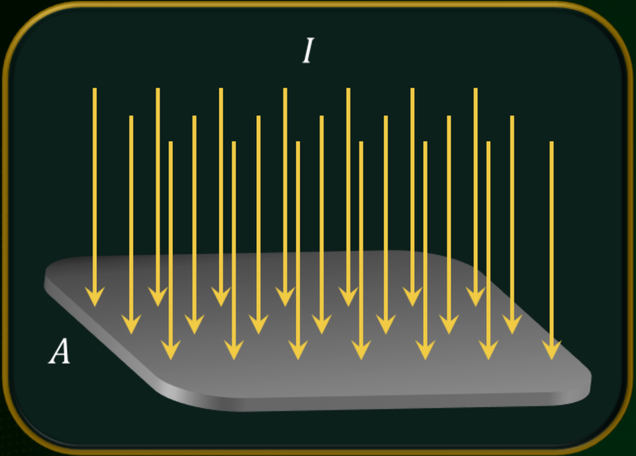
$|\Delta p| = 2mv$

$|\Delta p| = 2mv\cos\theta$

- In case of a photon, momentum is given by, $p = \dfrac{h}{\lambda}$

Change in momentum → Force → Radiation Pressure

Radiation Pressure – Complete Absorption



Radiation pressure(P) is the pressure experienced by the surface exposed to the radiation.

$$\boxed{P = \frac{F}{A}}$$

F: Normal force on plate due to photons

A: Area of the plate

Complete absorption: Normal incidence

Absorption coefficient $(\alpha) = 1$

Reflection coefficient $(r) = 0$

Initial momentum of one photon $= \frac{h}{\lambda}$

Final momentum of one photon $= 0$

$\therefore$ Change in momentum of one photon $= \frac{h}{\lambda}$

Intensity of the incident beam, $I = \frac{E}{At}$

Energy incident per unit time, $\frac{E}{t} = IA$

Energy of one photon, $E_1 = \frac{hc}{\lambda}$

Energy incident per unit time, $\frac{E}{t} = \frac{Nhc}{\lambda}$

Intensity of the incident beam, $I = \frac{E}{At}$

Energy incident per unit time, $\frac{E}{t} = IA$

$\Rightarrow N = \frac{IA\lambda}{hc}$

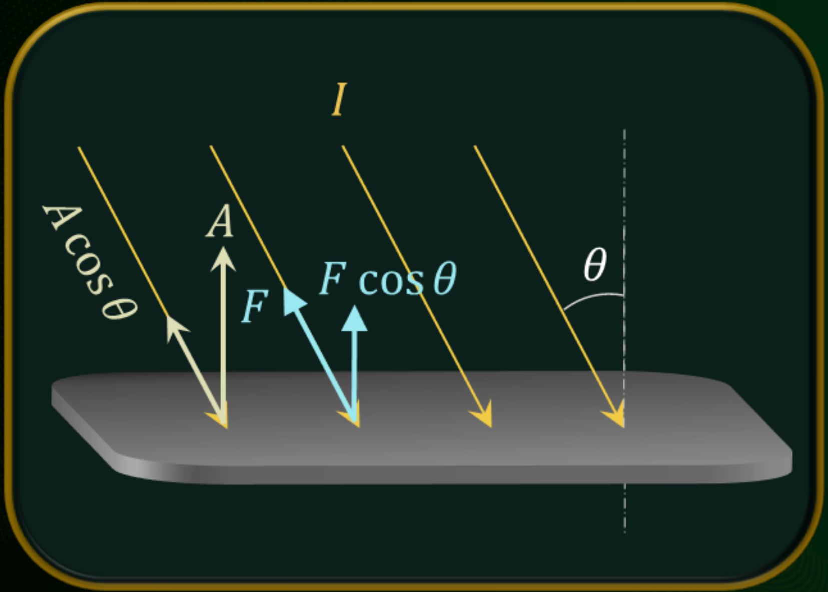
Total change in momentum per unit time, $\frac{\Delta p}{t} = \frac{Nh}{\lambda}$

Force on plate due to photons, $F = \frac{IA}{c}$

Radiation pressure, $P = \frac{F}{A} = \frac{I}{c}$

Radiation Pressure – Complete Absorption

Complete Absorption: Oblique Incidence



$$\begin{bmatrix} \text{Absorption coefficient } (\alpha) = 1, \\ \text{Reflection coefficient } (r) = 0 \end{bmatrix}$$

Energy incident per unit time $= IA\cos\theta$

No. of photons incident per unit time, $N = \dfrac{IA\cos\theta\,\lambda}{hc}$

Change in momentum of one photon $= \dfrac{h}{\lambda}$

Total change in momentum per unit time

$$\frac{\Delta p}{t} = N\frac{h}{\lambda} = \frac{IA\cos\theta\,\lambda}{hc}\frac{h}{\lambda} = \frac{IA\cos\theta}{c} \quad \Longrightarrow F = \frac{IA\cos\theta}{c}$$

On plate: component of force perpendicular to surface

$$F_{\perp} = F\cos\theta = \frac{IA\cos^2\theta}{c}$$

Radiation pressure, $\boxed{P = \dfrac{F\cos\theta}{A} = \dfrac{I}{c}\cos^2\theta}$

The intensity of direct sunlight before it passes through the earth's atmosphere is $1.4\,\frac{kW}{m^2}$. If it is completely absorbed, find the corresponding radiation pressure.

A $6.8 \times 10^{-4}\,\frac{N}{m^2}$

B $4.7 \times 10^{-6}\,\frac{N}{m^2}$

C $3.4 \times 10^{-4}\,\frac{N}{m^2}$

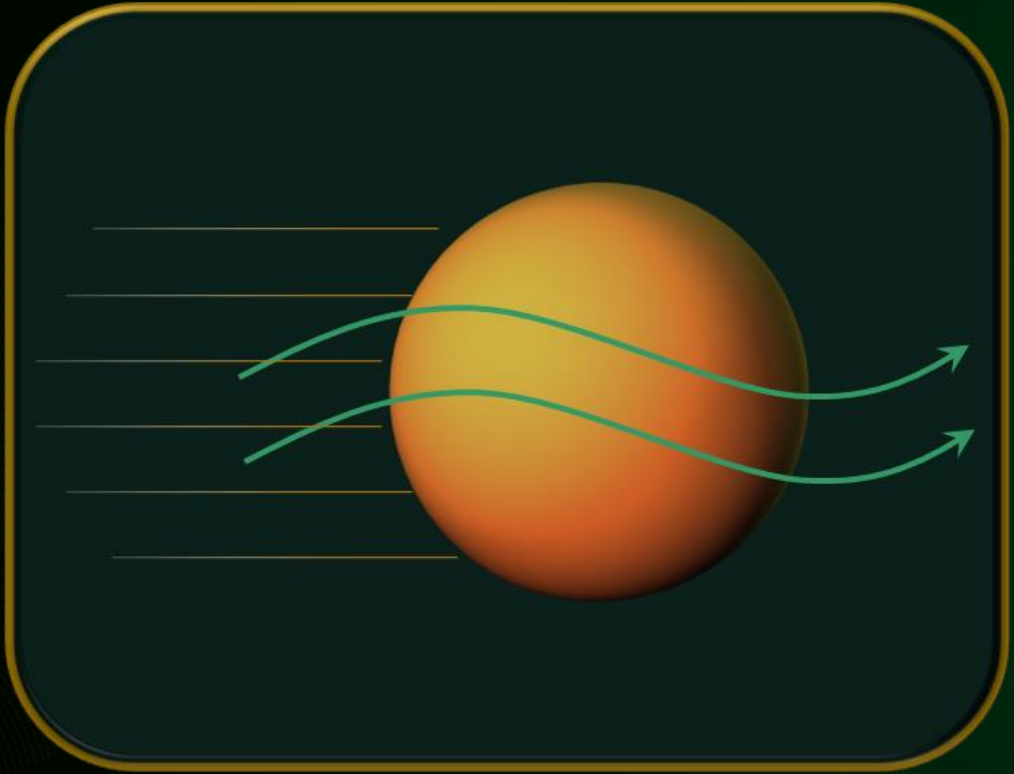
D $2.0 \times 10^{-6}\,\frac{N}{m^2}$

Solution:

For complete absorption, $P = \frac{I}{c}$

$$\Rightarrow P = \frac{1.4 \times 10^3}{3 \times 10^8} = 4.7 \times 10^{-6}\,\frac{N}{m^2}$$

Matter Waves



- In 1924, the French physicist Louis Victor de–Broglie put forward the bold hypothesis that moving particles of matter should display wave like properties under suitable conditions.
- The waves associated with moving particles are called matter waves or de-Broglie waves.
- Formula:

$$\boxed{\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2m\,(KE)}} = \frac{h}{\sqrt{2mqV}}}$$

Putting below values in the above equation,

Planck's constant: $h = 6.62 \times 10^{-34}\ m^2 kg/s$
Mass of electron: $m_e = 9.1 \times 10^{-31}\ kg$
Charge of electron: $q = 1.6 \times 10^{-19}\ C$

$$\boxed{\lambda(\text{Å}) = \frac{12.27}{\sqrt{V}}}$$

A proton and α – particle are accelerated from rest to the same energy. The de-Broglie wavelengths λ_p and λ_α are in the ratio:

A $4:1$

B $2:1$

C $1:1$

D $2\sqrt{2}:1$

Solution:

De-Broglie wavelength is given by,

$$\lambda = \frac{h}{\sqrt{2mE}}$$

$$\therefore \lambda \propto \frac{1}{\sqrt{m}}$$

$$\Rightarrow \frac{\lambda_p}{\lambda_\alpha} = \frac{\sqrt{m_\alpha}}{\sqrt{m_p}} = \sqrt{\frac{4m}{m}} = 2$$

The de-Broglie wavelength of a neutron in thermal equilibrium with heavy water at a temperature T $(Kelvin)$ and mass m is:

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A $\dfrac{h}{\sqrt{3mkT}}$

B $\dfrac{2h}{\sqrt{3mkT}}$

C $\dfrac{2h}{\sqrt{mkT}}$

D $\dfrac{h}{\sqrt{mkT}}$

Solution:

Kinetic energy of neutron is given by,

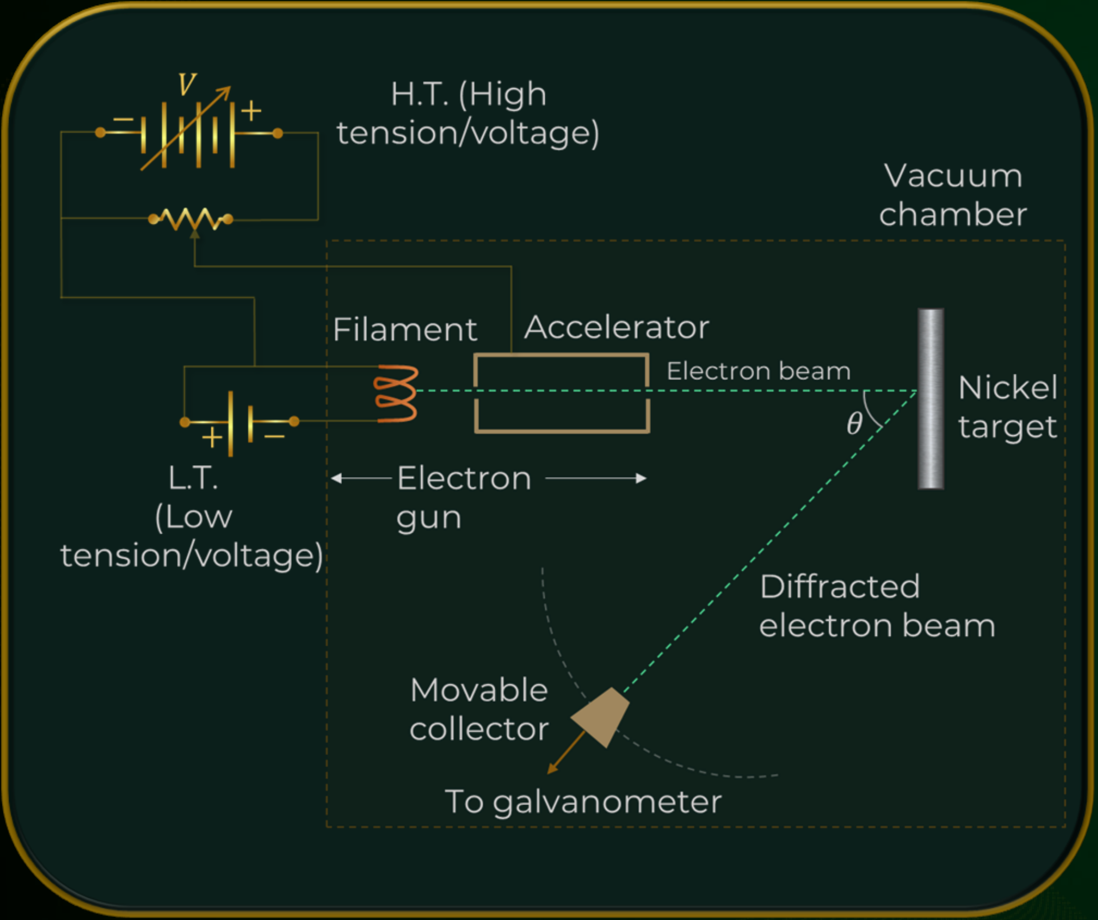
$$KE = \frac{3}{2}kT \quad \text{(Where, } k = \text{Boltzmann constant)}$$

The de-Broglie wavelength of a neutron is,

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2m\,(KE)}}$$

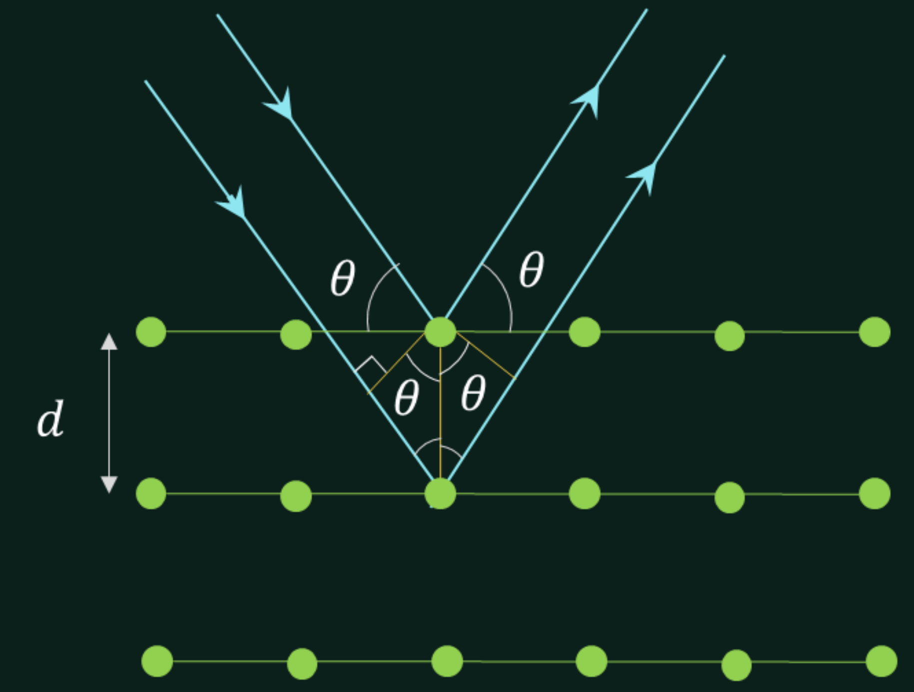
$$\boxed{\Rightarrow \quad \lambda_n = \frac{h}{\sqrt{3mkT}}}$$

Davisson and Germer Experiment



- Obtained the variation of the intensity (I) of the scattered electrons by changing the angle of scattering (θ).
- The experiment was performed by varying the accelerating voltage from $44\,V$ to $68\,V$.
- It was noticed that a strong peak appeared in the intensity (I) of the scattered electron for an accelerating voltage of $54\,V$ at a scattering angle $\theta = 50°$.
- This peak was the result of constructive interference of the electrons scattered from the nickel target.

Bragg's Law

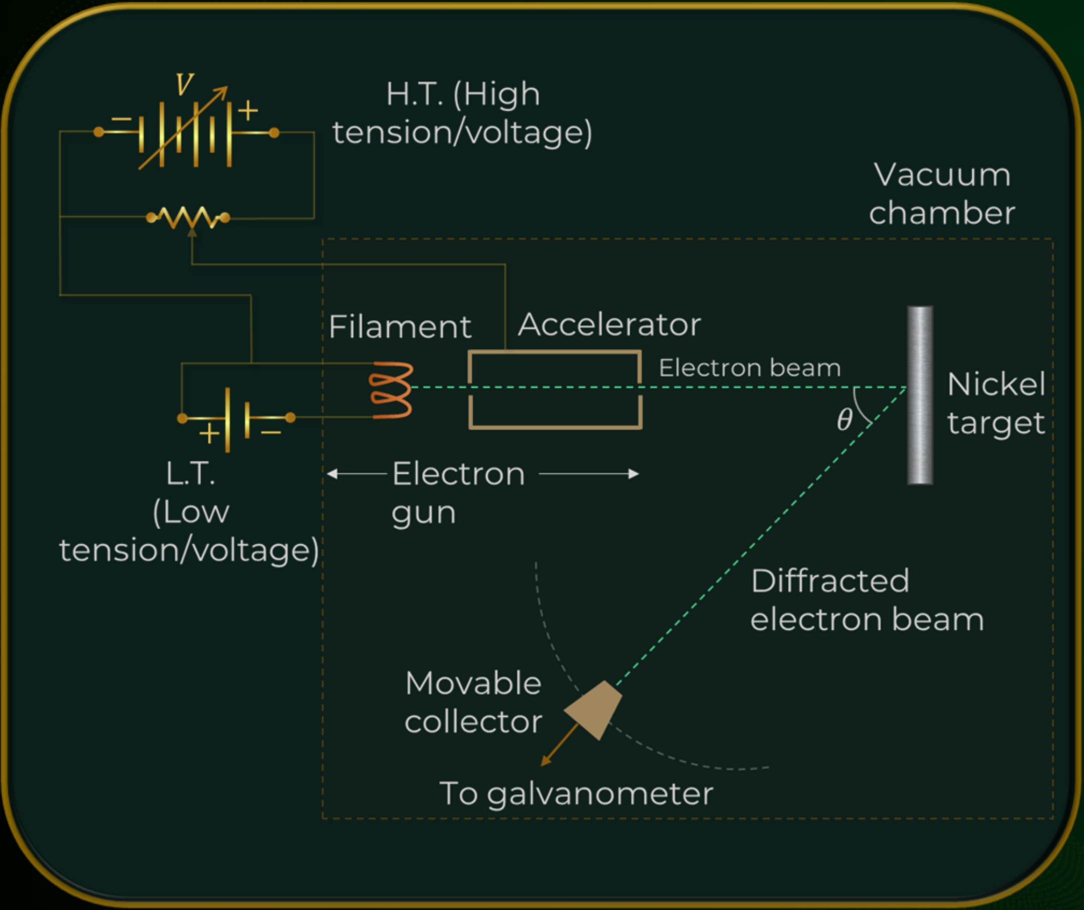


Bragg's Law: When X – rays are incident on a crystal surface, the angle of incidence will be equal to the angle of scattering and for constructive interference, path difference is equal to an integer multiple of wavelength.

Mathematically, Bragg's law equation can be represented as:

$$\boxed{n\lambda = 2d\sin\theta}$$

Davisson and Germer Experiment



- From the electron diffraction measurements, the wavelength of matter waves was practically found to be $0.165\ nm$.
- Theoretically, the de-Broglie wavelength (λ) associated with electrons is:

  For $V = 54\ V$:

  $$\lambda = \frac{h}{p} = \frac{1.227}{\sqrt{54}}\ nm$$

  $$\Rightarrow \lambda = 0.167\ nm$$

- Thus, Davisson and Germer experiment confirms the wave nature of electrons and the de-Broglie's hypothesis.

?

In the Davisson and Germer experiment, the velocity of electrons emitted from the electron gun can be increased by:

A Increasing the potential difference between the anode and filament

B Increasing the filament current

C Decreasing the filament current

D Decreasing the potential difference between the anode and filament

Properties of Matter Waves

- Matter waves are related to moving particles and independent of the charge of the particle.
- The phase velocity of matter waves can be greater than the speed of light.
- In ordinary situation, de-Broglie wavelength is very small and wave nature of matter can be ignored.
- The wave and particle nature of moving bodies are mutually exclusive, i.e., they can never be observed at the same time.
- Matter wave represents the probability of finding a particle in space.

Base Ball

Mass: $138\ g$

Speed: $30\ m/s$

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{0.138 \times 30}$$

$$\lambda = 1.6 \times 10^{-34}\ m$$

An Electron

Mass: $9.1 \times 10^{-31}\ kg$

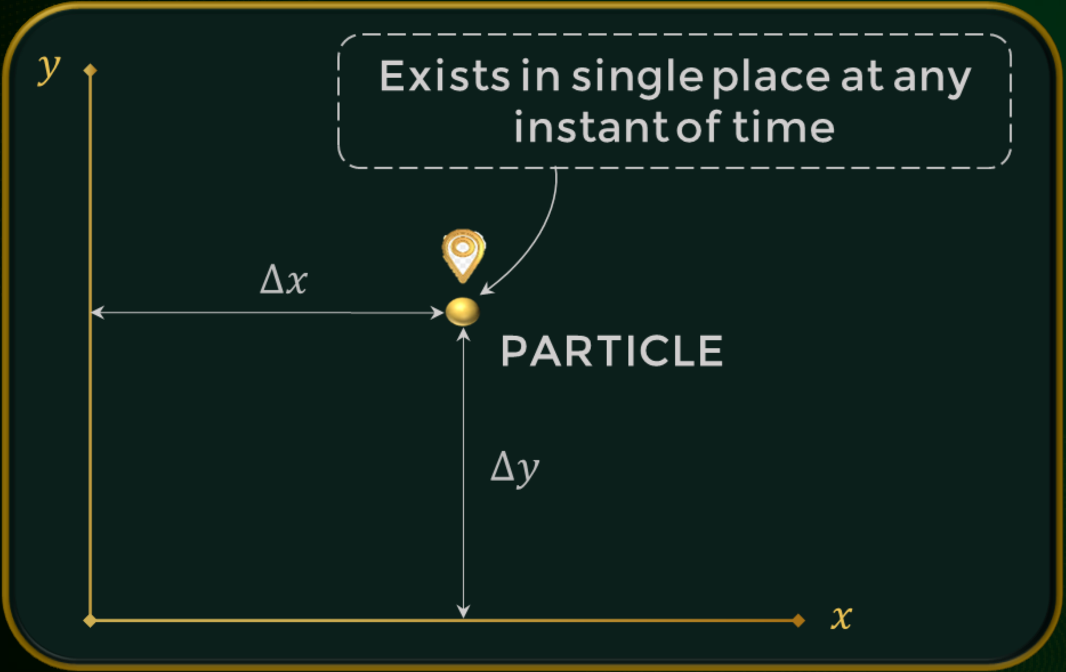
Speed: $3 \times 10^{6}\ m/s$

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 3 \times 10^{6}}$$

$$\lambda = 2.42 \times 10^{-10}\ m$$

Heisenberg's Uncertainty Principle

- It is not possible to measure both the position and momentum of a particle at the same time exactly.
- Uncertainty principle exists because everything in universe behaves both as particle and wave at the same time.



- If Δx is uncertainty in specification of position and Δp is uncertainty in specification of momentum, then,

$$\Delta x \times \Delta p \geq \frac{h}{4\pi}$$

An electron is confined to a region of width $5.00 \times 10^{-11}\ m$, which is its uncertainty in position (Δx). Estimate the minimum uncertainty in its momentum.

A $2 \times 10^{-23}\ kg\ ms^{-1}$

B $1.5 \times 10^{-23}\ kg\ ms^{-1}$

C $2.33 \times 10^{-23}\ kg\ ms^{-1}$

D $1.05 \times 10^{-24}\ kg\ ms^{-1}$

Solution:

According to Heisenberg's uncertainty principle,

$$\Delta x \times \Delta p \geq \frac{h}{4\pi}$$

So, minimum uncertainty in its momentum:

$$\boxed{\Delta p_x = \frac{h}{4\pi\Delta x} = \frac{6.62 \times 10^{-34}}{4 \times 3.14 \times 5 \times 10^{-11}} = 1.054 \times 10^{-24}\ kg\ ms^{-1}}$$