# Dual Nature of Radiation.

## Free electrons in metals

- The loosely bound electrons which are free to move easily within the metal surface but can't leave the metal surface are called free electrons.
- The free electrons are held inside the metal by attractive forces of the surface called restraining forces.

## Work Function ($\phi_0$)

It is the minimum energy required by an electron to just escape from the metal surface so as to overcome the restraining forces at the surface.

for caesium $\phi_0 = 2.14$ eV - it means it ejects electrons with light of lower energy

for platinum $\phi_0 = 5.65$ eV - it means it ejects electron with light of higher energy.

## Electron emission

The phenomenon of emission of electrons from the surface of a metal is called electron emission.

It can happen only when electron has energy more than work function.

## Types of electron emission

### ① Thermionic emission

The phenomenon of emission of electrons from metal surface when heated suitably is called thermionic emission

- Energy required for electron emission is supplied by thermal energy.
- Emitted electrons are called thermal electrons.
- No. of thermions emitted depends on tem. of metal surface

### ② Photoelectric emission

The phenomenon of emission of electrons from metal surface when light radiations of suitable frequency fall on it.

- Energy supplied by light photon
- Emitted electrons called photoelectrons.
- No. of photoelectrons emitted depends on intensity of incident light

### ③ Field emission

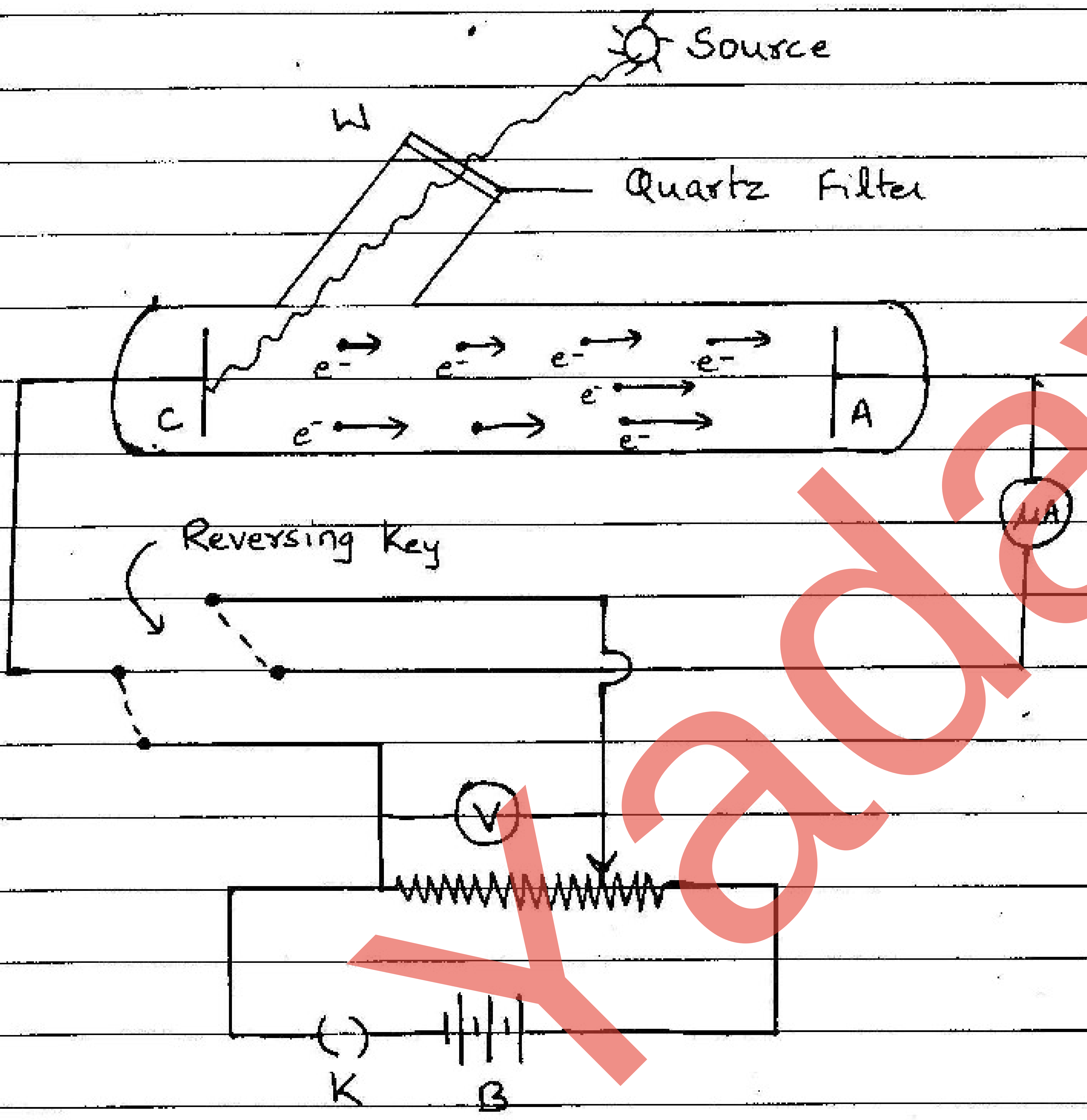
The phenomenon of emission of electrons from metal surface under the application of strong electric field.

### ④ Secondary emission

The phenomenon of emission of electrons from metal surface in large no. when fast moving electrons strike metal surface.

- Energy supplied by fast moving electrons
- Emitted electrons called secondary electrons.

## Experimental Study of photoelectric effect



## Construction

→ Evacuated glass or quartz tube enclosing photo sensitive plate C called emitter & metal plate A called collector

→ plate A can be given required +ve or -ve potenti w.r.t C using reversing key

→ Transparent window W is covered with filter to allow light of particular wavelength to pass through it

→ V measures p.d betⁿ A & C
μA " photoelectric current in the circuit.

## Working

→ Monochromatic radiations of suitable frequency after being filtered from UI fall on C.

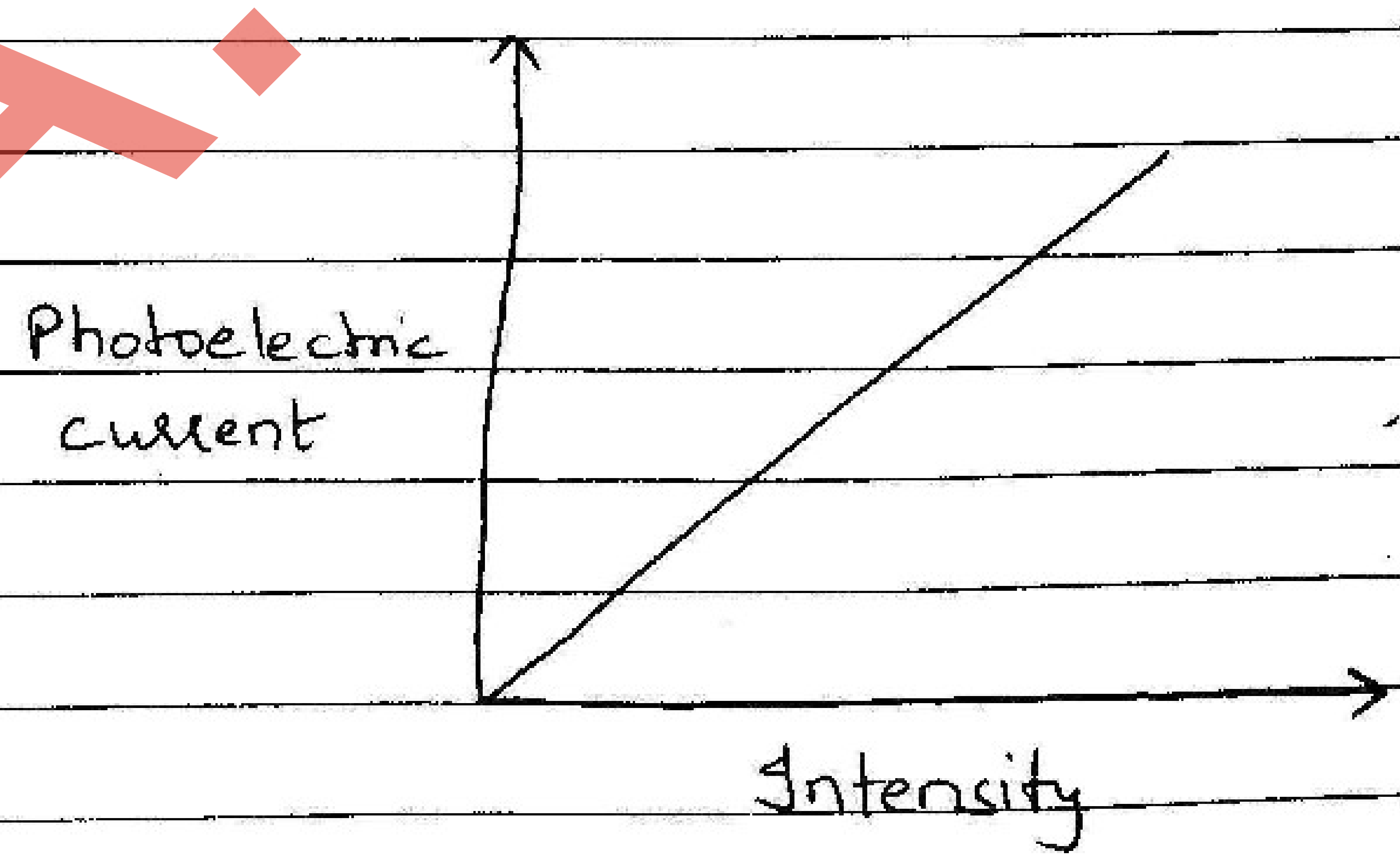
→ Photo-electrons are emitted from C, which get accelerated towards A (if it is kept +ve).

→ These electrons flow in the outer circuit resulting in photoelectric current, which is measured by μA.

## (a) Effect of intensity of incident radiation

- Maintain A at definite +ve potential w.r.t C so that emitted electrons are accelerated towards A.
- Using incident radiations of fixed frequency note the photoelectric current from μA.
  Vary the intensity of incident radiation keeping the radiation source at different distance w.r.t C & note the reading of μA.
- It is found that

no. of photoelectrons emitted per second ∝ intensity of incident radiation.



## (b) Effect of potential of A w.r.t C

* - Maintain A at some accelerating +ve potential w.r.t
- Illuminate C with radiations of fixed frequer $\nu$ & fixed intensity $I_1$.
- Vary +ve potential of A & note photoelectric current each time.
- It is found photoelectric current increases wi increase in +ve potential of A untill at a particular value of A it attains a maximum value called saturation current.
- Saturation current is that state when all photoelectrons emitted from C reaches A.

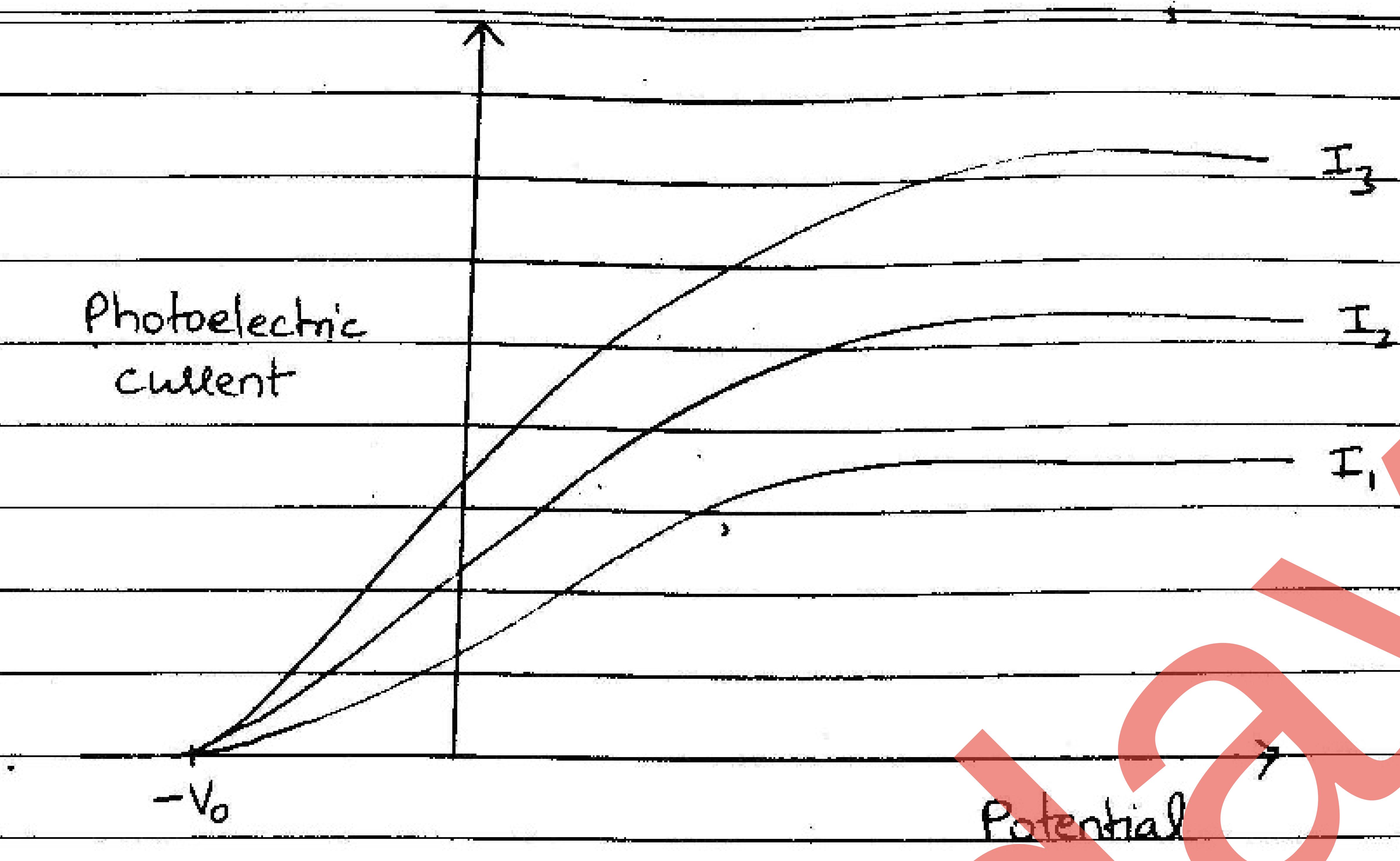
* - Now apply a -ve potential to A w.r.t C.
- The photoelectric current decreases because photoelectrons emitted from C are repelled & only energetic photoelectrons reach A.
- On further increasing -ve potential of A photoelectric current decreases rapidly & becom 0 at certain value of -ve potential, $V_0$

"The minimum negative potential $V_0$, given to A w.r.t C at which the photoelectric current becomes zero is called stopping potential o cut-off potential"

Max. kinetic energy at cut-off potential

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

On repeating the above experiment with different intensity of light we get :



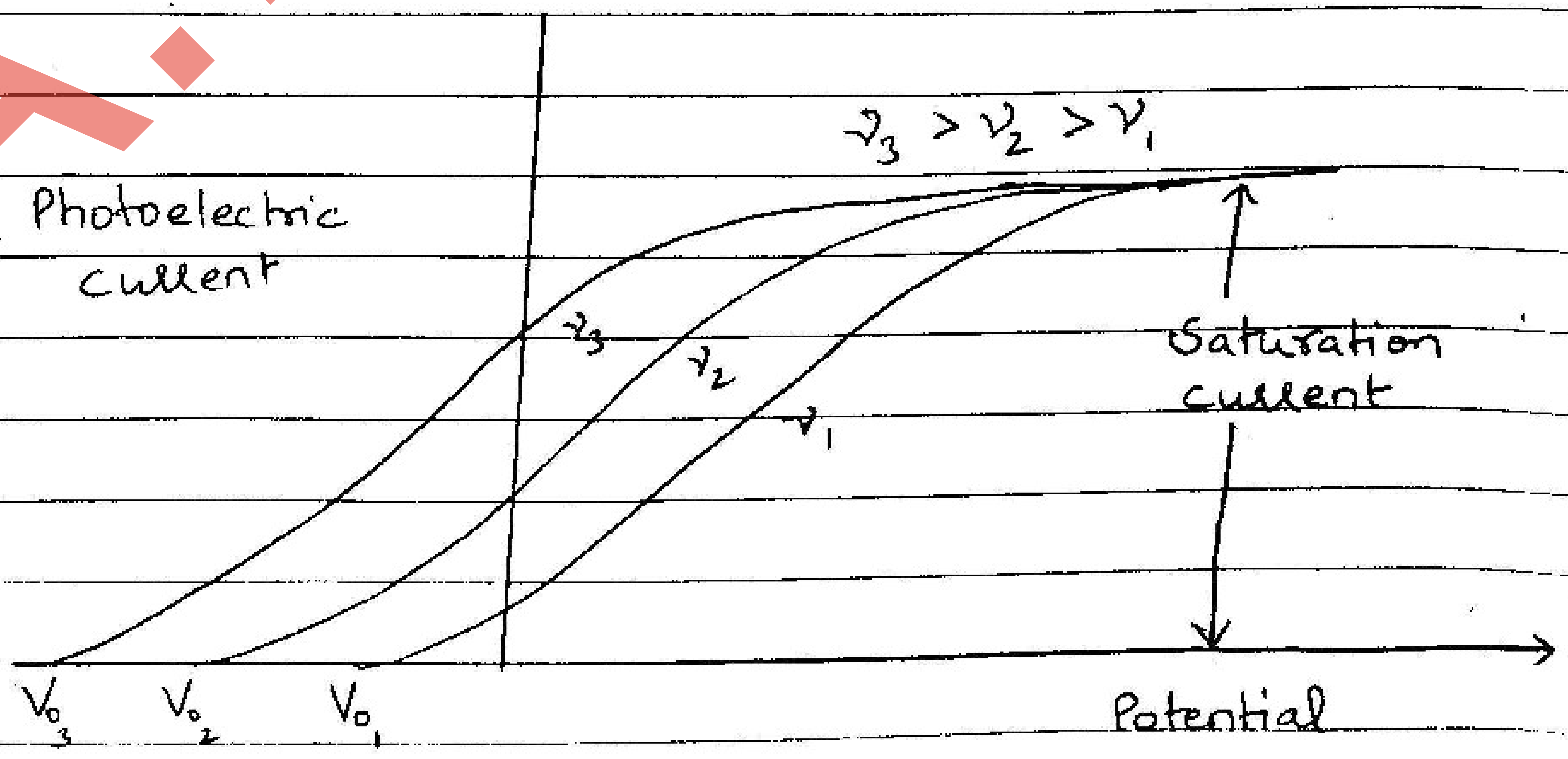
## Conclusion

(a) All photoelectrons emitted from C do not have same K.E.

(b) For radiations of given frequency & material of plate C, the value of $V_0$ is independent of intensity of incident radiation

[i.e. K.E. of emitted photoelectrons depend upon radiation source & material of C but not on intensity of incident radiation]

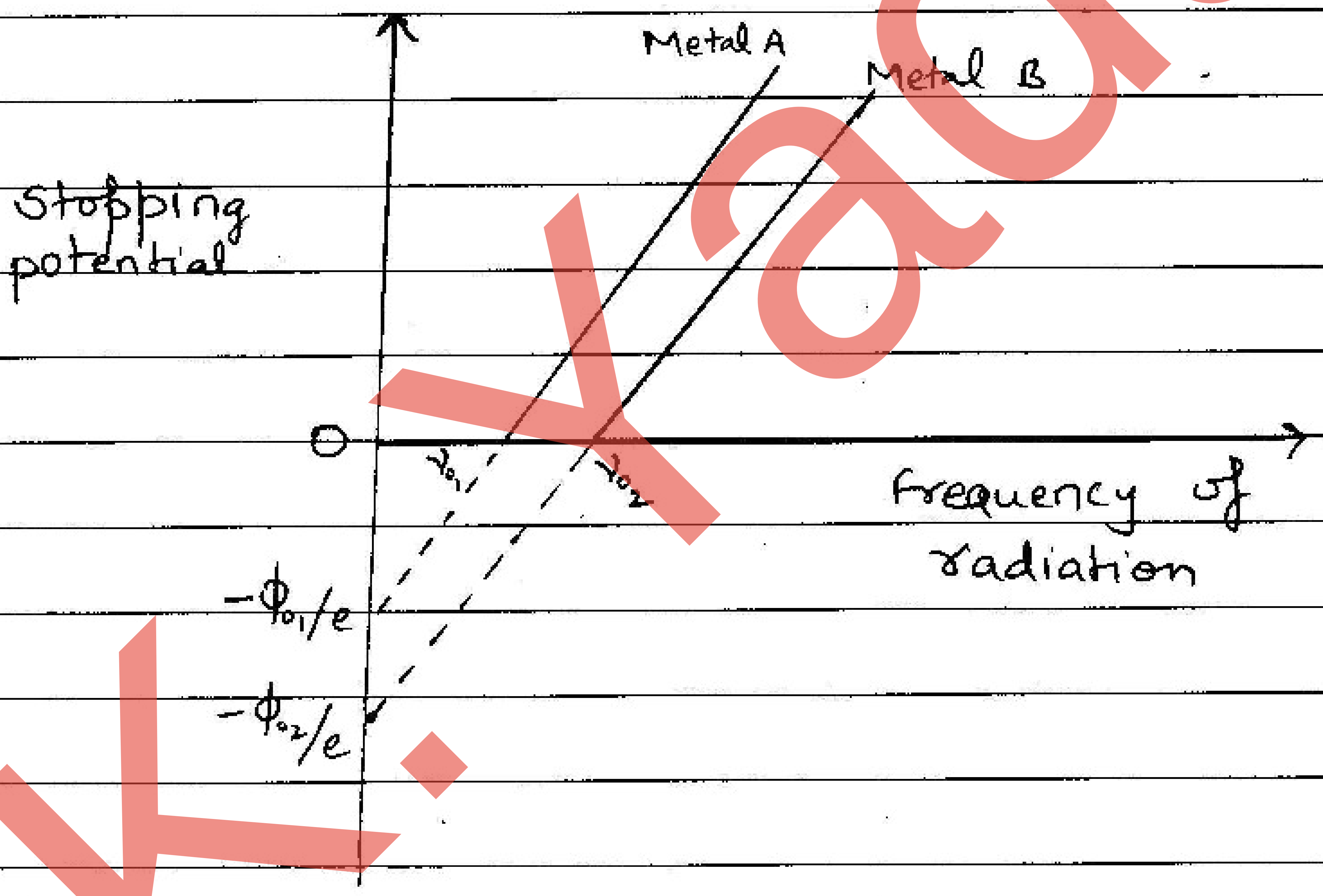
(c) Effect of frequency of incident radiation



## Conclusion

1) The value of $V_0$ is different for radiation of different frequency.
2) The value of $V_0$ is more -ve for radiation of higher incident frequency.
3) The value of saturation current - depends on intensity of incident radiation
independent of frequency " " "

## (d) Effect of nature of material of C



## Conclusion

1) For a given photosensitive material, $V_0$ varies linearly with frequency of incident radiation
2) For a given photosensitive material, there is a minimum cut-off frequency $\nu_0$ called threshold frequency for which $V_0 = 0$.
3) higher is the work function for a photosensitiv material, greater is threshold frequency.
4) The intercept on potential axis $= \frac{-\phi_0}{e}$

## Laws of photo-electric emission

① For a given metal & frequency of incident radiation, no. of photoelectrons ejected per sec. is directly proportional to intensity of incident light.

② For a given metal, there exists a certain minimum frequency of incident radiation below which no emission of photoelectrons takes place. This frequency is called threshold frequency.

③ Above threshold frequency, the max. K.E. of emitted photoelectron is independent of the intensity of incident light but depends upon the frequency of incident light

④ Photoelectric emission is an instantaneous process as time lag betⁿ incidence of radiation & emission of photoelectron is very small.

## Einstein's Photoelectric equation

- Einstein explained various laws of photoelectric emission on the basis of Planck's quantum theory.
- According to quantum theory "light radiation consist of tiny packets of energy called quanta. One quantum of light radiation is called photon, which travels with the speed of light"

The energy of photon is

$$E = h\nu$$

- Einstein assumed that one photoelectron is ejected from metal surface when one photon of radiation falls on it.

Consider a photon of light of frequency $\nu$, incident on a photosensitive metal surface. The energy of the photon is spent in 2 ways –

(a) a part of energy (equal to $\phi_0$) is used in liberating the electron from metal surface.

(b) remaining energy is used in imparting max K.E. to emitted photoelectron.

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

$$\therefore \quad h\nu = \phi_0 + \frac{1}{2} m v_{max}^2$$

or $$\boxed{K_{max} = \frac{1}{2} m v_{max}^2 = h\nu - \phi_0}$$

$$\phi_0 = h\nu_0$$

$$\therefore \quad \boxed{K_{max} = h(\nu - \nu_0)}$$

Explanation of laws of photoelectric emission

① As one photon ejects one photoelectron so no. of photoelectrons emitted per sec. depends on no. of photons falling on metal surface which in turn depends on intensity of light

If intensity increases, photon no. increases & hence photoelectrons increases.

② $K_{max} = h(\nu - \nu_0)$

if $\nu < \nu_0$ , K.E = -ve (not possible)

So, photoelectric emission does not take place for incident radiation below threshold frequency.

③ If $\nu > \nu_0$ , K.E. $\propto \nu$
i.e. $K_{max}$ depends only on frequency of incident light.

④ The phenomenon of photoelectric emission has been conceived as an effect of elastic collision betⁿ photon & electron inside the metal. So the absorption of energy by electron from photon takes place without any time lag

Relation betⁿ $V_0$, $\nu$ & $\phi_0$

$$K_{max} = h\nu - \phi_0$$
$$= h(\nu - \nu_0)$$

Also, $K_{max} = eV_0$

$$\therefore eV_0 = h(\nu - \nu_0)$$

$$= h\left(\frac{c}{\lambda} - \frac{c}{\lambda_0}\right)$$

$$\boxed{eV_0 = K_{max} = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)}$$

## Particle nature of light

## Characteristic properties of photon

① In interaction of radiation with matter, radiatio behave as if it is made of particles like photo

② Each photon has energy $E = h\nu = \frac{hc}{\lambda}$ &

momentum $p = \frac{h\nu}{c} = \frac{h}{\lambda}$

③ photon energy is independent of intensity of radiations.

④. All photons emitted from a source of radia travel through space with same speed c.

⑤ The velocity of photon is different in different medium.

⑥ The rest mass of a photon is zero.

$$m_0 = m\sqrt{1 - v^2/c^2}$$

for photon $v = c$, so $m_0 = 0$

⑦ Photons are not deflected by electric & magnetic fields. This shows that photons are electrically neutra

⑧ In a photon-particle collision, energy & momentum are conserved but no. of photons may not be conserved.

## De-Broglie Hypothesis

"A moving particle sometimes acts as a wave & sometimes as a particle." The wave associated with moving particle is called de-broglie wave whose wavelength is

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

## Derivation

Acc. to Planck's Quantum Theory

$$E = h\nu \quad ①$$

Acc. to Einstein's mass energy relation

$$E = mc^2 \quad ②$$

So,

$$mc^2 = h\nu$$

$$m = \frac{h\nu}{c^2}$$

Momentum of photon is

$$p = mc$$

$$= \frac{h\nu}{c^2} \times c$$

$$= \frac{h\nu}{c}$$

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

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

## Relation betⁿ $\lambda$ & $T$

The average kinetic energy of particle at gi
tem $T$ is

$$K = \frac{3}{2}kT$$

Also, $K = \frac{1}{2}mv^2$

$$p = mv$$
$$= \sqrt{2mK}$$
$$= \sqrt{\cancel{2}m \times \frac{3}{\cancel{2}}kT}$$
$$= \sqrt{3mkT}$$

$$\therefore \boxed{\lambda = \frac{h}{p} = \frac{h}{\sqrt{3mkT}}}$$

## De-broglie wavelength of an electron

Consider an electron of mass 'm' & charge
Let $v$ be the velocity acquired by electro
when accelerated from rest through a potential difference of $V$ volt.

Gain in K.E. of electron $= \frac{1}{2}mv^2$

Work done on electron $= eV$

$$\therefore \frac{1}{2}mv^2 = eV$$

$$v = \sqrt{\frac{2eV}{m}}$$

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

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

$m = 9 \times 10^{-31}$

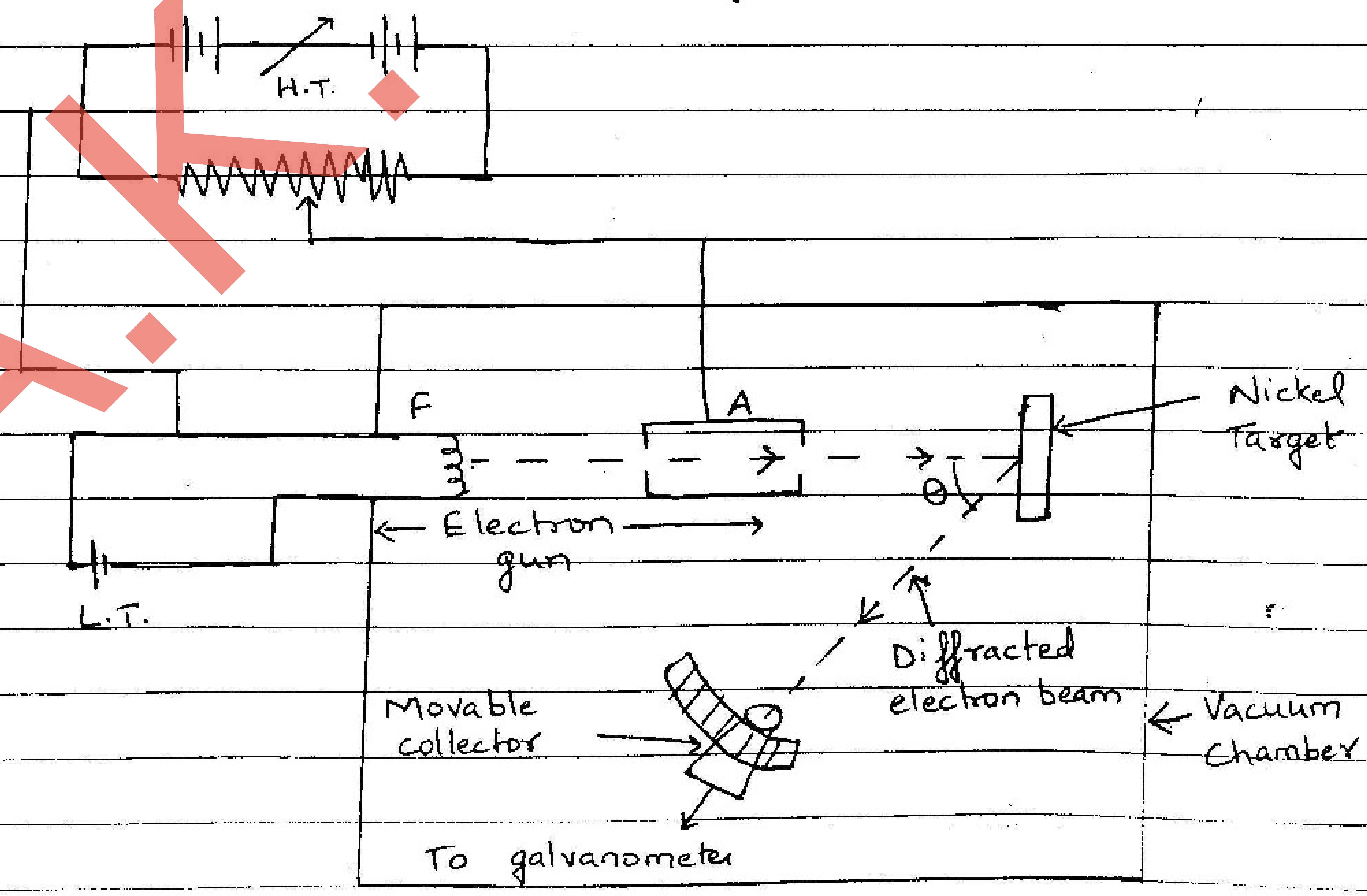
$e = 1.6 \times 10^{-19}$

$$\lambda = \frac{12.27}{\sqrt{V}} \times 10^{-10}\ m$$

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

## Davisson and Germer Experiment

(to show wave nature of electron)



- It consists of an electron gun comprising of a tungsten filament F (coated by $Ba_2O$ heated by low voltage power supply L.T.)
- Electrons emitted by F are accelerated to a desired velocity by applying suitable voltage from higher voltage power supply H.
- Electrons are made to pass through a cylinder producing a fine collimated beam.
- The beam is made to fall on nickel surf
- Electrons are scattered in all directions by atoms of the crystal.
- The intensity of scattered electron in a given direction is measured by electron detector (collector) connected to a sensitive galvanometer (which records current)
- Deflection of $\propto$ intensity of electron beam galvanometer entering collector
- By moving the detector at different positi the intensity of scattered electron beam measured for different values of θ (angle of scattering)

- The experiment was done by varying the voltage from 44 V to 68 V.
- It was found a strong peak appeared i in intensity of scattered electron for 54 at θ = 50°
- The strong peak is due to constructive interference of electrons scattered from diff layers of regularly spaced atoms of crystal.

- From electron diffraction measurements, the wavelength of electron is 0.165 nm

- for $V = 54V$

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

$$= \frac{1.227}{\sqrt{54}} nm$$

$$= 0.167 \ nm$$

So, there is an excellent agreement betn theoretical value & experimental value of $\lambda$. Thus, the experiment confirms the wave nature of electrons & de-broglie relation