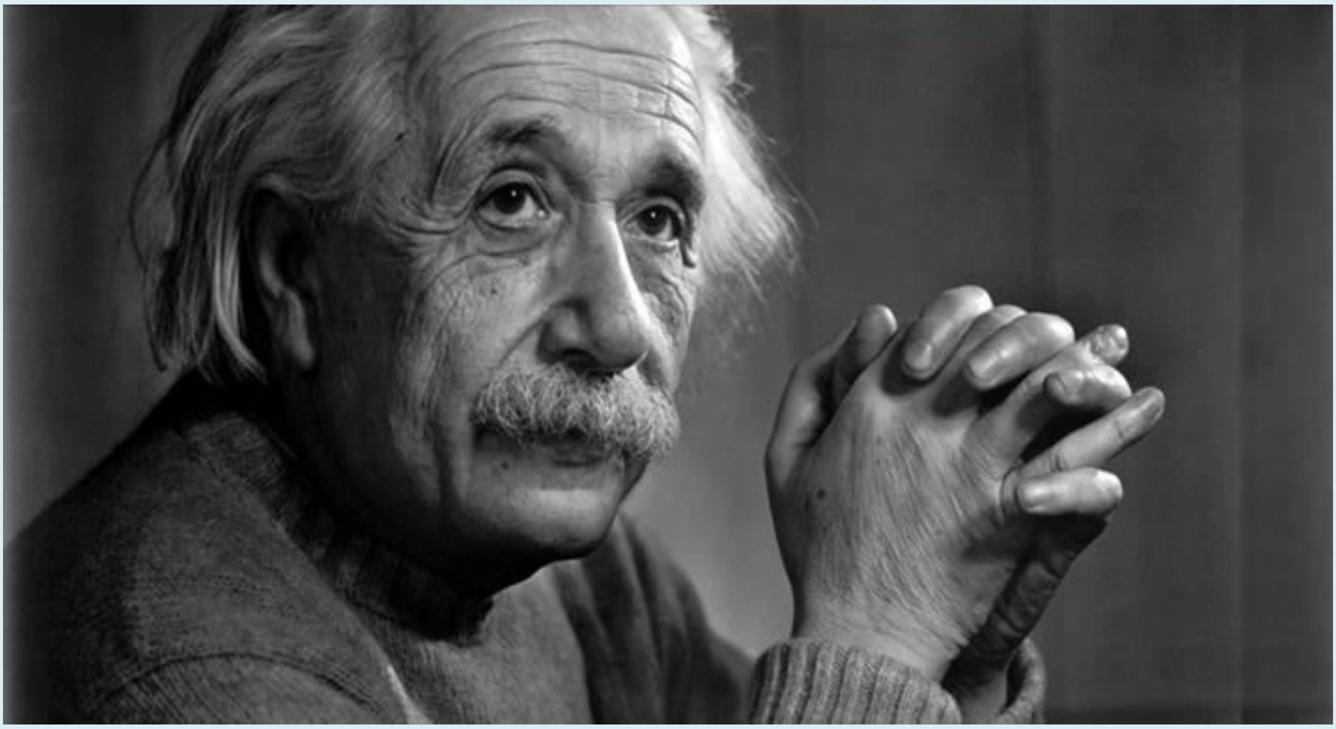
Chapter–11

# Dual Nature of Radiation and Matter



**CBSE CLASS XII NOTES**

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# 11. DUAL NATURE OF RADIATION AND MATTER

## ELECTRON EMISSION

Metals have free electrons (negatively charged particles) that are responsible for their conductivity. However, the free electrons cannot normally escape out of the metal surface. If they get sufficient energy electrons can escape out of the metal surface.

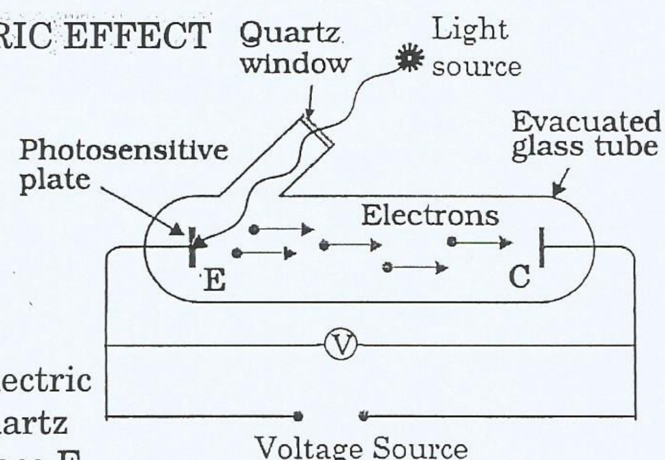
The minimum energy required by an electron to escape from the metal surface is called the ***work function*** of the metal. The work function depends on the properties of the metal and the nature of its surface. It is generally denoted by $\varphi_0$ and measured in eV (electron volt).

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

## PHOTO ELECTRIC EFFECT

The emission of electrons from a solid or liquid surface when it is subjected to electromagnetic radiation of suitable frequency is known as Photo-electric effect.

## EXPERIMENTAL STUDY OF PHOTO ELECTRIC EFFECT

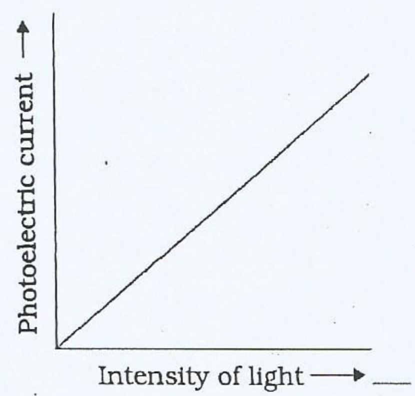



In 1887, Hertz discovered photoelectric effect while studying emission of electromagnetic waves by spark discharge. Hallwachs and Lenard investigated the phenomenon of photoelectric emission in detail.

The experimental arrangement to study photoelectric effect is shown. The ultraviolet rays entering quartz window are incident on the photo-sensitive surface E, known as cathode / emitter kept inside an evacuated glass tube. It emits the electrons (photoelectrons) and is collected by Collector plate C. Collector C can be kept at a positive or negative potential with respect to E. An ammeter is also included to measure photocurrent (the current produced by photoelectrons).

## OBSERVATIONS / RESULTS OF THE EXPERIMENT

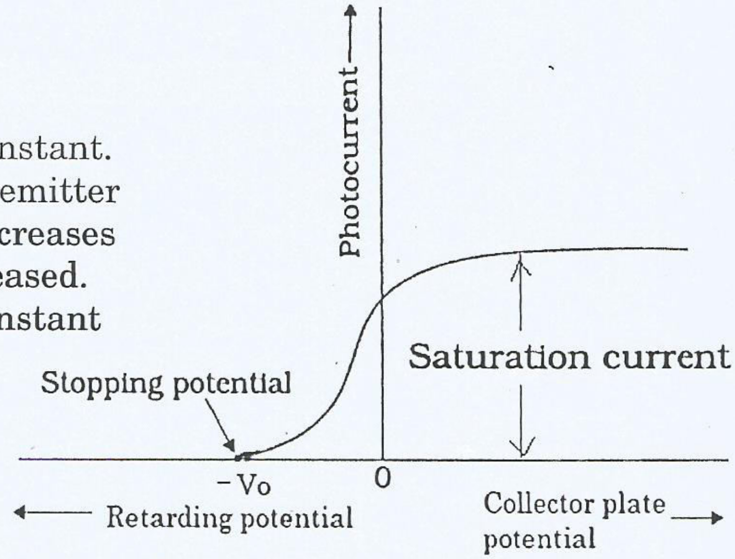
### Dependence of photo current on intensity of light




Collector C is made positive with respect to emitter E.
When frequency of light and accelerating potential (collector potential) are kept constant, photocurrent $\alpha$ intensity of light

## Dependence of photocurrent on potential

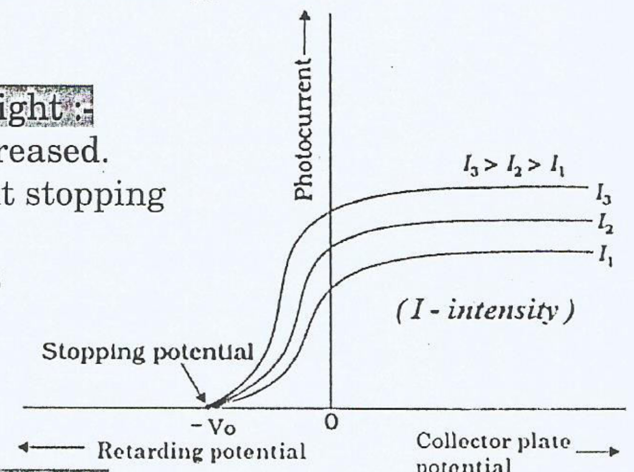
Frequency and intensity of light are kept constant.
Collector C is made positive with respect to emitter E (accelerating potential) :- Photocurrent increases initially when accelerating potential is increased. Soon it reaches a maximum and remains constant even when the voltage is increased.
This maximum of current is called saturation current. (Collector is able to collect all the electrons emitted by emitter)




Collector C is made negative with respect to emitter E (retarding potential) :- photoelectrons get repelled by collector and only energetic electrons are able to reach collector. Photocurrent decreases and finally becomes zero. The minimum retarding potential at which the photocurrent becomes zero is called cut-off potential or stopping potential (Vo).
Photoelectric current becomes zero when the retarding potential is sufficient to stop even the photoelectrons, with the maximum kinetic energy ($K_{max}$).
Therefore $\mathbf{K_{max} = e\,V_o}$

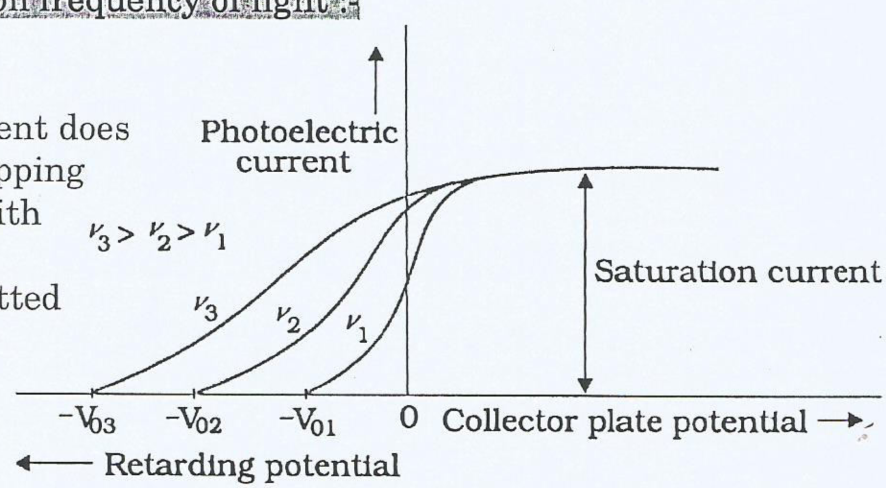
## Dependence of stopping potential on intensity of light :-

Keeping frequency constant, intensity of light increased.
Saturation photocurrent was found to increase but stopping potential remained the same.
This shows that energy of the emitted electrons is independent of the light intensity.

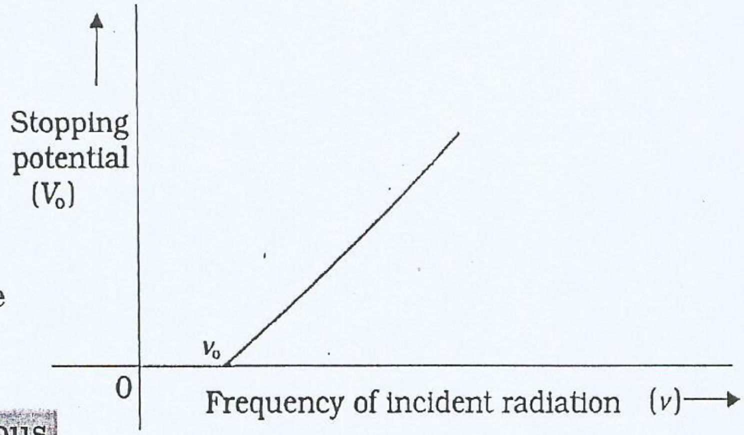



## Dependence of stopping potential on frequency of light :-

Intensity of light is kept constant but frequency is varied.
It is observed that saturation current does not change with frequency but stopping potential became more negative with increase in frequency.
The number of photoelectrons emitted per second does not depend on frequency but energy of emitted electrons is determined by the frequency of light.



Stopping potential increases linearly with frequency. Whatever is the intensity, the photoelectric emission begins only after a minimum frequency. The minimum cut-off frequency of the incident radiation below which no photoelectron emission takes place is called the *threshold frequency* ($\nu_0$).




Photoelectric emission is almost instantaneous.

## FAILURE OF WAVE THEORY OF LIGHT IN EXPLAINING OF PHOTO ELECTRIC EFFECT

According to wave theory, light is an electromagnetic wave consisting of electric and magnetic fields with continuous distribution of energy over the region of space over which the wave is extended and energy increases with increase in intensity (amplitude).

Free electrons present on the metal surface absorb energy continuously from the incident wave front. Since a large number of electrons absorb energy, the energy absorbed per electron per unit time is very small. So photo electric emission won't occur instantaneously, according to wave theory.

The greater the intensity of light, the greater should be the energy absorbed by each electron. So according to wave theory, the maximum kinetic energy of the photoelectrons must increase with increase in intensity which is against the observation

If the light is intense enough photo electric effect will occur irrespective of the frequency of light, which is against the observation.

## EINSTEIN'S EXPLANATION OF PHOTOELECTRIC EFFECT

According to Einstein :

(i) light consists of packets of energy known as quantum. (each quantum is called photon)

(ii) Each photon has an energy $\mathbf{E = h}\nu$ , where $\nu$ is the frequency of light.

(iii) Intensity of light is number of photons passing through unit area per second

(iv) Electron – photon interaction is one to one i.e. one photon can cause emission of one electron only.

Einstein's photo electric equation :- $K_{max} = h\nu - \phi_0$

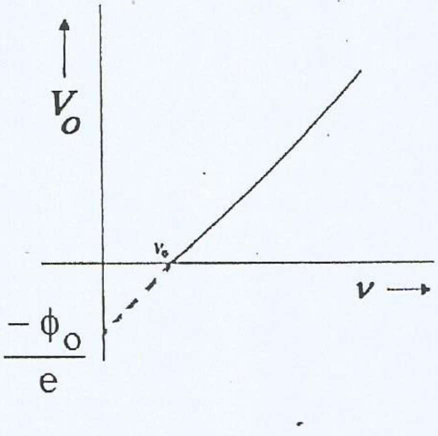
where $K_{max}$ – maximum kinetic energy of emitted electrons
$h\nu$ – is the energy of incident light
$\phi_0$ – work function of the metal

*When intensity of light increases more number of photons is incident on the metal and hence more electrons are emitted causing an increase in photocurrent.*

We have, $K_{max} = e V_o$ substituting this in Einstein's photo electric equation

$$e V_o = h\nu - \phi_0$$

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




*According to the above equation, stopping potential does not depend on the intensity of light but is directly proportional to the frequency of light.* So when frequency increases stopping potential also increases linearly as shown in the adjacent graph. Slope of the graph gives 'h/e' and intercept on y – axis gives $-\phi_0 / e$

But for photoemission to begin minimum energy $h\nu_0 = \phi_0$ should be given. Otherwise, as per the Einstein's *equation if* $h\nu < \phi_0$*, kinetic energy becomes negative, which is not possible.* Therefore, the minimum frequency required for photoemission is (*It happens when* $K_{max} = 0$)

Threshold frequency $\nu_0 = \dfrac{\phi_0}{h}$

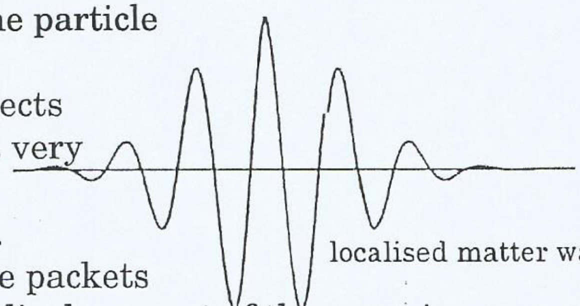
## WAVE NATURE OF MATTER

According to de Broglie, matter (particles) shows wave nature just like waves show particle properties.

de Broglie wavelength (wavelength associated with matter) $\boxed{\lambda = \dfrac{h}{p} = \dfrac{h}{m v}}$

h → Planck's constant　　p → momentum of the particle

m → mass of the particle　　v → velocity of the particle



localised matter wave

The matter waves associated with macroscopic objects are not noticeable because mass 'm' of the object is very large compared to the value of Planck's constant ($6.63\times 10^{-34}$ Js ). Hence 'λ' will be extremely small. Matter waves are represented using localized wave packets as shown in the adjacent figure. In regions where displacement of the wave is maximum probability of finding the particle is maximum.

Note : *A harmonic wave has a definite wavelength. So uncertainty in its wavelength $\Delta\lambda = 0$ and hence uncertainty in its momentum $\Delta p = 0$ , as per de Broglie's equation. If matter waves are represented by harmonic waves (sine / cosine function) the uncertainty in the position of the particle ($\Delta x$) becomes infinity as $\Delta p = 0$. For a particle $\Delta x$ can't be infinity. So matter waves are represented using wave packets which has $\Delta x \neq 0$.*

## de Broglie WAVELENGTH OF AN ELECTRON

An electron of mass 'm' and charge 'e' is accelerated by a potential 'V'. The kinetic energy of the electron $K = e V = \frac{1}{2} m v^2 = \frac{1}{2} (mv)^2 / m$

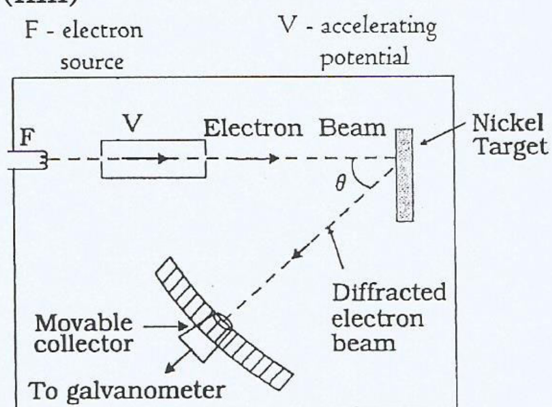
Or $mv = (2 m e V)^{1/2}$

From de Broglie equation $\lambda = h / mv$

$$\lambda = \frac{h}{\sqrt{2 m e V}}$$

Substituting the value of constants $\lambda = 1.227 / \sqrt{V}$ (nm)

## DAVISSON – GERMER EXPERIMENT




This experiment was performed to verify the wave nature of particles.

The electron beam is made to fall on the surface of a nickel crystal. The scattered electrons are detected using a detector connected to a galvanometer. Galvanometer deflection is proportional to the intensity of scattered electrons.

The variation of the intensity (*I*) of the scattered electrons with the angle of scattering $\theta$ is obtained for different accelerating voltages V.

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 54V at a scattering angle $\theta = 50^\circ$.*

*The appearance of the peak in a particular direction is due to the constructive interference of electrons scattered from different layers of the regularly spaced atoms of the crystals.* This interference effect shows that electron behaves like a wave.

From the electron diffraction measurements, the wavelength of matter waves was found to be 0.165 nm.

The de Broglie wavelength associated with electrons at an accelerating voltage of 54 V is $\lambda = 1.227 / \sqrt{V} = 1.227 / \sqrt{54} = 0.167$ nm

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