# 11. Dual nature of matter & Radiations

The discovery of phenomena like interference, diffraction and polarisation of light established that the light is of wave nature. The Maxwell's equations of electromagnetism and Hertz experiment on the production and detection of electromagnetic waves in 1886 strongly, supported the concept of wave nature of light.

In 20th century the discoveries of photoelectric effect by Hertz, Compton effect by compton were explained by quantum theory of light. According to which, the light consist of the packets of energy which travel in straight line, with the speed of light.

Each packet of energy is called photon ($h\nu$). Thus the particle nature of light was established.

## Free Electrons -

In metals, the electrons in the outer shells (Called valance electrons) of the atoms are loosely bound. They are free to move easily within the metal surface but can not leave the metal surface. such loosely bound electrons are called free electrons.

The free electrons are held inside the metal, by attractive force of the surface called restraining forces.

## Work Function ($\phi_0$) -

Work function of a metal is the minimum energy required by an electron to just escape from the metal surface so as to overcome the restraining foces at the surface.

Work function is represented by $\phi_0$ and measured in ev.

# Electron Emission -

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

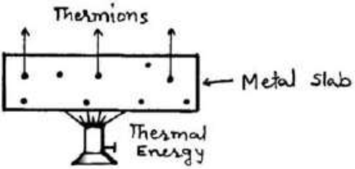
The electron emission from a metal surface is possible if the energy possessed by electrons is more than the work function of the metal.

The required energy for the electron emission from the metal surface can be supplied to the free electrons by one of the following physical processes.

## (i) Thermionic emission -

It is the phenomena of emission of electrons from the metal surface when heated suitably. The energy required for the emission of electrons from metal surface is being supplied by thermal energy.

The emitted electrons are called thermal electrons or thermions. The number of thermions emitted depends on the temperature of the metal surface.

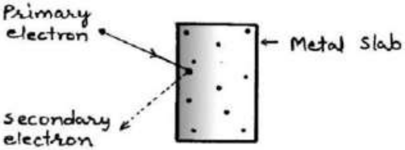



## (ii) Secondary Emission -

It is the phenomena of emission of electrons from the surface of metal in large number when fast moving electrons (primary electrons) strike the metal surface.

The fast moving electrons are high energy electrons. As they fall on metal surface, they transfer their energy to the free electrons of the metal by which their energy becomes more than the work function of the metal so they are emitted from the metal surface.

The electrons so emitted are called secondary electrons.

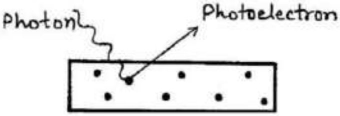



## (iii) Photoelectric Emission-

It is the phenomena of emission of electrons from the surface of metal when light radiation of suitable frequency fall on it.

Here the energy to the free electrons for their emission is being supplied by light photon. The emitted electrons are called photoelectrons.

The number of photo electrons emitted depends on the intensity of the incident light.




## (iv) Field Emission / Cold Cathode Emission-

It is the phenomena of emission of electrons from the metal surface under the application of a strong electric field.

When a very strong electric Field ($10^8\ Vm^{-1}$) is applied to metal, it emitts electrons.

## Photoelectric Effect

The emission of electrons from the surface of metals, when radiations of suitable frequency fall on them.

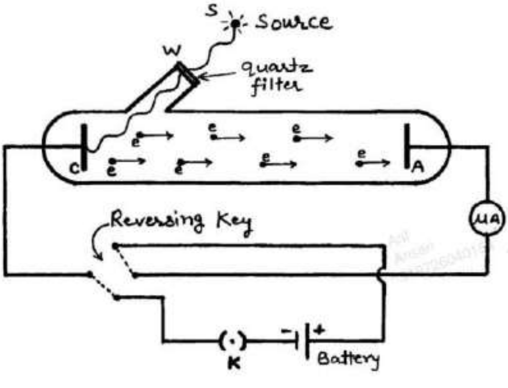
The emitted electrons are called photo-electrons and the current so produced is called photoelectric current.

## Experimental Study of Photoelectric Effect -

The apparatus consist of an evacuated glass or quartz tube which encloses a photosensitive plate C (called emitter) and a metal plate A (Called Collector).

A transparent window W is sealed on the glass tube which can be covered with a filter for a light of particular radiation. This will allow the light of particular wavelength to pass through it.

The plate A can be given a desired positive or negative potential with respect to plate C, using the arrangement as shown in figure.



**Working -**

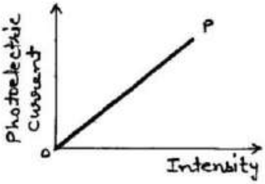
When a monochromatic radiations of suitable frequency obtained from source S, fall on the photosensitive plate C, the photoelectrons are emitted from C, which get accelerated towards the plate A (collector) if it is kept at positive potential.

These electrons flow in the outer circuit resulting in the photoelectric current. Due to it, the microammeter shows a deflection. The reading of microammeter measures the photoelectric current.

This experimental arrangement can be used to study the variation of photoelectric current with the following quantities.

## (i) Effect of Intensity of the incident radiation

By varying the intensity of the incident radiations, keeping the frequency constant, It is found that the photoelectric current varies linearly with the intensity of the incident radiation.



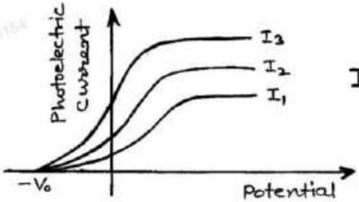

Also the number of photoelectrons emitted per second is directly proportional to the intensity of the incident radiations.

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

It is found that the photoelectric current increases gradually with the increase in positive potential of plate A.

At one stage for a certain positive potential of plate A, the photoelectric current becomes maximum or saturates. After this if we increase the positive potential of plate A, there will be no increase in the photoelectric current.

This maximum value of current is called Saturation current. The saturation current Corresponds to the state when all the photoelectrons emitted from C reach the plate A.




$I_3 > I_2 > I_1$

Now apply a negative potential on plate A w.r.t. plate C. We will note that the photoelectric current decreases, because the photoelectrons emitted from C are repelled and only energetic photoelectrons are reaching the plate A.

By increasing the negative potential of plate A, the photoelectric current decreases rapidly and becomes zero at a certain value of negative potential $V_0$ on plate A.

This maximum negative potential $V_0$, given to the plate A w.r.t. plate C at which the photoelectric current becomes zero is called stopping potential or cut off potential.

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

where $e$ = charge on electron, $m$ = mass of electron

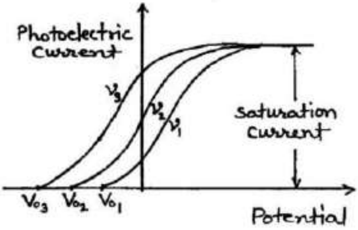
$V_{max}$ = maximum velocity of emitted photoelectron.

The value of stopping potential is independent of the intensity of the incident radiation. It means, the maximum Kinetic energy of emitted photoelectrons depends on the radiation source and nature of material of plate C but is independent of the intensity of incident radiation.

## (iii) Effect of frequency of the incident radiation -

When we take the radiations of different frequencies but of same intensity, then the value of stopping potential is different for radiation of different frequency.

The value of stopping potential is more negative for radiation of higher incident frequency. The value of saturation current depends on the intensity of incident radiation but is independent of the frequency of the incident radiation.

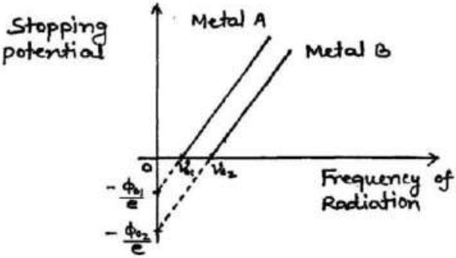



$\nu_3 > \nu_2 > \nu_1$

## (iv) Effect of frequency on stopping potential -

For a given photosensitive material, the stopping potential varies linearly with the frequency of the incident radiation.

For every photosensitive material, there is a certain minimum cut off frequency $\nu_0$ (threshold frequency) for which the stopping potential is zero.

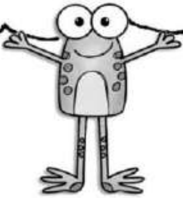



the intercept on the potential axis $= -\frac{\phi_0}{e} = -\frac{h\nu_0}{e}$

Hence work function $\phi_0 = e \times$ magnitude of intercept on the potential axis

**Note -** It is found that, if the incident radiation is of higher frequency than that of threshold frequency for which the emission of photoelectron is just possible, the photoelectric emission starts instantaneously, even if the incident light is very dim.

The time lag between the incidence of radiation and emission of photo-electrons is less than $10^{-9}$ sec



## Laws of Photo-electric emission -

(1) For a given metal and frequency of incident radiation, the number of photoelectrons ejected per second is directly proportional to the intensity of the incident light.

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

(3) Above the threshold frequency, the maximum Kinetic energy of the emitted photoelectron is independent of the intensity of the incident light but depends only upon the frequency of incident light.

(4) The photoelectron emission is an instantaneous process. The time lag between the incidence of radiations and emission of photoelectrons is very small, less than even $10^{-9}$ second.

**Q.** (CBSE 2013) The stopping potential in an experiment on photo-electric effect is 2V. What is the maximum Kinetic energy of the photoelectrons emitted.?

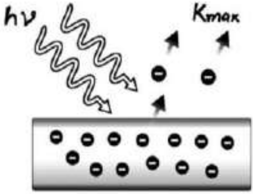
**Sol.** Given that $V_0 = 2V$

so Maximum Kinetic Energy $K_{max} = eV_0$

$$K_{max} = e \times 2 = 2 \text{ eV}.$$

# Einstein's Photoelectric Equation

According to the plank's quantum theory Light radiations consist of tiny packets of energy called photon.




Energy of Photon $E = h\nu$

$h$ = plank's constant
$\nu$ = frequency of light

Einstein assumed that one photoelectron is ejected from a metal Surface if one photon of suitable light radiation fall on it.

(i) A part of photon energy is used to free the electron from the metal surface which is equal to the work function ($\phi_0$) of the metal.

(ii) The rest of the energy of the photon is used in giving the maximum Kinetic energy $K_{max}$ to the emitted photoelectron.

Max. Kinetic Energy of photoelectron $K_{max} = \frac{1}{2} m v_{max}^2$

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

This equation is called Einstein's photoelectric equation

Also $\phi_0 = h\nu_0$ where $\nu_0$ is threshold frequency

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

If $V_0$ is the cut off potential or stopping potential and e is the charge on the electron, then

If $V_0$ is the cut off potential or stopping potential and $e$ is the charge on the electron, then

$$K_{max} = eV_0 \quad \text{— (2)}$$

If $\nu_0$ is the threshold frequency then

$$\text{work function } \phi_0 = h\nu_0 \quad \text{— (3)}$$

$$eV_0 = K_{max} = h\nu - h\nu_0$$

$$\boxed{eV_0 = h(\nu - \nu_0)}$$

Also
$$eV_0 = K_{max} = h\left(\frac{c}{\lambda} - \frac{c}{\lambda_0}\right)$$

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

YOU ARE
SO CLOSE
TO THE
VICTORY,
DON'T YOU
DARE GIVE
UP NOW.

# Important Graphs of Photoelectric Effect-

## (i) Frequency ($\nu$) and Stopping Potential ($V_0$) graph

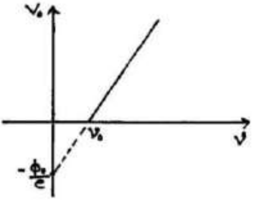
As we know $\quad eV_0 = h\nu - \phi_0$

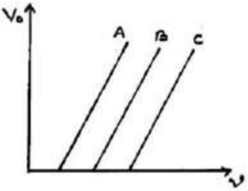
or $\quad V_0 = \frac{h}{e}\nu - \frac{\phi_0}{e}$

so $\quad V_0 \propto \nu$

Therefore $\nu - V_0$ graph is a straight line.

* Comparing the above relation with $y = mx + c$, we note that the slope of $\nu - V_0$ graph is $h/e$. The x-intercept is $\nu_0$ and the y-intercept is $-\phi_0/e$.

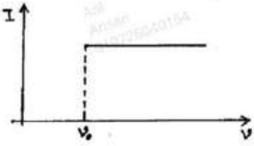



* Frequency ($\nu$) and stopping potential ($V_0$) graphs for different materials will be represented by parallel straight lines, because the slope of each straight line is $h/e$ (constant) but the threshold frequency for different materials is different.

## (ii) Frequency ($\nu$) and photoelectric current graph

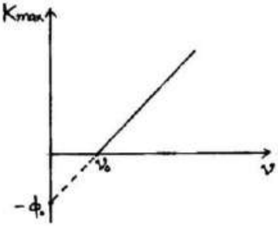
The graph shows that the photoelectric current is independent of frequency of the incident light, till intensity remains constant.



## (iii) Frequency ($\nu$) and maximum Kinetic energy graph

As $\quad K_{max} = h\nu - \phi_0$

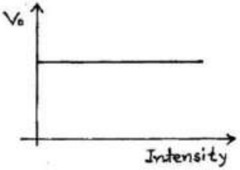
so $\quad K_{max} \propto \nu$




The $\nu - K_{max}$ graph is a straight line. Comparing the above relation with $y = mx + c$, we note that slope of $\nu - K_{max}$ graph is $h$, $x$-intercept is $\nu_0$ and $y$-intercept is $\phi_0$.

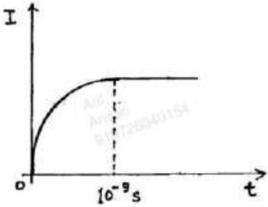
## (iv) Intensity and stopping potential graph

This graph shows that the magnitude of the stopping potential is independent of the intensity of the incident radiation, till the frequency of the radiation remains constant.




## (v) Time and photoelectric Current graph

This graph shows that the photoelectric current attains the saturation value in $10^{-9}$ sec. from the start of radiation falling on photosensitive material, irrespective of the intensity of incident light.



## Particle Nature of Light (Photon)

(1) In interaction of radiation with matter, radiation behaves as it is made of particles like photons.

(2) Each photon has energy $E \left(= h\nu = hc/\lambda\right)$ and momentum $p \left(= \frac{h\nu}{c} = \frac{h}{\lambda}\right)$.

(3) Irrespective of the intensity of radiation, all the photons of a particular frequency $\nu$ or wavelength $\lambda$ have the same energy $E \,(= h\nu)$ and the same momentum.

(4) By increasing the intensity of radiation of a given frequency or wavelength on a metal surface, there is only increase in the number of photons per second falling on that surface, while each photon is having the same energy.

(5) All the photons emitted from a source of light travel through space with the same speed which is equal to the speed of light.

(6) The frequency of photon which shows a definite energy (or color), does not change when photon travels through different media.

(7) The velocity of photon in different media is different which is due to change in its wavelength.

(8) Photons are not deflected by electric and magnetic fields. Hence photons are electrically neutral.

(9) The rest mass of a photon is zero.

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 -

$$\boxed{m = \frac{m_0}{\sqrt{1 - v^2/c^2}} \quad \text{or} \quad m_0 = m\sqrt{1 - v^2/c^2}}$$

## Failure of Wave Theory of Light to explain photoelectric Effect -

Huygen's wave theory of light could not explain the photoelectric emission due to the given reasons.

(1) According to wave theory of light, if the intensity of light is increased, there will be increase in amplitude of waves and hence energy carried by waves will increase.

When beam of light falls on a metal surface, the energy carried by light is distributed uniformly over the entire surface of metal. All the free electrons present in the surface of metal will receive the light energy and they will be ejected out of metal surface.

When the waves of light of higher intensity falls on a metal surface it will impart more energy to the electrons in metal. Due to which the Kinetic energy of the ejected electrons will increase.

This is against the experimental facts that the maximum Kinetic energy of the ejected photoelectrons is independent of the intensity of incident light.

(2) According to the wave theory, by increasing the intensity of the incident wave of light, the energy can be increased and photoelectric emission will take place even if the frequency of the incident light is less than threshold frequency.

But it is against the experimental fact that no photoelectric emission takes place from a metal surface if the frequency of the incident light is less than the threshold frequency, no matter whatever be the intensity.

(3) When the wave of light falls on a metal surface, the energy of the wave of light will not go to a particular electron in metal but will be distributed to all the electrons present in the illuminated portion of metal surface. As a result of which the electrons will take some time in accumulating the energy required for their emission from metal surface.

This is also against the experimental fact that the emission of photoelectrons takes place immediately after the light is incident on the metal.

## Dual Nature of Radiation -

The radiation sometimes behaves as a wave and sometimes as a particle, hence radiation has dual nature. In a particular experiment, the radiation has a particular nature (Wave nature or Particle nature)

The various phenomena related to radiation can be devided into three categories:

(1) The phenomena like interference, diffraction and polarisation etc. can be explained on the basis of electromagnetic (wave) nature of radiation only.

(2) The phenomena like photoelectric effect, compton effect etc. Can be explained on the basis of quantum (particle) nature of radiation.

(3) The phenomena like rectilinear propagation, reflection, refraction etc. can be explained on the basis of either of the wave nature or of the particle nature of radiation.

## De-Broglie Dualistic Hypothesis

According to de-Broglie a moving material particle sometimes act as a wave and sometimes as a particle or a wave is associated with moving particle. The wave associated with moving particle is called matter wave or de-Broglie wave whose wavelength called de-Broglie wavelength is given by.

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

## Derivation of de-Broglie wavelength -

According to Plank's quantum theory, the energy of a photon of a radiation of frequency $\nu$ and wavelength $\lambda$ is -

$$E = h\nu \qquad —①$$

If photon is considered to be a particle of mass m, then according to Einstein mass-energy relation, the energy associated with it is given by -

$$E = mc^2 \qquad — ②$$

From eq. ① and ② we get -

$$h\nu = mc^2 \qquad \text{or} \qquad mc = \frac{h\nu}{c}$$

Momentum of Photon P = mass x velocity = mc

$$P = \frac{h\nu}{c} = \frac{h}{\lambda} \qquad \left(\nu = \frac{h}{\lambda}\right)$$

or $$\boxed{\lambda = \frac{h}{P} = \frac{h}{mv}}$$

De-Broglie assumed that the above equation is equally applicable to both the photon of radiation and other material particle.

## De-Broglie wavelength of a charge particle

Lets consider a charge particle of charge $q$ having mass $m$ is accelerated by potential difference $V$, then

Kinetic energy of the charge particle is

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

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

Momentum of the charge particle $p = mv$

or $$p = \sqrt{2mqV}$$

The wavelength associated with moving particle is given by

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

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

## De-Broglie Wavelength of an Electron

If $\lambda$ is the de-Broglie wavelength associated with the electron, then -

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

By substituting the values of $m$, $e$ and $h$ we get -

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9 \times 10^{-31} \times 1.6 \times 10^{-19} \times V}} = \frac{12.27}{\sqrt{V}} \times 10^{-10}\ m$$

$$\boxed{\lambda = \frac{12.27}{\sqrt{V}}\ \mathring{A}}$$