Dual Nature of Radiation

Dual nature of Radiation and Matter

The maxwell's equations of electromagnetic and Haltz experiment on generation of electro-magnetic wave establish the wave nature of light

After the discoveries of photoelectric effect Combton effect establish the particle nature of light.

Therefore, it was Concluded that light has **dual nature.**

Electron Emission

In metals the electrons of outershell loosely bounded its atom, they are free within the metal surface but Can not leave the surface such e⁻s are called **free electron.**

These electrons Can be emitted from the metal the phenomenon of emission of e⁻ from the surface of metal is called electron emission.

There are following physical processes for emi

(1) Thermynic emission When sufficient thermal energy imparted free electrons by suitable heating electrons come out from the surface of metal this phenomenon is known Thermynic emission & these e⁻ are known Thermains.

(2) Photoelectric emission When a suitable frequency of light fall on the surface of metal. The electron emitted from the surface this phenomenon is called photo-electric effect and electrons are called photo electrons.

(3) Field emission It is the phenomenon of emission of electron by applying a very strong electric field to the metal.

(4) Secondary emission When the fast moving electron which is called Primary electron strikes the surface of metal electron emitted from the surface this electron is called secondary electron and this phenomenon is called Secondary emission.

Work Function

The minimum energy require by an e^- to ~~stay~~ escape from the metal surface is called work function of metal. It is denoted by ϕ_0 or W_0

- It depends upon nature of metal
- and on temperature if we increase the temp. it decreases.

1.1 Photoelectric Effect and Current

The phenomenon of emission of electrons fr
the surface of metal, when a light beam of
suitable frequency is incident on it, is called

photoelectric effect. The emitted electrons are called **photoelectrons** and the current so produced is called **photoelectric current**.

Observation of Photoelectric Effect

Hertz's Observation

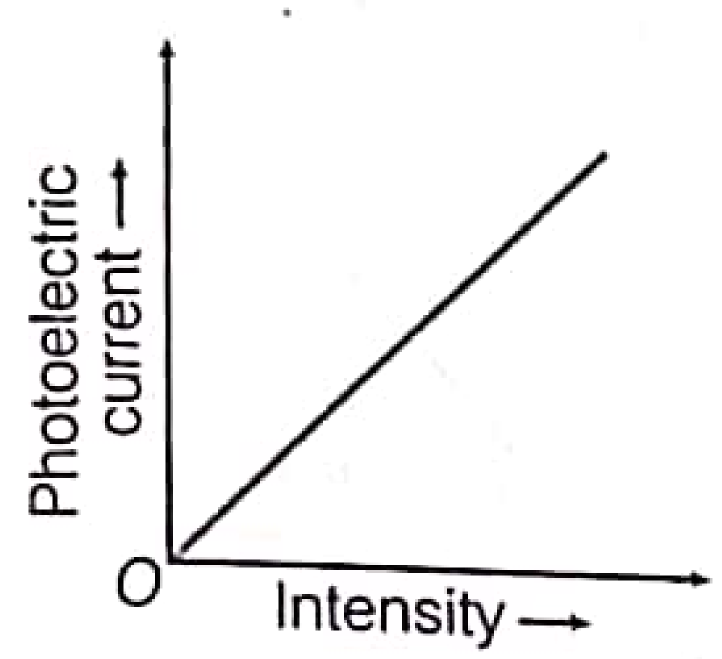
The phenomenon of photoelectric emission was discovered in 1887 by Heinrich Hertz during his electromagnetic wave experiment. In his experimental investigation on the production of electromagnetic waves by means of spark across the detector loop were enhanced when the emitter plate was illuminated by ultraviolet light from an arc lamp.

Lenard's Observation

Lenard observed that when ultraviolet radiation were allowed to fall on emitter plate of an evacuated glass tube enclosing two electrodes, current flows. As soon as, the ultraviolet radiations were stopped, the current flow also stopped. These observations indicate that when ultraviolet radiations fall on the emitter plate, electrons are ejected from it which are attracted towards the positive plate by the electric field.

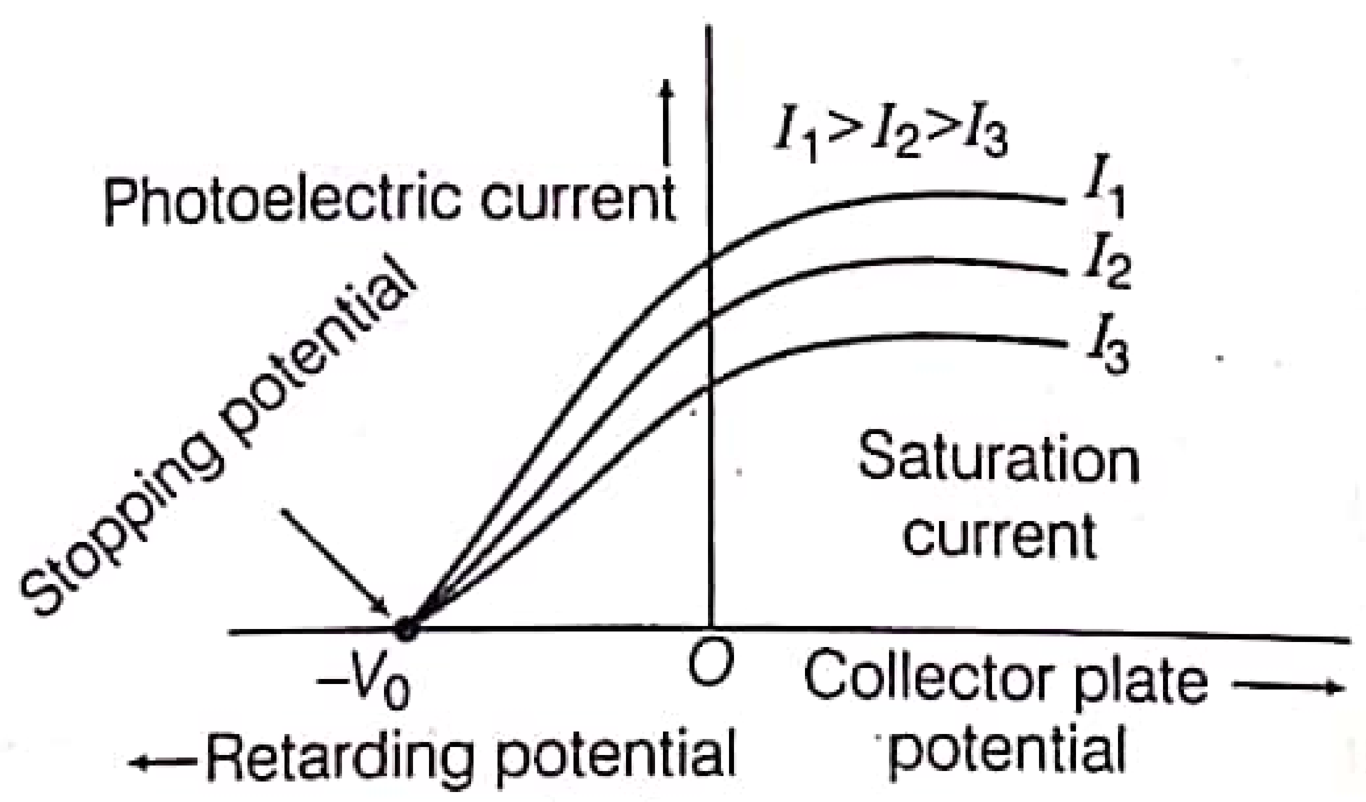
Effect of Intensity of Light on Photoelectric Current

For a fixed frequency of incident radiation and accelerated potential the photoelectric current increases linearly with increase in intensity of incident light.



Effect of Potential on photoelectric Current

For a fixed frequency and intensity of incident light, the photoelectric current increases with increase in the potential applied to the collector, as shown in the graph.



Variation of photoelectric current *versus* potential for different intensities but constant frequency

From the given graph, *we observe that*

(*i*) When all the photoelectrons reach the collector plate and if we increase potential applied to collector plate further, then photoelectric current does not increase, this maximum value of photoelectric current is known as **saturation current.**

(*ii*) **Cut-off Potential** For a particular frequency of incident radiation, the minimum negative (retarding) potential V_0 given to plate for which the photoelectric current becomes zero, is called cut-off or stopping potential.

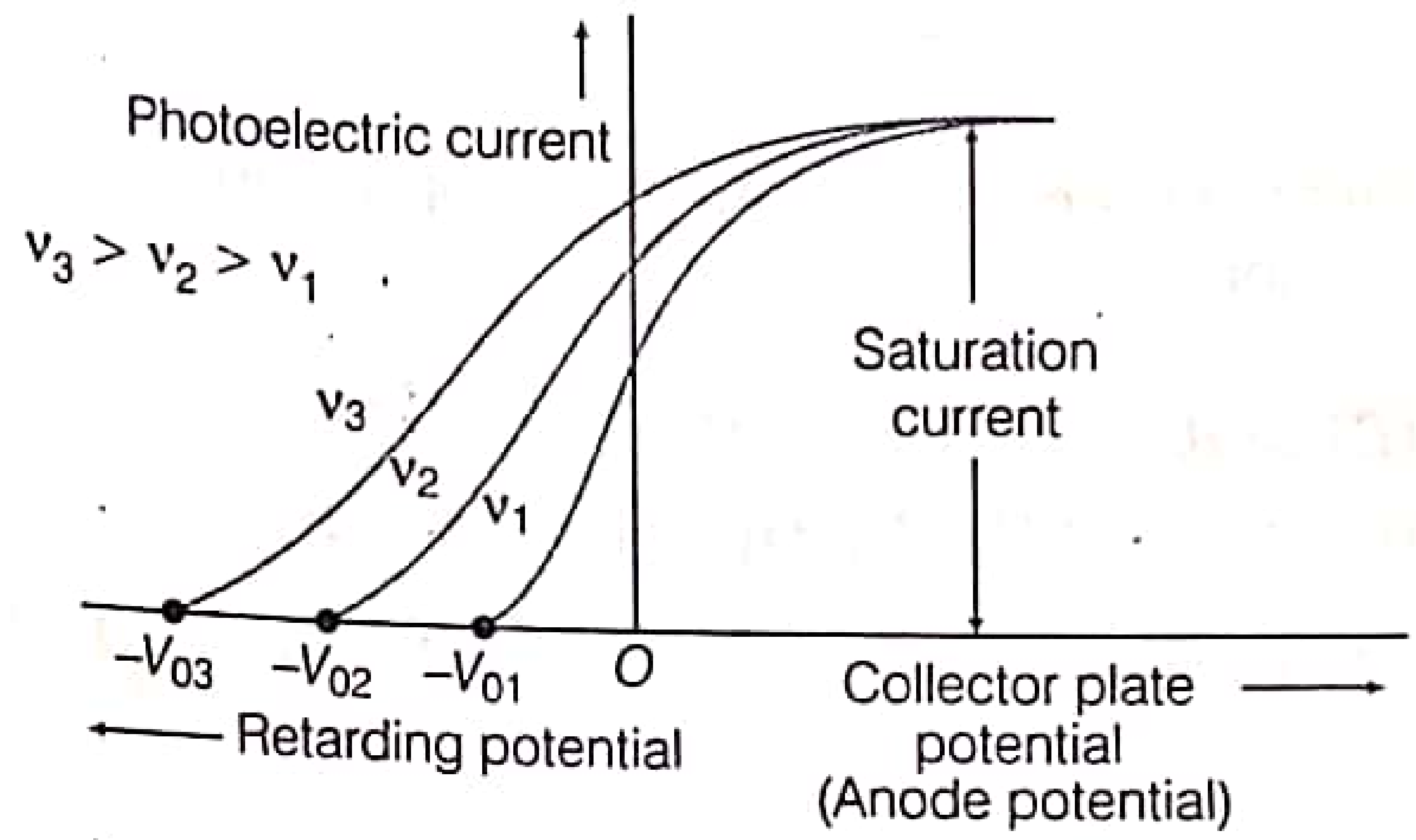
$$KE_{max} = eV_0$$

$$\boxed{\frac{1}{2}mv^2_{max} = eV_0}$$

NOTE Photoelectric current is zero whenever no electron even the fastest photoelectrons cannot reach the plate A.

Effect of Frequency of Incident Radiation on Stopping Potential

We take radiations of different frequencies but of same intensity. For each radiation, we study the variation of photoelectric current against the potential difference between the plates.



Variation of photoelectric current *versus* potential for different frequencies but constant intensity of light

Laws of Photoelectric Emission

The laws of photoelectric emission are as follow

(*i*) For a given material and frequency of incident radiation, the photoelectric current or the number of photoelectrons ejected per second is directly proportional to the intensity of the incident radiation.

(*ii*) For a given material and frequency of incident radiation, saturation current is found to be proportional to the intensity of incident radiation, whereas the stopping potential is independent of its intensity.

(*iii*) For a given material, there exists a certain minimum frequency of the incident radiation below which no emissions of photoelectrons takes place. This frequency is called **threshold frequency** or cut-off frequency of that material. Above the threshold frequency, the maximum kinetic energy of the emitted photoelectrons or equivalent stopping potential is independent of intensity of incident light but depends only upon the frequency (or wavelength) of the incident light.

(*iv*) The photoelectric emission is an instantaneous process. The time lag between the incidence of radiations and emission of photoelectron is very small, less than even 10^{-9} s.

Einstein Photoelectric Equation

On the basis of planck's quantum theory, Einstein derived an equation for the photoelectric effect. This equation is known as Einstein photoelectric equation.

Einstein's photoelectric equation

$$h\nu = \phi_0 + K_{max}$$

where, $h\nu$ = energy of photon and ϕ = work function

Relation between Stopping Potential (V_0) and Threshold Frequency (ν_0)/Wavelength (λ_0)

We know that $h\nu = KE_{max} + \phi_0$

where, ϕ_0 = work function

$$KE_{max} = h\nu - \phi_0 \quad \text{also,} \quad \phi_0 = h\nu_0$$

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

$$\Rightarrow \quad KE_{max} = h(\nu - \nu_0)$$

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

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

$[\because KE_{max} = eV_0]$

$$\nu = \frac{c}{\lambda} \text{ and } \nu_0 = \frac{c}{\lambda_0}$$

$$V_0 = \frac{h}{e}\left[\frac{c}{\lambda} - \frac{c}{\lambda_0}\right]$$

$$V_0 = \left(\frac{hc}{e}\right)\left[\frac{1}{\lambda} - \frac{1}{\lambda_0}\right]$$

For photoelectric emission $\lambda < \lambda_0$ and $\nu > \nu_0$.

Some Important Graphs Related to Photoelectric Effect

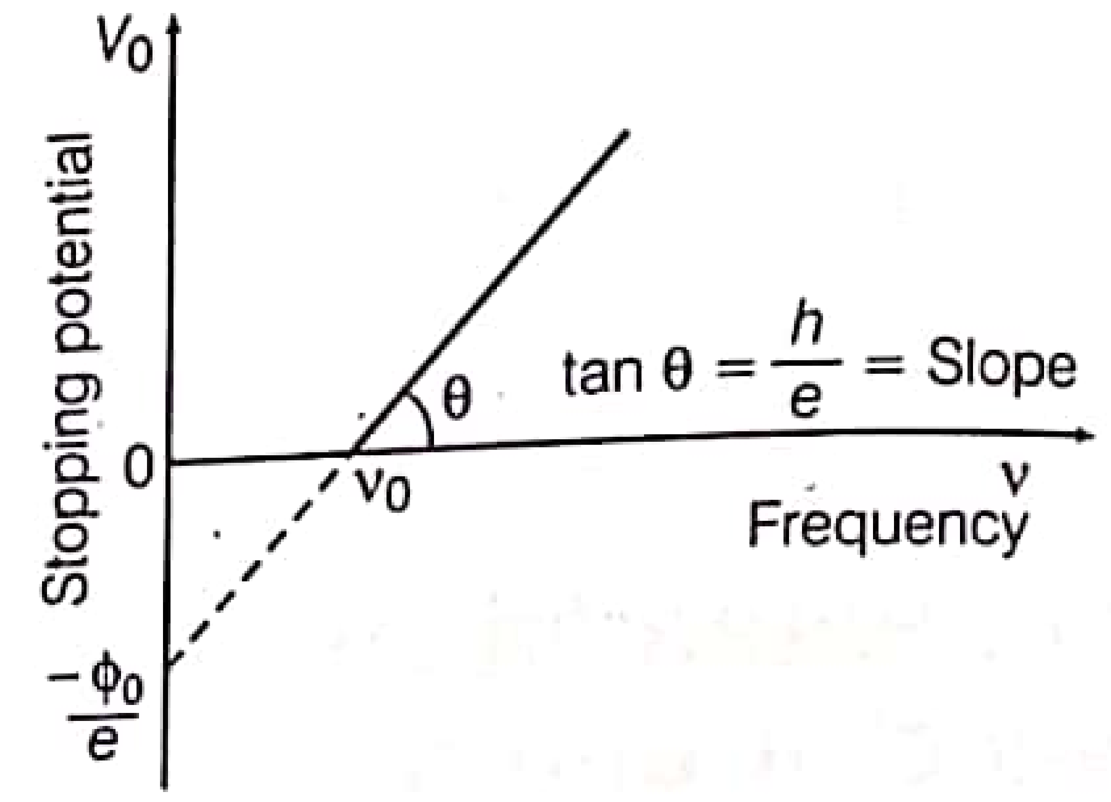
There are following graph related to phetoelectric effect

(*i*) Graph between frequency (ν) and stopping potential V_0, we know that

$$eV_0 = h\nu - \phi_0$$

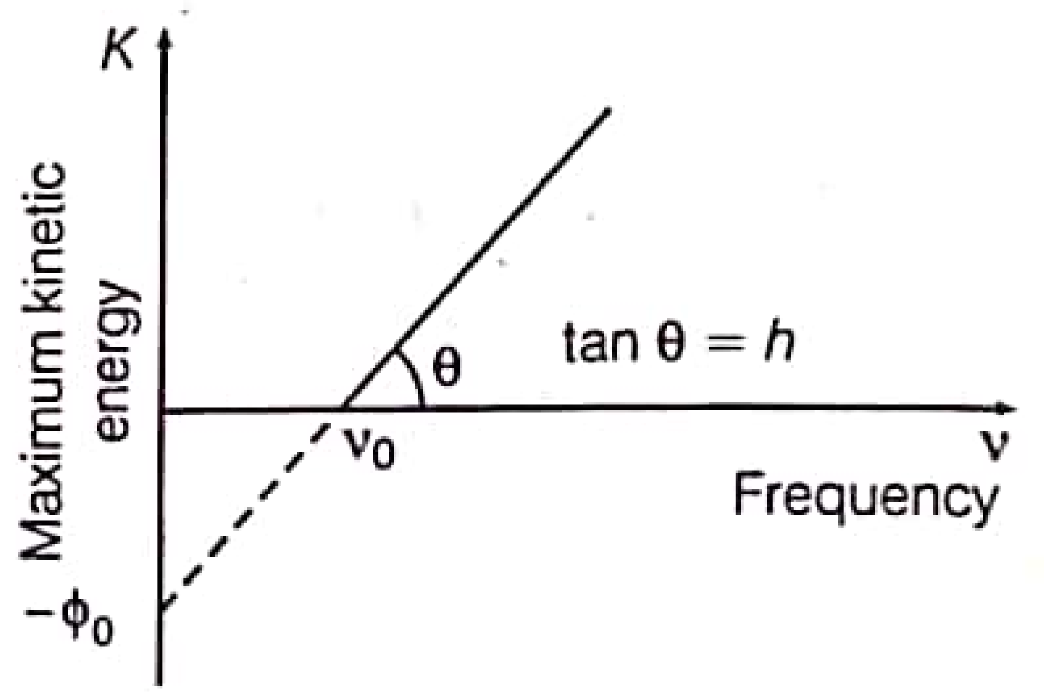
$$V_0 = \frac{h}{e}\nu - \frac{\phi_0}{e}$$

So, $V_0 \propto \nu$

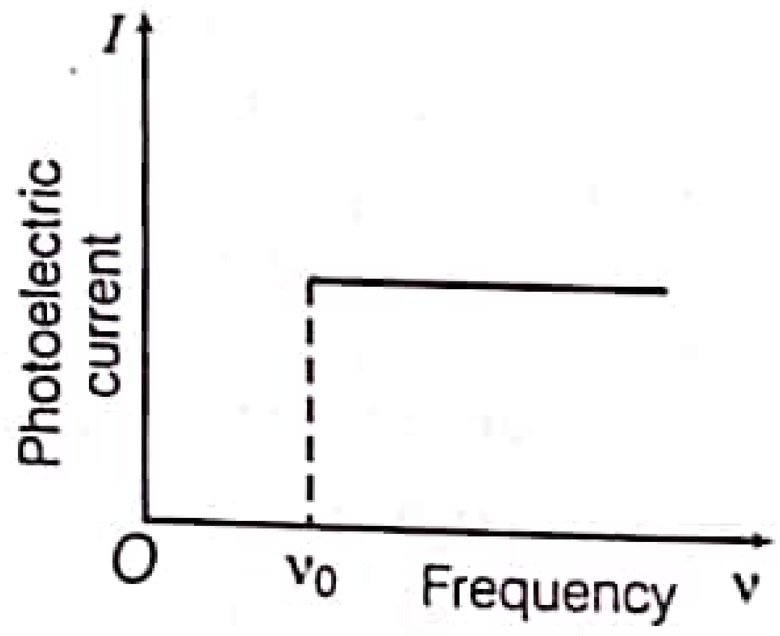


(*ii*) Frequency (ν) *versus* maximum kinetic energy graph, $KE_{max} = h\nu - \phi_0$

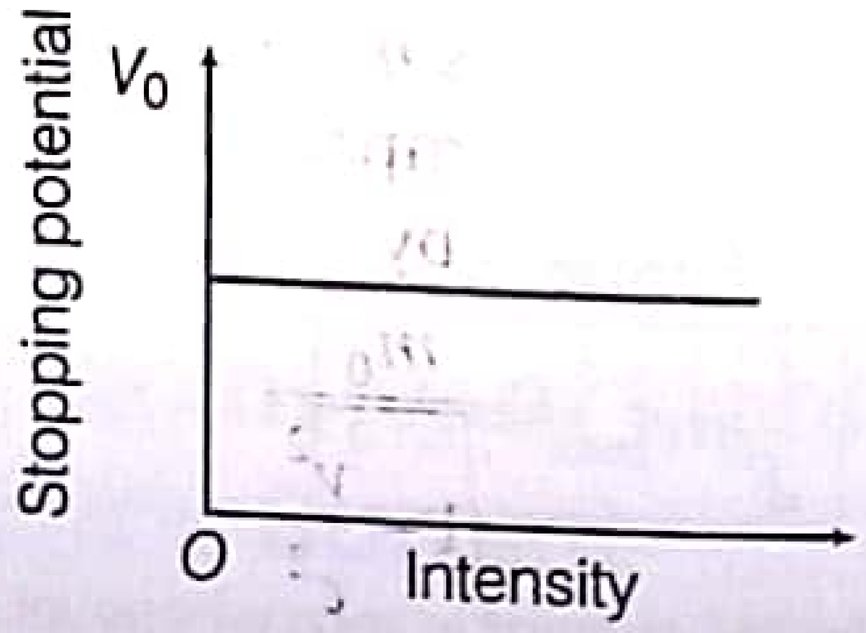
So, $KE_{max} \propto \nu$



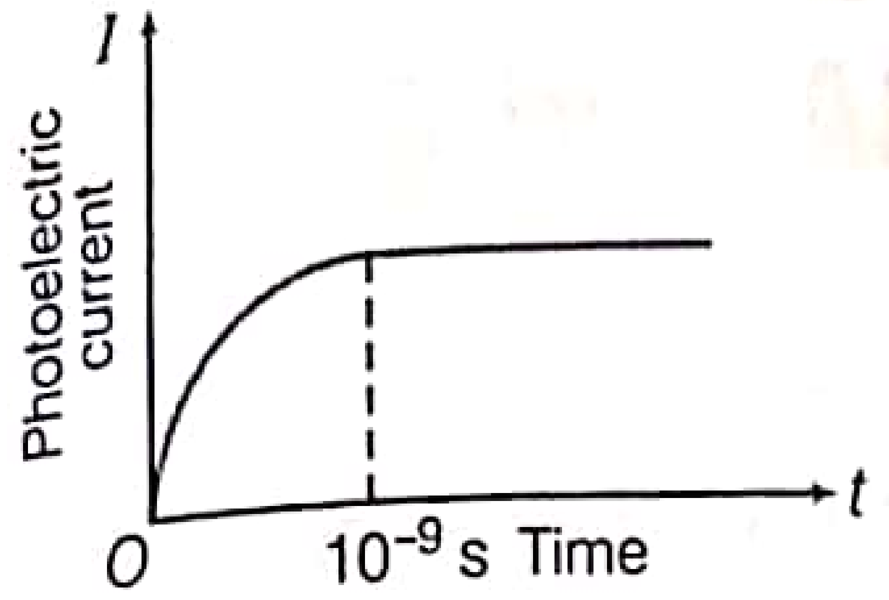
(*iii*) Frequency (ν) *versus* photoelectric current (I) graph. This graph shows that the photoelectric current (I) is independent from the frequency ($\nu \geq \nu_0$) of the incident light till intensity remains constant.



(*iv*) Intensity *versus* stopping potential (V_0) graph



(v) Photoelectric current (I) *versus* time lag (t) graph is given by



1.2 Particle Nature of Light: The Photon

Photoelectric effect thus gave evidence that light consists of packets of energy. These packets of energy are called **light quantum** that are associated with particles named as **photons**. So, photons confirm the particle nature of light.

Energy of photon is given by $E = h\nu = \frac{hc}{\lambda}$

and the momentum of photon is given by

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

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

Characteristic Properties of Photons

Different characteristic properties of photons are given below:

(i) In interaction of radiation with matter, radiation behaves as it is made up of particles called **photons**.

(ii) A photon travels at a speed of light c in vacuum (i.e. 3×10^8 m/s).

(iii) It has zero rest mass, i.e. the photon cannot exist at rest. According to the theory of relativity, the mass m of a particle moving with velocity v, comparable with the velocity of light c is given by

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

$$\Rightarrow \quad m_0 = m\sqrt{1 - \frac{v^2}{c^2}}$$

where, m_0 is the rest mass of the particle. As, a photon moves with the speed of light, i.e. $v = c$, hence $m_0 = 0$. So, rest mass of photon is zero.

(iv) The inertial mass of a photon is given by

$$m = \frac{E}{c^2} = \frac{h}{c\lambda}$$

(v) Photons travel in a straight line.

(vi) Irrespective of the intensity of radiation, all the photons of a particular frequency ν or wavelength λ have the same energy

$$E\left(= h\nu = \frac{hc}{\lambda}\right)$$

and momentum, $p\left(= \frac{h\nu}{c} = \frac{h}{\lambda}\right)$.

(vii) Energy of a photon depends upon frequency of the photon, so the energy of the photon does not change when photon travels from one medium to another.

(viii) Wavelength of the photon changes in different media, so velocity of a photon is different in different media.

(ix) Photons are not deflected by electric and magnetic fields. This shows that photons are electrically neutral.

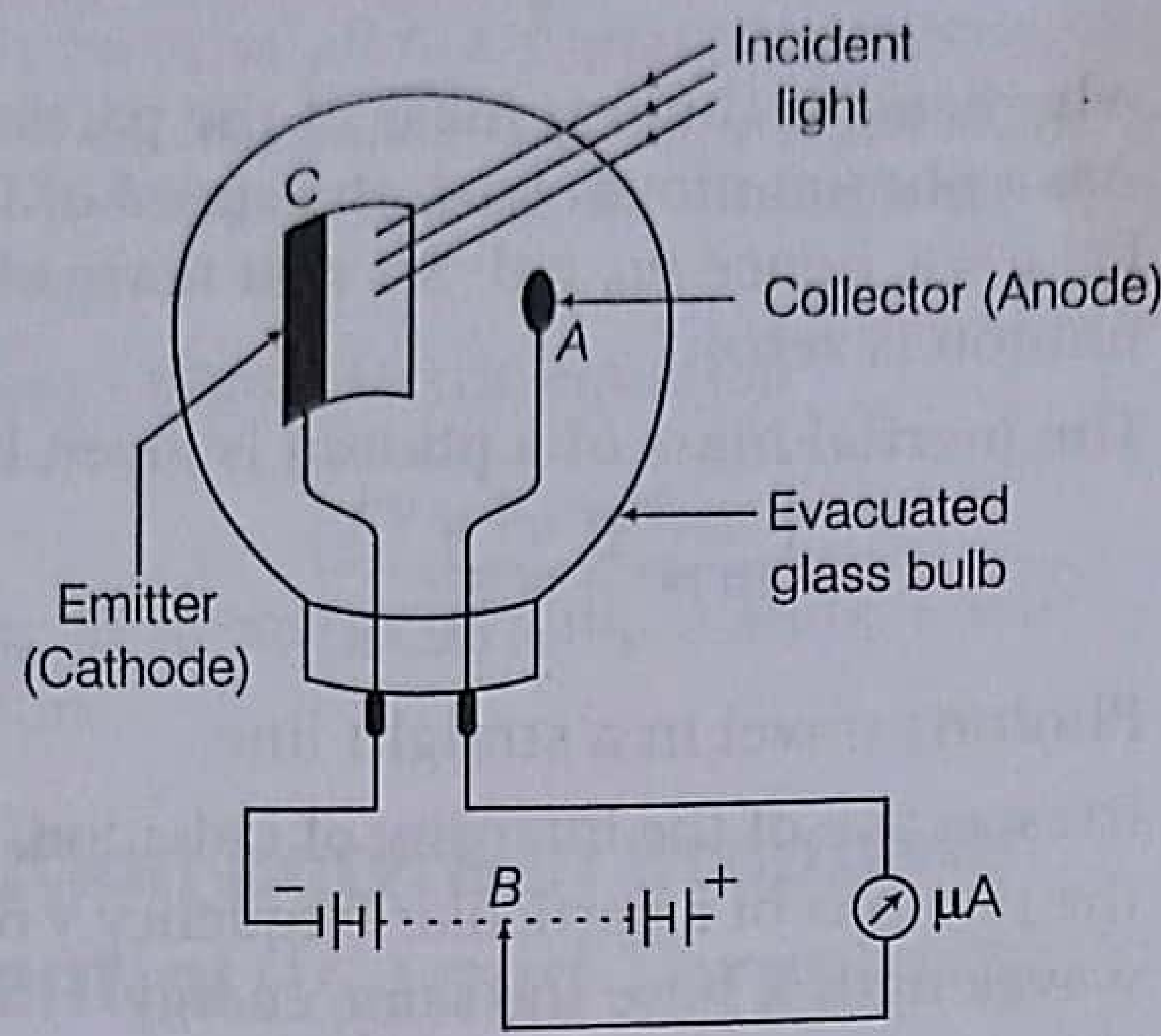
(x) In a photon-particle collision (such as photoelectron collision), the energy and momentum are conserved.

However, the number of photons may not be conserved in a collision.

(xi) Photons may show diffraction under given conditions.

1.3 Photocell

It is a device which converts light energy into electrical energy. It is also called an **electric eye.** As, the photoelectric current set up in the photoelectric cell corresponding to incident light provides the information about the objects as it has been seen by our eye in the presence of light.



Photocell

A photocell consists of a semi-cylindrical photosensitive metal plate C (emitter) and a wire loop A (collector) supported in an evacuated glass or quartz bulb. When light of suitable wavelength falls on the emitter C, photoelectrons are emitted.

Applications of Photocell

Some applications of photocell are given below

(*i*) Used in television camera for telecasting scenes and in photo telegraphy.

(*ii*) Reproduction of sound in cinema film.

(*iii*) Used in counting devices.

(*iv*) Used in burglar alarm and fire alarm.

(*v*) To measure the temperature of stars.

(*vi*) In paper industry to measure the thickness of paper.

(*vii*) To locate flaws or holes in the finished goods.

(*viii*) To determine opacity of solids and liquids.

(*ix*) Automatic switching of street lights.

(*x*) Used as photoelectric sensors.

(*xi*) To control the temperature of furnace.

(*xii*) Used for the determination of Planck's constant.

Nature of Radiation

of electromagnetic radiation phenomenon of interference, d polarisation. On the other hand, effect supported particle's nature of we assume dual nature of light.

e Nature of Particles

Broglie Hypothesis)

de-Broglie, a wave is associated with rial particle which controls the ery respect. The wave associated with rial particle is called **matter wave** or **vave** whose wavelength is called avelength.

atter wave equation is given by

$$= \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mK}}$$

omentum (particle nature), = velocity of moving particle, th associated with the particle ic energy of the particle.

Relation between de-Broglie Wavelength (λ) and Temperature (T)

From kinetic theory of matter, the average kin energy of a particle at a given temperature T kelvin is given by

$K = \frac{3}{2} k_B T$ where, k_B = Boltzmann constant.

If a particle of mass m moving with velocity v, then its kinetic energy, $K = \frac{1}{2} mv^2$

Momentum of particle is

$$p = mv = \sqrt{2mK} = \sqrt{2m \times \frac{3}{2} k_B T} = \sqrt{3mk_B T}$$

de-Broglie wavelength, $\lambda = \frac{h}{p} = \frac{h}{\sqrt{3\, mk_B T}}$

2.3 de-Broglie Wavelength of an Electron

Let us consider a particle of charge q having m is accelerated by potential difference V, th

$$\frac{1}{2} mv^2 = qV$$

$\Rightarrow \qquad v = \sqrt{\dfrac{2qV}{m}}$

$\Rightarrow$ Momentum, $p = mv = \sqrt{2qVm}$

The wavelength associated with moving charged particle is given by

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2qVm}}$$

If accelerated particle is electron, then

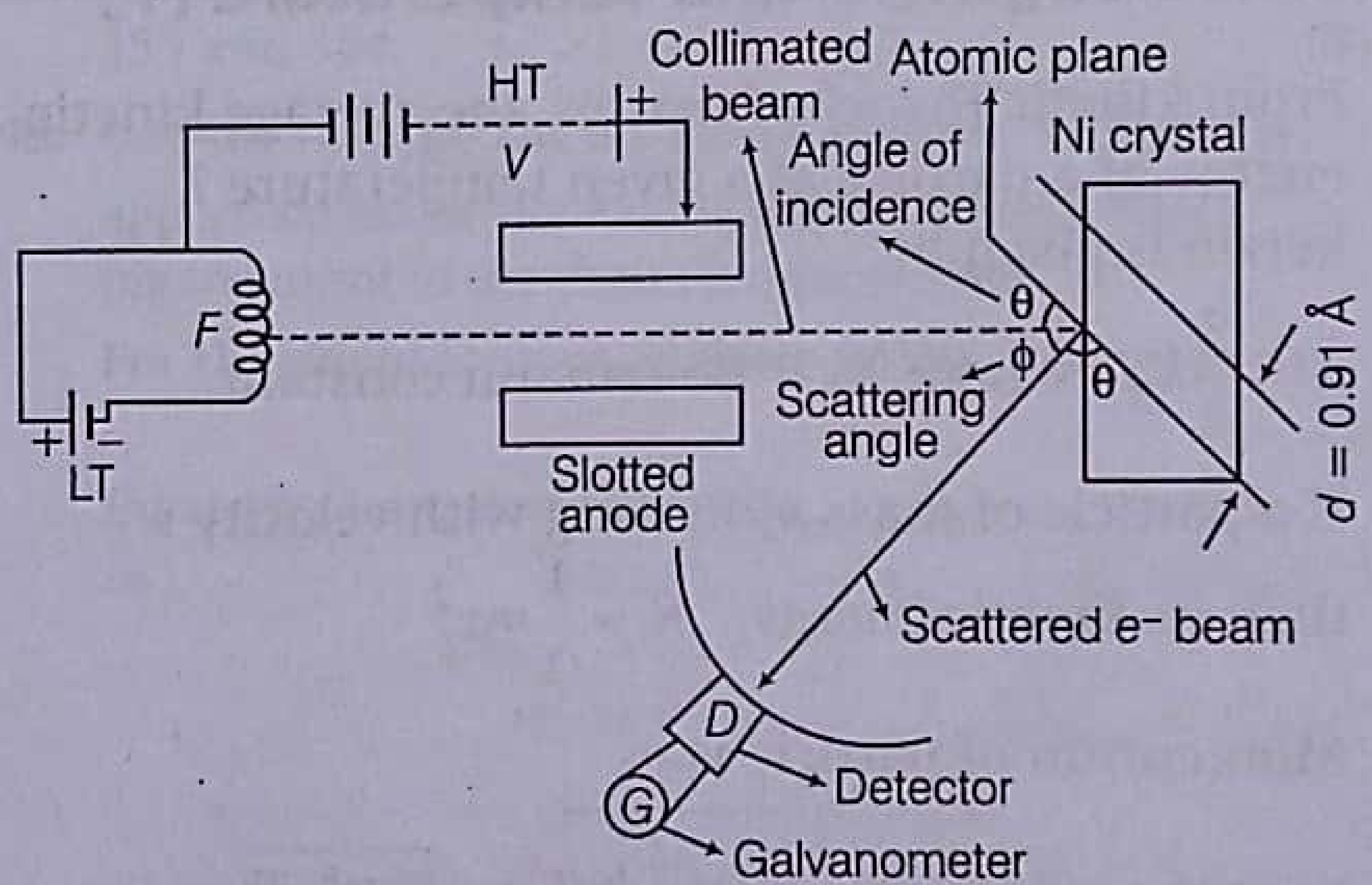
$$\lambda = \frac{h}{\sqrt{2eVm_e}}$$

where, m_e = mass of electron

or $\qquad \lambda = \dfrac{12.27}{\sqrt{V}}$ Å for electron beam.

Davisson-Germer Experiment

The wave nature of electron was verified by Davisson-Germer experiment in 1927. The experimental arrangement is shown in the figure.

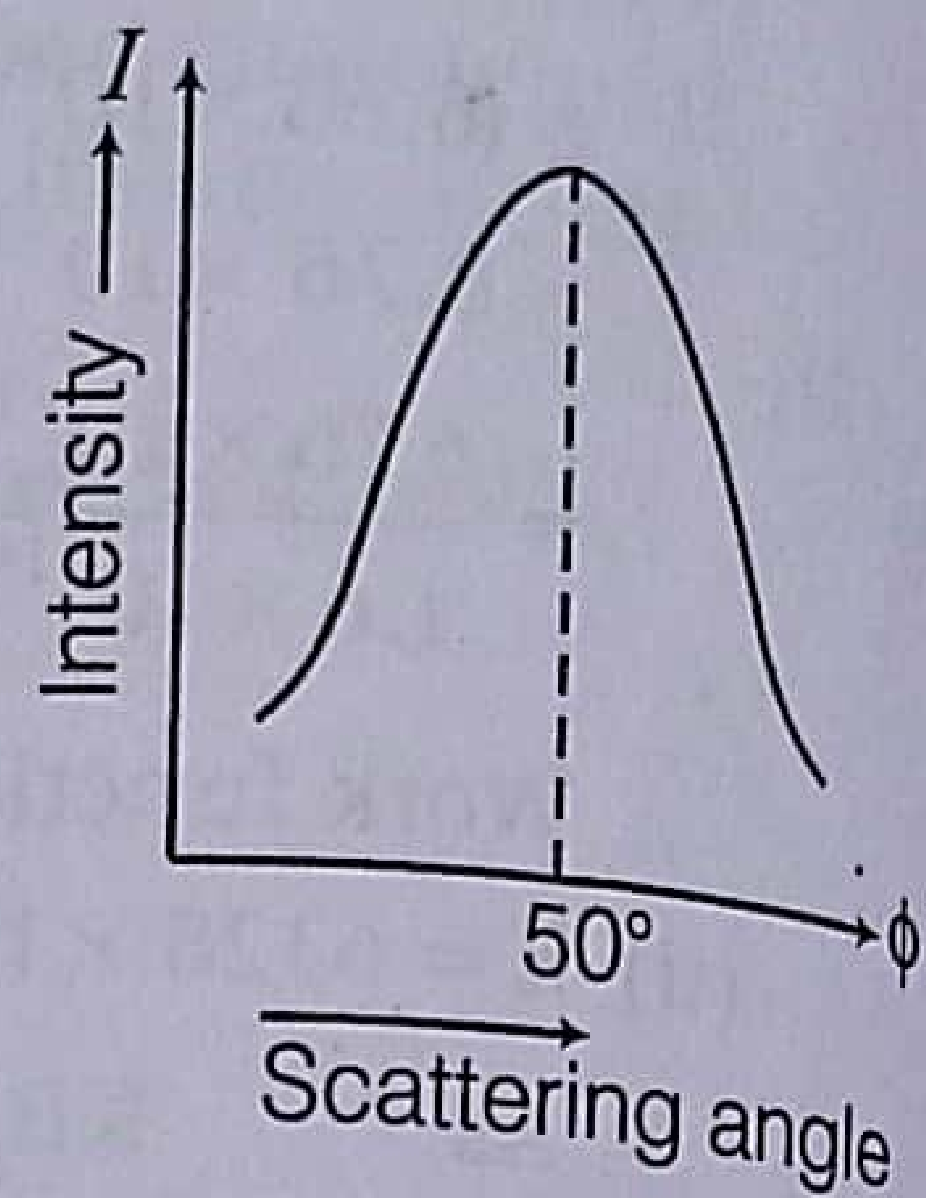


Experimental arrangement to demonstrate the wave nature of electron

It consists of an electron gun which comprises of a tungsten filament F coated with barium oxide and heated by a low voltage power supply. Electrons emitted by the filament are accelerated to a desired velocity by applying suitable potential from a high voltage power supply.

They are made to pass through a cylinder with free holes along its axis producing a fine collimated beam. The beam is made to fall on the surface of a nickel crystal. The electrons are scattered in all directions by the atoms of the crystal. A beam of electrons emitted by the electron gun is made to fall on nickel crystal cut along cubical axis at a particular angle.

The scattered beam of electrons is received by detector which can be rotated at any angle. The energy of the incident beam of electrons varied by changing the applied voltage to the electron.



Intensity of scattered beam of electrons is found to maximum when angle of scattering is 50° and accelerating potential is 54 V.

Here, $\theta + 50° + \theta = 180°$, i.e. $\theta = 65°$

For Ni crystal, lattice spacing $(d) = 0.91$ Å

For first principle maximum, $n = 1$

Electron's diffraction is similar to X-ray diffraction. According to Bragg's equation,

$$2d \sin\theta = n\lambda \quad \text{gives} \quad \lambda = 1.65 \text{ Å}$$

According to de-Broglie hypothesis,

$$\lambda = \frac{12.27}{\sqrt{V}} \text{ Å} = \frac{12.27}{\sqrt{54}} \text{ Å}$$

∴ de-Broglie wavelength of moving electron at $V = 54$ is 1.67Å which is in close agreement with 1.675 Å.

This proves the existence of de-Broglie waves for slow moving electrons.