DUAL NATURE OF RADIATION AND MATTER

Electron Emission: Emission of electrons from the metal surface is called electron emission.

There are three types of electron emission –

1. Thermionic Emission (By heating)
2. Field Emission (By apply very high electric field)
3. Photoelectric Emission (By electromagnetic radiation)

Work function: The minimum energy required by an electron to escape from the metal surface is called work function (W_0 or ϕ_0)

- Work function depends on:
  - → Nature of metal
  - → Conditions of its surface
- It is denoted by W_0 or ϕ_0
- Unit → electron volt (eV)
- $1\ eV = 1.6 \times 10^{-19}\ J$
- Its value is lowest for caesium (= 2.14 eV) and highest for platinum (= 5.65 eV)
- 1 eV is the energy gained or lost by an electron while passing through a potential difference of 1 volt

Photoelectric Effect: When light of suitable frequency illuminates a metal surface, electrons are emitted from the metal surface. This phenomenon is called photoelectric effect.

Threshold Frequency (ν_0): The minimum value of frequency of incident radiation below which photoelectric emission stops is called threshold frequency.

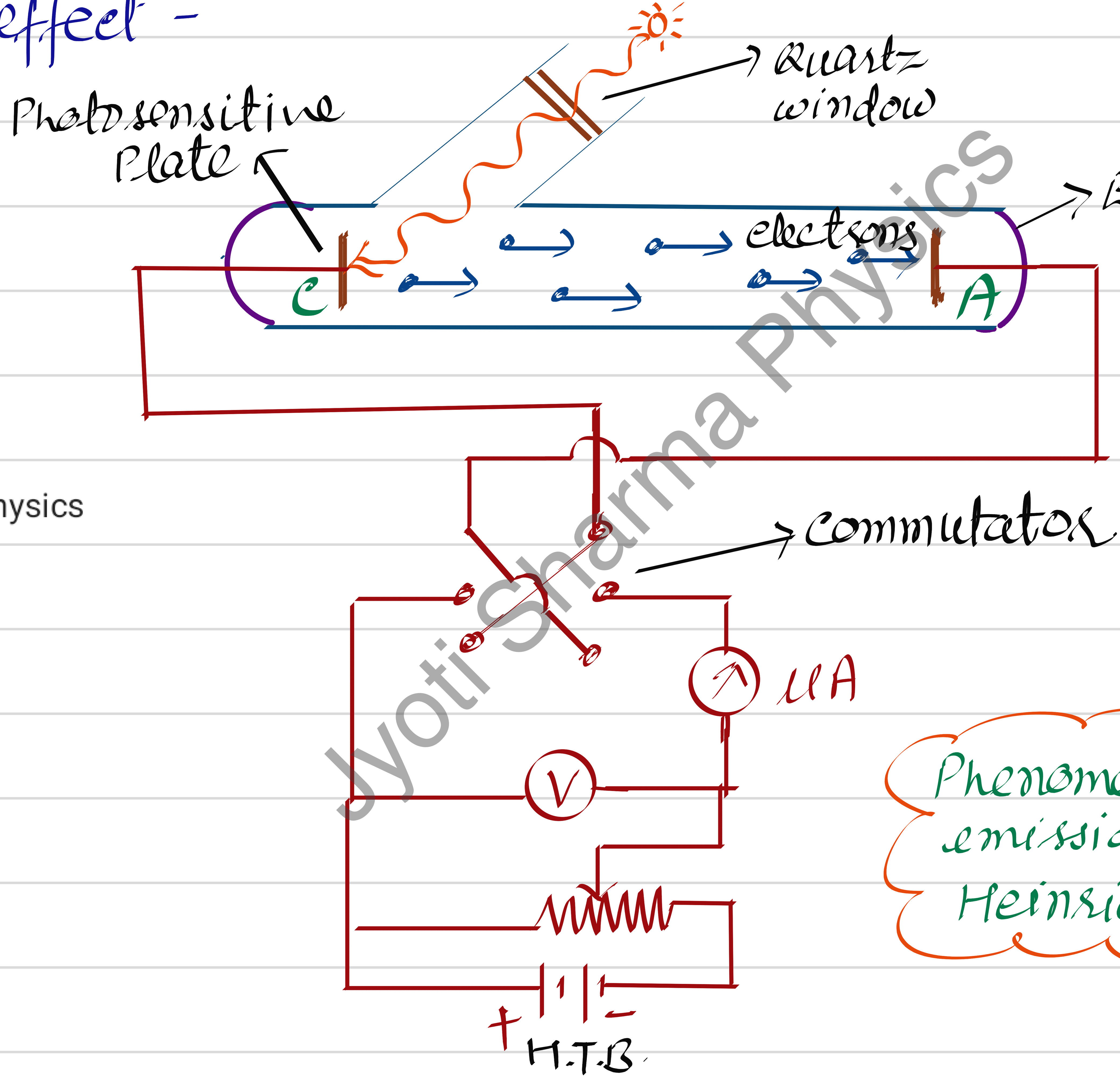
OR

The minimum frequency of incident radiation for which photoelectric emission is possible is called threshold frequency.

- Li, Na, K, Cs and Rb are highly photosensitive.
- Zn, Cd, Mg, Al etc respond only to UV light.

Experimental Study of Photoelectric Effect:

Fig. shows the experimental arrangement of photoelectric effect -



Phenomenon of photoelectric emission was discovered by Heinrich Hertz in 1857-1894

Hallwachs and Lenard investigated the photoelectric emission. Experimental arrangement is shown in fig. It consists two plates, 'C' → cathode and 'A' → Anode. Plates are connected to a sensitive ammeter and to a potential divider. Potential difference can be varied and direction can also be changed.

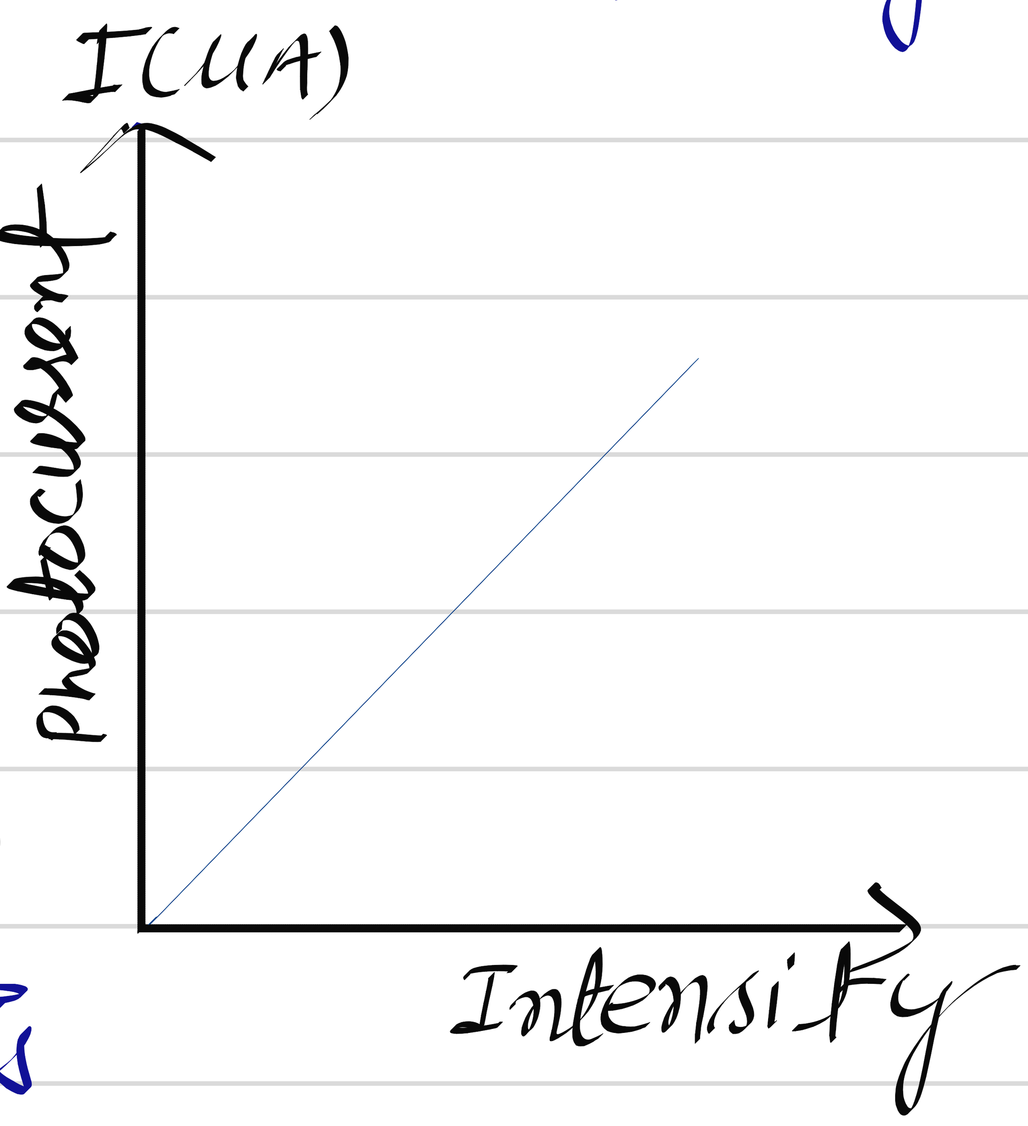
* Photoelectric current depends on:
  - Intensity of incident light
  - Potential difference b/w the two electrodes
  - Nature of emitter plate.

Observations of Experiment:

1. Effect of Intensity of light:

The rate of electron emission or the photoelectric current is directly proportional to the intensity of incident light.

Photocurrent $I_e \propto$ Intensity I



* Intensity related to no. of photons
* Intensity → $I = \frac{Power}{Area}$
* If power of light source (Watt) is increased, no. of photons also increases and more electron are emitted so photocurrent also increases.

e.g A 100 watt bulb flows more photocurrent than a 60 watt bulb.

Effect of Potential difference: When light of suitable frequency falls on photosensitive plate 'C' photoelectrons are emmited and accelerated towards plate A and photoelectric current produces.

This photocurrent increases when +ve potential of plate 'A' increases. The maximum current is called saturation current.

Now if potential of plate 'A' is decreases it attains a −ve potential w.r.to plate 'C' for which photoelectric current stops. This −ve potential of plate 'A' for which electrons emission from plate 'C' stops is called stopping potential (V_0).

Stopping Potential (V_0): The minimum negative potential (V_0) for which photoelectric current becomes zero is called cut off potential or stopping potential.

* Stopping potential depends on: → Frequency of incident light
  → Nature of emitter plate

For a given frequency of incident light, the stopping potential is independent of its intensity.

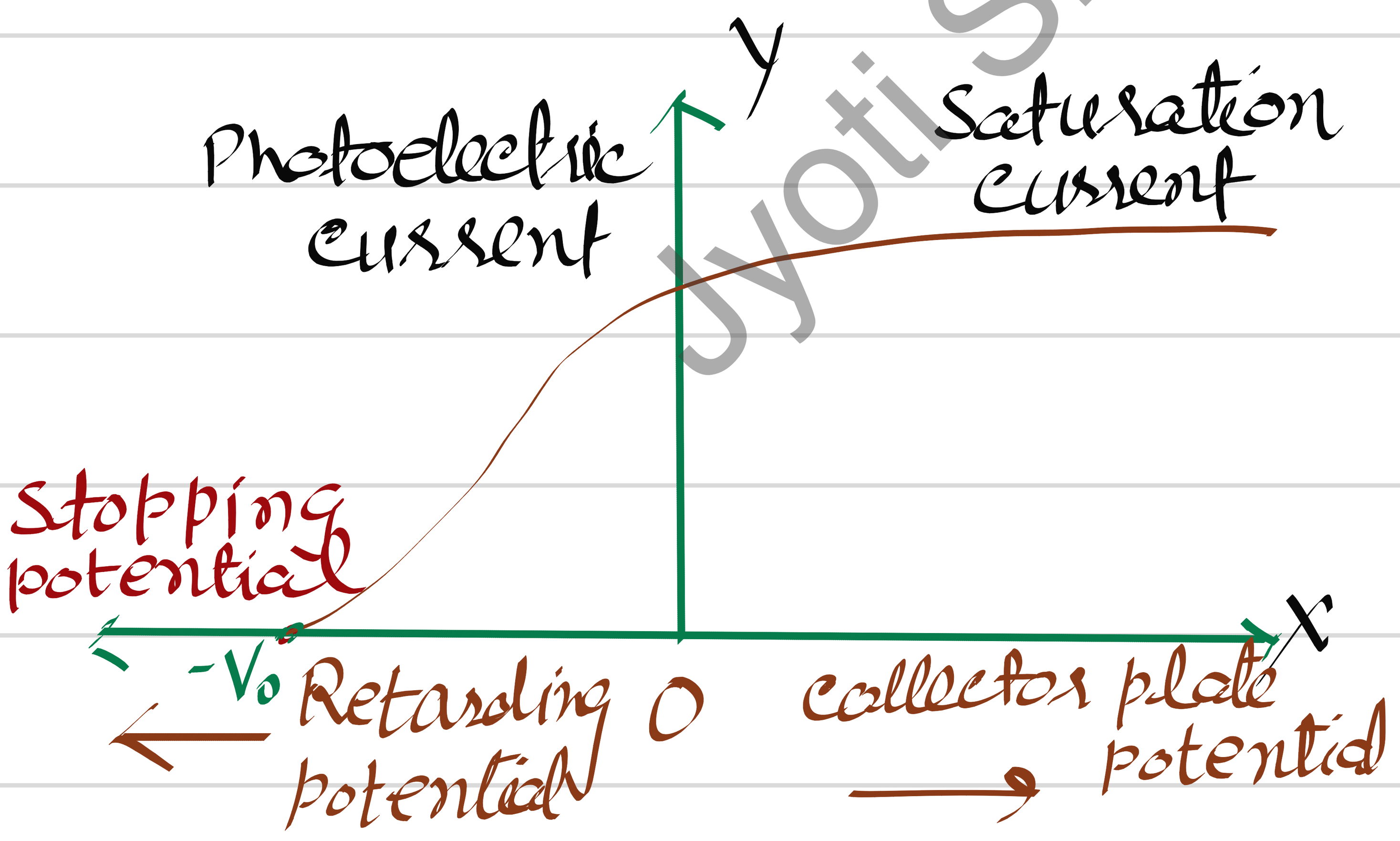
Stopping potential V_0 does not depend on intensity

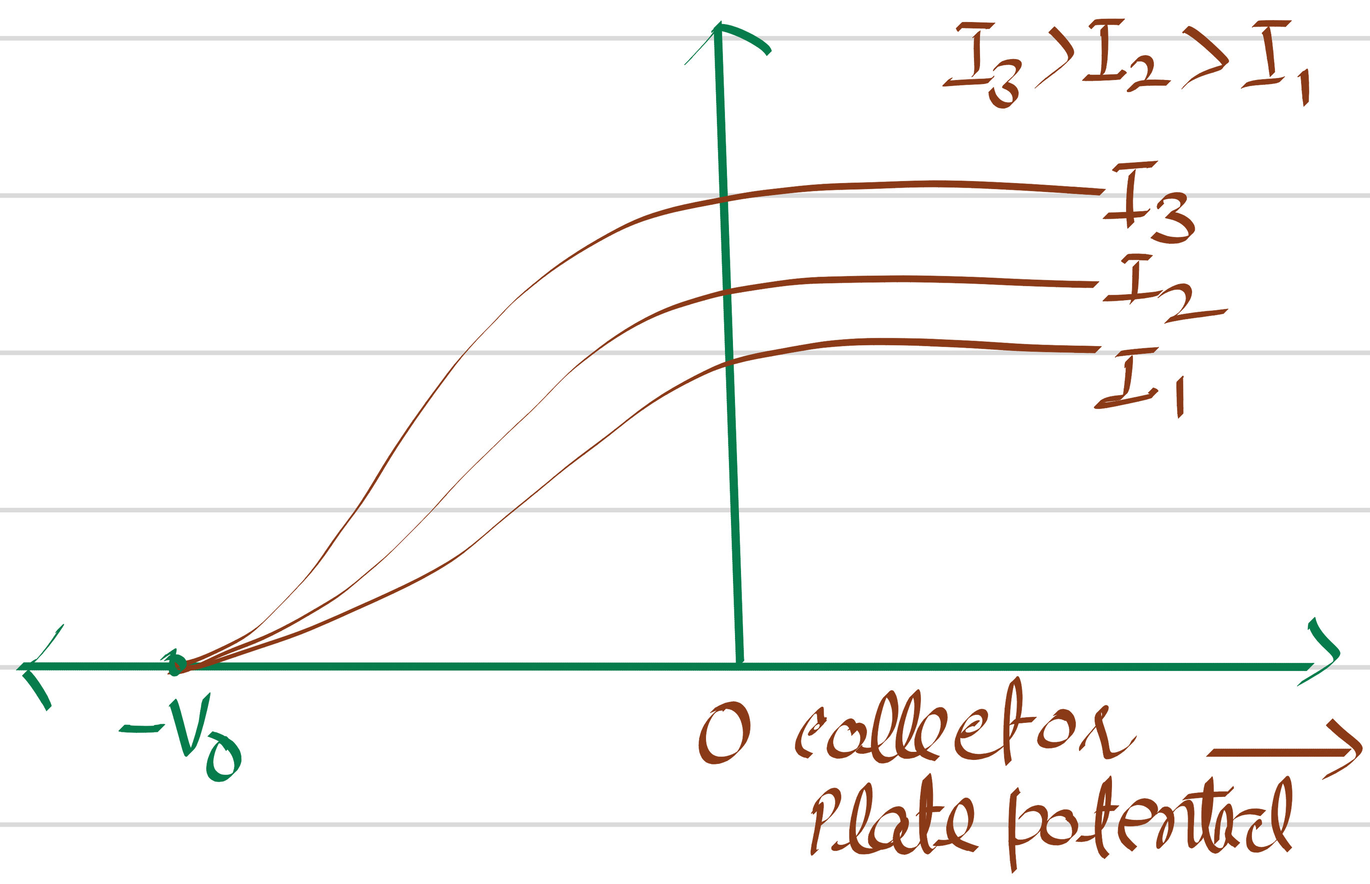
It depends on maximum kinetic energy of emitted electrons.

$$K_{max} = eV_0 = \frac{1}{2} m v_{max}^2$$

i.e. $\boxed{K_{max} \propto V_0}$

Variation of photocurrent with varying potential





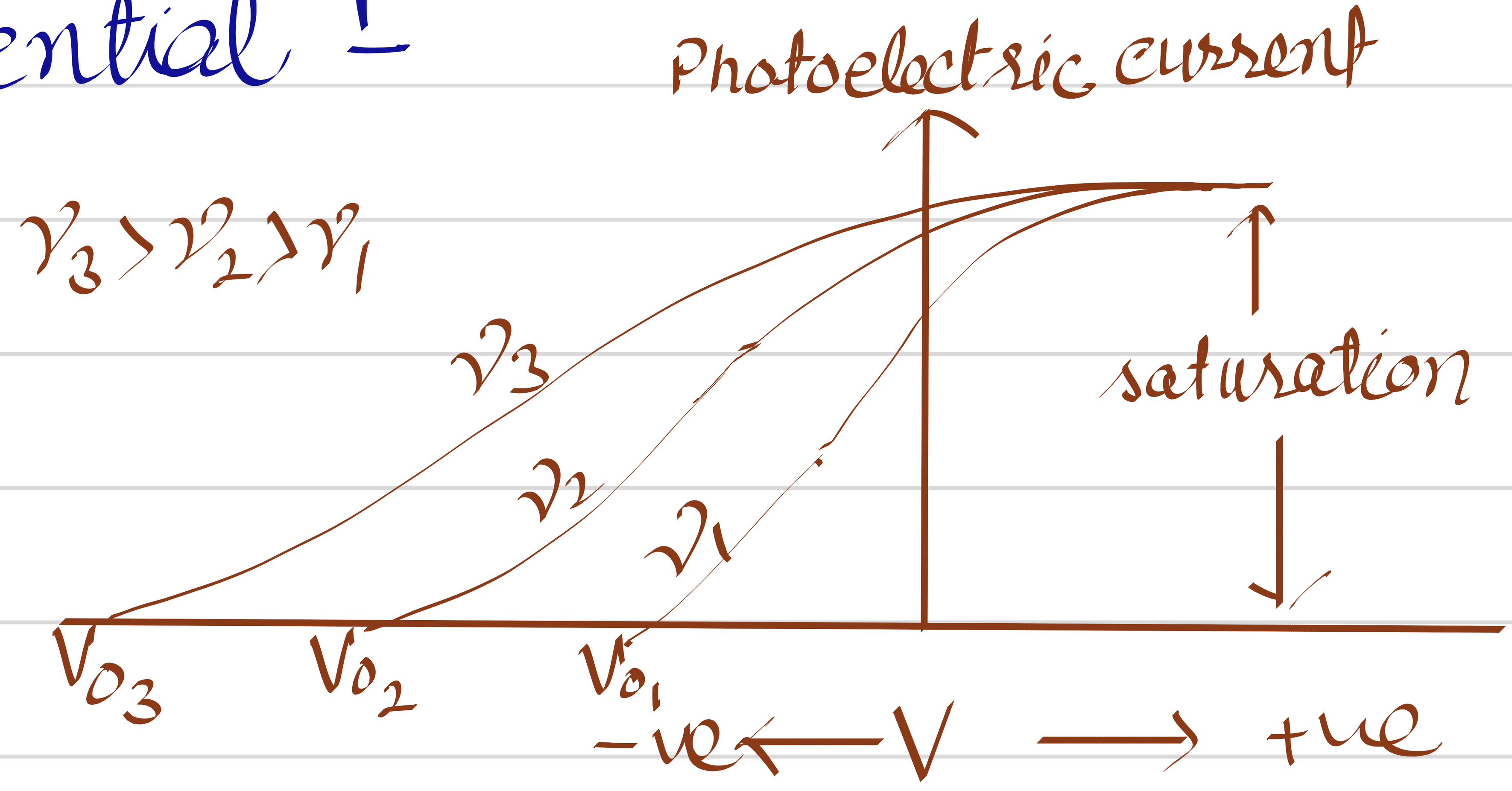
for different intensities

→ Thus for a given frequency of incident radiation, the stopping potential is independent of it intensity.
→ Maximum K.E does not depend upon the intensity of incident radiation.

Effect of frequency of incident radiation on stopping potential:

We adjust the same intensity of light radiation at various frequency.

Variation of photocurrent with collector plate potential :-



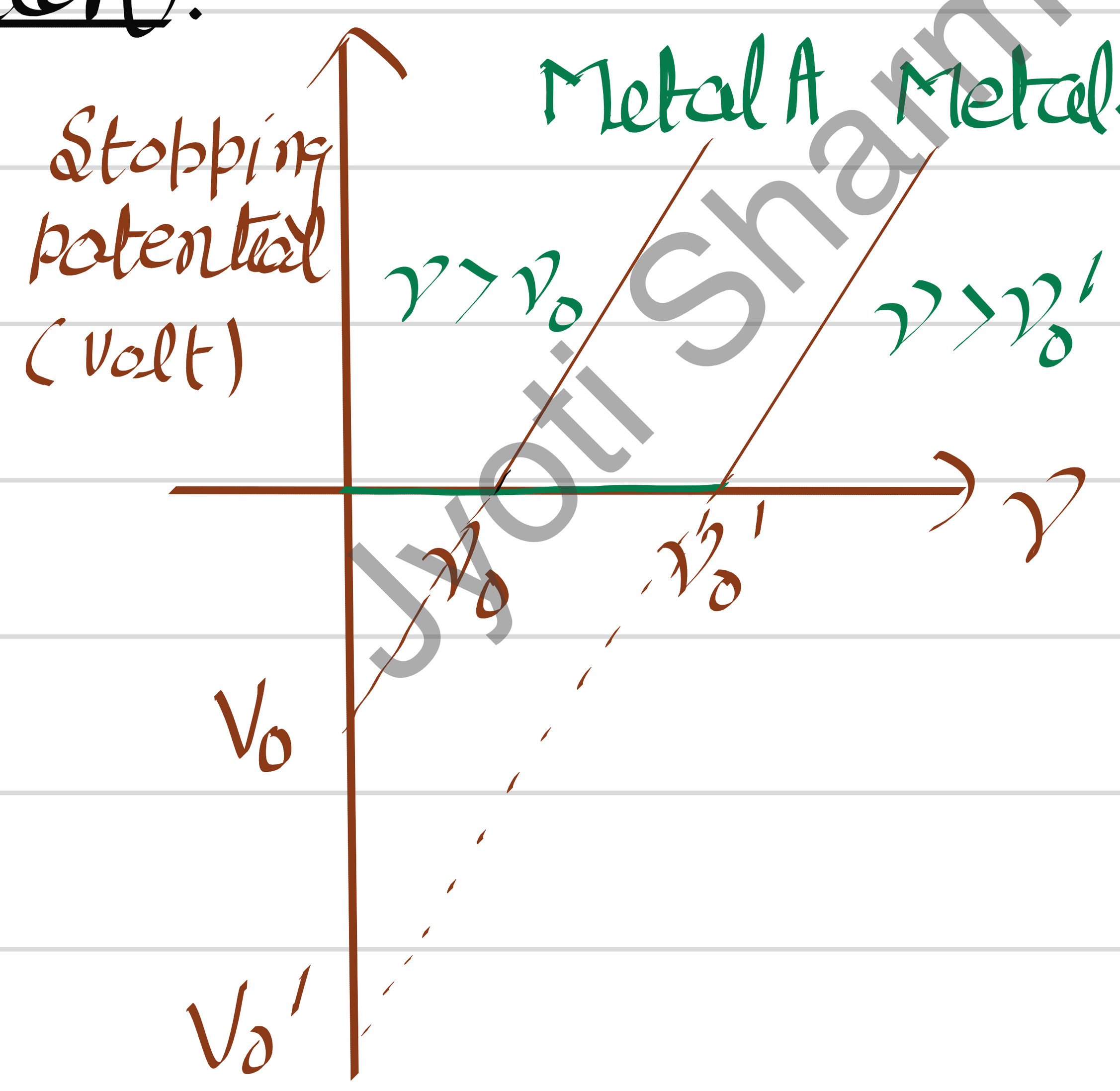
$\nu \rightarrow$ frequency

→ Value of stopping potential depends upon the frequency of incident radiation. $V_0 \propto \nu$

→ For different value of stopping potential saturation current is same for different frequencies.

→ Saturation current does not depend upon frequency

Variation of stopping potential V_0 with frequency of incident radiation:



$V_0 \rightarrow$ Stopping potential

$\nu \rightarrow$ Frequency of incident radiation

$\nu_0 \rightarrow$ Threshold frequency

$V_0 = -\frac{W_0}{e}$, $V_0' = -\frac{W_0'}{e}$

→ Greater frequency of incident light → greater max. K.E thus greater retarding potetial is needed to stop photoelectrons.

→ Graph b/w V_0 and ν shows that

(I) V_0 varies linearly with ν

(II) There exists a certain minimum cut off frequency ν_0 for which the stopping potential is zero called threshold frequency (ν_0)

(III) If $\nu < \nu_0$ no photoelectric emission is possible even

Frequency → Colour of light
Intensity → Power (Watt) of light

if the intensity is large.

(iv) Value of ν_0 is different for different materials.

Conclusions of Experiment

KEY POINTS ↓

- → Electrons are emitted when light hits a photo-sensitive metal surface
- → Emission starts only if light's frequency is above threshold frequency [$\nu > \nu_0$]
- → Higher frequency increases K.E. of emitted electrons
- → Increasing light intensity increases the number of emitted electrons, but not their energy [$eV_0 = K_{max}$]
- → The stopping potential measures the maximum K.E. of emitted electrons. Higher stopping potential indicates higher energy electrons. [$eV_0 = K_{max} = \frac{1}{2}mv_{max}^2$]

* Energy of emitted electrons depends on frequency of incident light only.

* Photocurrent depends on intensity of incident light only.

Law of Photoelectric Emission:

1. Photocurrent ∝ Intensity of light
2. Below threshold frequency no electrons emittion is possible
3. Above threshold frequency
   Stopping potential / Kmax ∝ ν (incident frequency)
   but independent of incident intensity.
4. The photoelectric emission is an instantaneous process.

Changing colour of light changes → ν & Kmax
changing watt of light bulb changes → Intensity

Einstein's theory of photoelectric effect:

Einstein explained photoelectric effect on the basis of Planck's quantum theory. The main points are-

1. Photoelectric emission is the result of interaction of two particles - one photon and other is electron.
2. The free electrons are bounded within the metal and minimum energy required to liberate an electron from metal surface is called work function (W_0 or ϕ_0)
3. Each photon interacts with one electron. The energy $h\nu$ of photon is used up in two parts -

(a) On part to liberate the electron.

(b) Remaining part is used in imparting K.E of the K.E to the ejected electron.

By conservation of energy

$$h\nu = \frac{1}{2} m v_{max}^2 + W_0$$

or

$$\frac{1}{2} m v_{max}^2 = K_{max} = h\nu - W_0 \quad \text{—(1)}$$

here $W_0 = h\nu_0$, then

$$K_{max} = h\nu - h\nu_0 = h(\nu - \nu_0) \quad \text{—(2)}$$

Equation (1) and (2) are called Einstein's photoelectric equations.

Explaination of laws of photoelectric effect by Einstein's equations -

Effect of intensity: Increase in intensity means increase in no. of photons striking per unit time. As one photon ejects one electron, so ejected photoelectron increases with increase in intensity.

Explanation of Threshold Frequency:

If $\nu < \nu_0$ i.e K.E is -ve, which has no meaning.
So emission does not occur below threshold frequency.

Explanation of K.E:

If $\nu > \nu_0$, then
$K_{max} \propto$ frequency (ν)

Graph b/w V_0 and ν

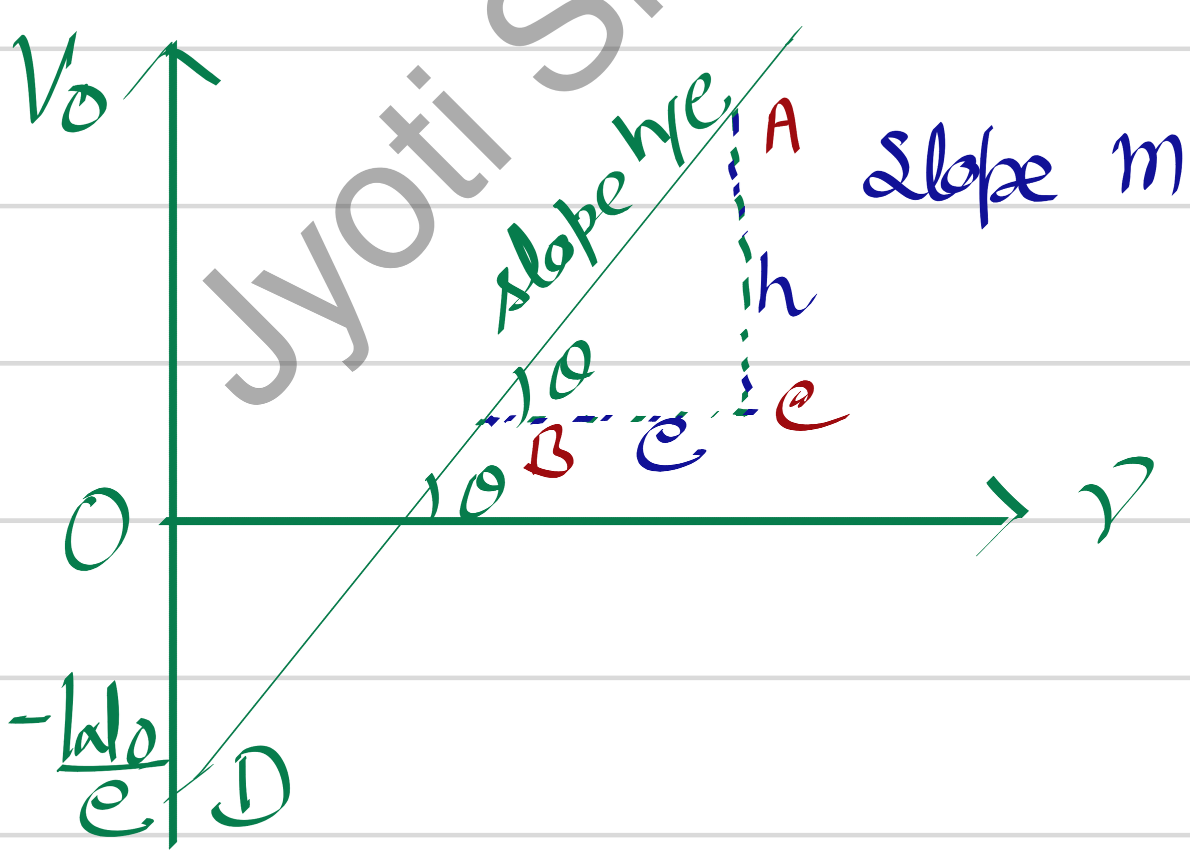
By Einstein equation

$$K_{max} = h\nu - W_0 \quad [K_{max} \rightarrow Max^m \text{ Kinetic energy}]$$

but $K_{max} = eV_0$

or $$V_0 = \left(\frac{h}{e}\right)\nu - \frac{W_0}{e} \quad \text{—(1)}$$

Compare with $y = mx + c$ [Straight line equation]



slope $m = \tan\theta = \frac{AC}{BC} = \frac{h}{e}$

$OD = -\frac{W_0}{e} \Rightarrow |W_0| = e \times OD$

→ Determination of Planck's constant and Work Function

From fig $\frac{h}{e} = \tan\theta = \frac{\Delta V_0}{\Delta \nu}$

or $\boxed{h = e \times \tan\theta}$

$= e \times$ slope of graph (V_0 vs ν)

* **Threshold Wavelength (λ_0):** The maximum wavelength of incident radiations capable of ejection of electrons from the metal surface.

$$\boxed{\lambda_0 = \frac{hc}{W_0}} \quad \left[W_0 = h\nu_0 = \frac{hc}{\lambda_0}\right]$$

Particle Nature of Light : The Photon :

→ Photon is a energy packet or quantum of energy.

$E = h\nu$

Where h is Planck's constant and ν is frequency of light

$h = 6.63 \times 10^{-34}$ Js

Energy of n photons

$E = nh\nu$

Properties of Photons

→ Photon travels with speed of light. ($c = 3\times10^{8}$ m/s)

→ Photons are massless, they do not have rest mass.

→ Photons are massless but they have momentum and can transfer energy.

→ The kinetic mass of a photon $m = \frac{E}{c^2} = \frac{h\nu}{c^2} = \frac{h}{c\lambda}$

→ The magnitude of momentum of a photon is

$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$ $[c = \nu\lambda]$

→ Photon energy $E = h\nu = \frac{hc}{\lambda} = \frac{6.6\times10^{-34}\times3\times10^{8}}{\lambda}$

or $\boxed{E = \frac{1242}{\lambda}\ eV}$ $[1J = 6.25\times10^{18} eV]$

→ Photons travel in straight line

→ Its velocity changes on changing medium.

→ Photons are electrically neutral.

→ They do not respond to magnetic field.

→ Total energy and total momentum of photons remain conserved during collision with matter.

→ All photons are identical.

Wave Nature of Matter:

Louis de Broglie proposed that all particles including matter, exhibit both wave-like and particle-like properties. This is known as wave particle duality.

According to de Broglie, the wavelength(λ) of a particle is inversely proportional to its momentum(p)

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

Matter Waves - The wave associated with a moving particle is called matter wave or de Broglie wave.

* This wave are more significant for microscopic particles like electrons.

de Broglie Relation

Energy of photon by quantum theory

$$E = h\nu$$

According to wave particle duality

$$c = \nu\lambda$$

or $\nu = \frac{c}{\lambda}$

so $E = \frac{hc}{\lambda}$

or $\lambda = \frac{hc}{E}$

here $E = pc$, then

$$\lambda = \frac{hc}{pc}$$

$$\boxed{\lambda = \frac{h}{p}}$$

For a particle momentum $p = mv$, then

$$\boxed{\lambda = \frac{h}{mv}}$$ → de Broglie Relation

* This relation shows that all moving particles not just photons, exhibit wave like behaviour.
* $\lambda \propto \frac{1}{v}$ and $\lambda \propto \frac{1}{m}$
* If $v = 0 \Rightarrow \lambda = \infty$
  i.e if particle is at rest λ is not observed.
* Matter wave are independent of charge.
* Matter waves are not electromagnetic waves.

Relation of de Broglie wavelength with potential

Consider a beam of electrons travelling through a potential V volt. The K.E.

$$E_K = eV = \frac{1}{2}mv^2$$ V → Potential, v → speed

but $$\frac{1}{2}mv^2 = \frac{p^2}{2m} \quad [p = mv]$$

then,

$$eV = \frac{p^2}{2m}$$

or $$p = \sqrt{2meV} = \sqrt{2mE_K}$$

By $$\lambda = \frac{h}{p}$$

$$\boxed{\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2mE_K}} = \frac{h}{\sqrt{2meV}}}$$

In general

$$\boxed{\lambda = \frac{h}{\sqrt{2mE_K}} = \frac{h}{\sqrt{2mqV}}}$$

Now $\lambda = \frac{6.62 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} V}}$

or $\lambda = \frac{12.27 \times 10^{-10}}{\sqrt{}} m = \frac{12.27}{\sqrt{}} A^\circ$

Short Answer Type 1 Questions (2 Mark)

1. State the laws of photoelectric emission.
2. Why photoelectric effect cannot be explained on the basis of wave nature of light? Give any two reasons.
3. An alpha (α) particle and a proton are accelerated from rest through the same potential difference. Find the ratio of their de-Broglie wavelengths associated with them.
4. A proton and an α- particle have the same de-Broglie wavelength. Determine the ratio of (i) their accelerating potentials (ii) their speeds.
5. When an electron in hydrogen atom jumps from the third excited state to the ground state, how would the de-Broglie wavelength associated with the electron change? Justify your answer.

Answers (Short Answer Type 1 Questions, 2 Mark)

1. (i) For a given photosensitive surface, photoelectric current is directly proportional to the intensity of incident light.
(ii) The maximum kinetic energy of photoelectrons does not depend on intensity but it depends on frequency of incident radiation and is directly proportional to it.
(iii) For a given photosensitive surface, there exists a certain minimum frequency of incident radiation, called threshold frequency below which no photoelectric emission takes place, whatever may be the intensity of incident radiation.
(iv)The photoelectric emission is an instantaneous process.
2. (i) According to wave theory, Kinetic energy of photoelectrons must increase as the intensity of light is increased. But, experimental observations show that, K.E. of photoelectrons does not depend on intensity of incident light.
(ii)According to wave theory, if the intensity of incident radiation is sufficient photoelectron emission should take place, whatever may be the frequency. But, experimental observations shows that, if , no emission of photoelectrons takes place, whatever may be the intensity.
3. $\lambda = \frac{h}{\sqrt{2mqV}}$ and V = Constant
⇨ $\frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{m_p}{m_\alpha}} \times \sqrt{\frac{q_p}{q_\alpha}} = \sqrt{\frac{m_p}{4m_p}} \times \sqrt{\frac{q_p}{2q_p}} = \frac{1}{2\sqrt{2}}$
4. (i) $\lambda = \frac{h}{\sqrt{2mqV}}$ $\Rightarrow V = \frac{h^2}{2mq\lambda^2}$
⇨ $\frac{V_P}{V_\alpha} = \frac{m_\alpha q_\alpha}{m_P\, q_P} = \frac{4m_P q_P}{m_P\, q_P} = \frac{8}{1}$

(ii) $\lambda = \frac{h}{mv}$ $\Rightarrow v = \frac{h}{m\lambda}$
$\Rightarrow \frac{v_P}{v_\alpha} = \frac{m_\alpha}{m_P} = \frac{4m_P}{m_P} = \frac{4}{1}$
5. For 3rd exited state n = 4,for ground state n = 1
Now $= \frac{h}{mv}$ $\Rightarrow \propto \frac{1}{v}$ but $v \propto \frac{1}{n}$
Therefore $\lambda \propto n$
⇨ $\frac{\lambda_2}{\lambda_1} = \frac{n_2}{n_1} = \frac{1}{4}$
⇨ $\lambda_2 = \frac{\lambda_1}{4}$, Hence, de-Broglie wavelength will decrease to one fourth of its value third excited state.