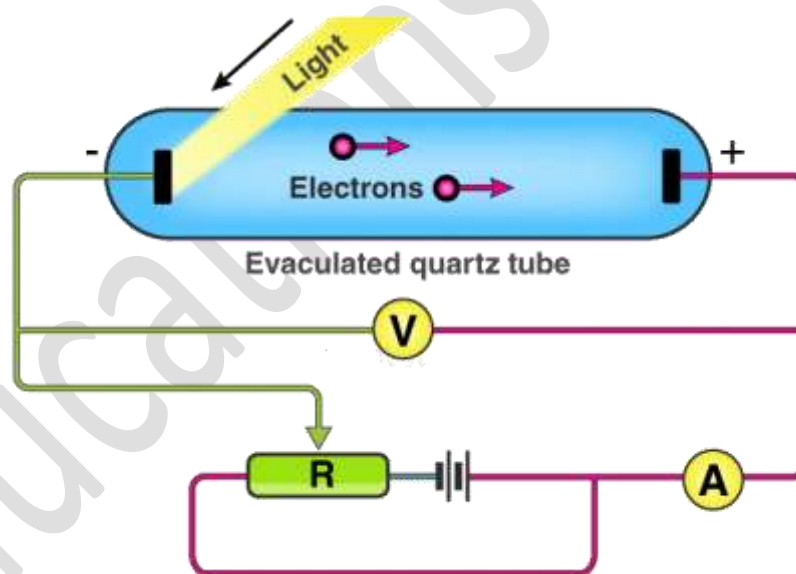




# CHAPTER - 11 DUAL NATURE OF RADIATION AND MATTER

Physics



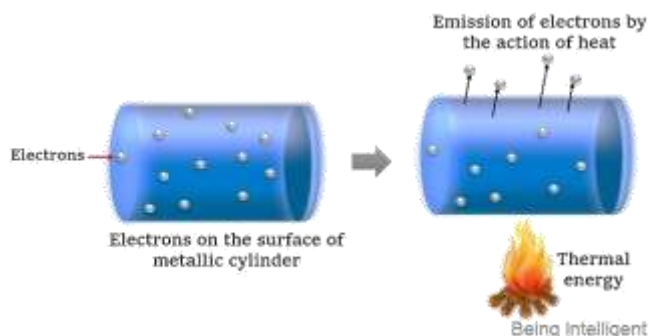
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## Chapter – 11

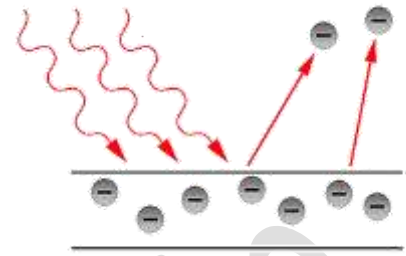
### Dual Nature of Radiation and Matter

(a) **Dual Nature of Radiation:** - The dual nature of radiation refers to the phenomenon where electromagnetic radiation exhibits both wave-like and particle-like characteristics.

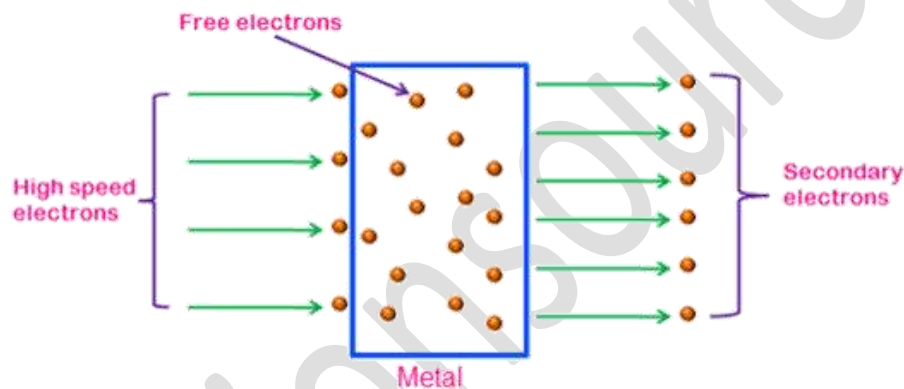
- **Free electrons:** - The electrons in the outermost orbit of an atom are loosely bound and can move freely in all possible directions within the metal even at room temperature.
- **Surface Barrier:** - It is the attracting force which is produced by positive charge pull back the electron or prevent the emissions of electron.
- **Work function ( $\phi_0$ ):** - The minimum energy required by the free electron to just leave the metal surface is known as the work function of the metal.
- The work function of a metal depends upon the properties of the metal, nature of the surface and impurities etc. Work function is denoted by  $\phi_0$  and can be measured in electron volt (eV) ( $1\text{eV} = 1.6 \times 10^{-19}\text{C} \times 1\text{V} = 1.6 \times 10^{-19}\text{J}$ ).
- **Electron Emission:** - Electron emission refers to the release or liberation of electrons from a material. This phenomenon can occur through various mechanisms, and electron emissions are categorized into different types based on the processes involved.
  - **Thermionic emission:** The process of emission of electrons when a metal is heated, is known as thermionic emission. The free electrons in the metal absorb the heat energy and can overcome the surface barrier. As a result, the free electrons are emitted from the metal surface. The electrons emitted in this way are known as thermions because they are emitted due to thermal energy.



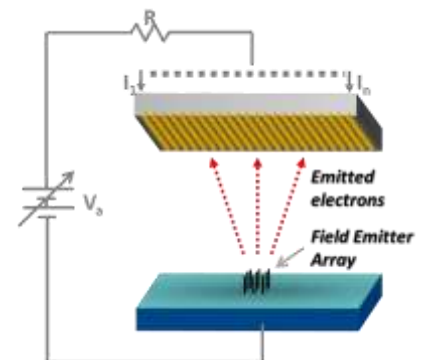
- **Photo-electric emission:** The process of emission of electrons when light of suitable frequency is incident on a metal surface is known as photo-electric emission. The free electrons in the metal absorb the energy of the incident light and cross the surface barrier. Hence, the free electrons are emitted from the metal surface.



- **Secondary emission:** The process of emission of free electrons when highly energetic electron beam is incident on a metal surface is called secondary emission. The electrons emitted so are known as secondary electrons.



- **Field emission:** The process of emission of free electrons when a strong electric field ( $=10^8$  V/m) is applied across the metal surface is known as field emission. This type of emission is also known as cold emission or cold cathode emission.



### (b) Hertz Observation: -

Heinrich Hertz's investigations into the interaction between electromagnetic radiation and matter, specifically the phenomenon of photoemission.

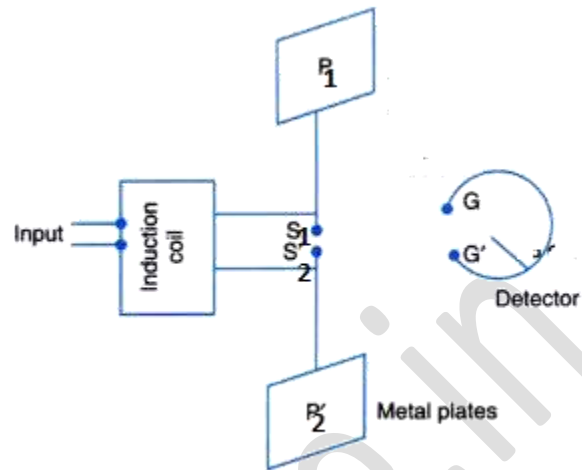
#### 1. Setup:

- Hertz used a detector or receiver made of a wire bent into a circle with metallic spheres, denoted as **G** and **G'** on each end.
- A small gap was maintained between these spheres (**G,G'**).

- Electromagnetic radiation was produced using an induction coil, plates  $P_1$  and  $P_2$ , and metallic spheres  $S_1$  and  $S_2$  attached to plates  $P_1$  and  $P_2$ .

## 2. Generation of Electromagnetic Radiation:

- Plates  $P_1$  and  $P_2$ , along with metallic spheres  $S_1$  and  $S_2$ , played a role in generating electromagnetic radiation when acted upon by the induction coil.
- The changing electric fields associated with the oscillating charges generated electromagnetic waves.



## 3. Detection of Electromagnetic Radiation:

- The wire loop with metallic spheres ( $G', G$ ) acted as a detector for the induced electromagnetic radiation.
- When electromagnetic radiation fell on the detector, it induced a potential difference across the gap ( $G', G$ ).

## 4. Observation under Ultraviolet Light:

- Hertz observed that sparks across the gap ( $G', G$ ) jumped more readily when the detector was exposed to ultraviolet light from an arc lamp.
- The increased spark activity indicated that the ultraviolet light was facilitating the emission of electrons from the metallic spheres ( $S_1$  and  $S_2$ ).

## 5. Conclusion:

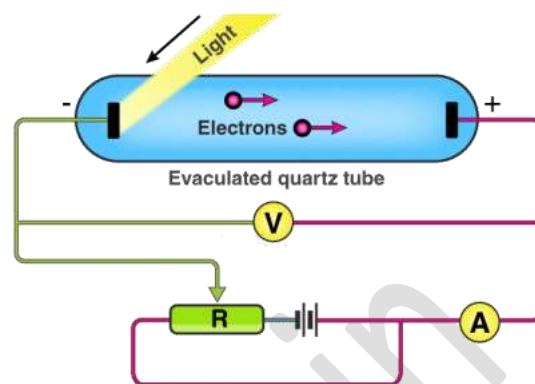
- Based on his observations, Hertz concluded that light, especially ultraviolet light, played a crucial role in facilitating the emission of electrons from the metallic spheres.
- This experiment provided early evidence for the photoelectric effect, where light induces the emission of electrons from a material.

It's important to note that while Hertz made significant contributions to understanding electromagnetic waves and their interactions with matter, it was Albert Einstein who later provided a theoretical explanation for the photoelectric effect in 1905, as mentioned in the previous response.

## (c) Photo Electric emissions by Hallwachs's and Lenard's observations: -

During the period between 1886 and 1902, Wilhelm Hallwachs and Philipp Lenard conducted an extensive study on the photoelectric effect. Lenard observed that when a potential difference was applied across two metal plates enclosed in an evacuated tube, there was no current flow in the circuit. However, when one plate, known as the emitter

plate, was enclosed in the evacuated tube and kept at a negative potential, exposure to ultraviolet radiation resulted in the initiation of current flow in the circuit. The current ceased when ultraviolet radiation was no longer incident on the emitter plate. This led Hallwachs to conclude that negatively charged particles were ejected from the zinc plate under the influence of ultraviolet radiation.



Following the discovery of the electron in 1897, it became clear that the exposure of the emitter plate to incident light caused the emission of electrons. Due to their negative charge, these emitted electrons were propelled towards the collector plate by the applied electric field. Hallwachs and Lenard further observed that when ultraviolet light fell on the emitter plate, no electrons were emitted at frequencies below a certain minimum value known as the threshold frequency. This minimum frequency depended on the nature of the material composing the emitter plate.

**Observation:** No electrons emitted when ultraviolet light frequency was below a certain threshold frequency.

**Threshold frequency:** The minimum frequency of incident light required to emit electrons from a metal surface is known threshold frequency.

**Conclusion:** Electrons are emitted only if incident light frequency exceeds the threshold frequency.

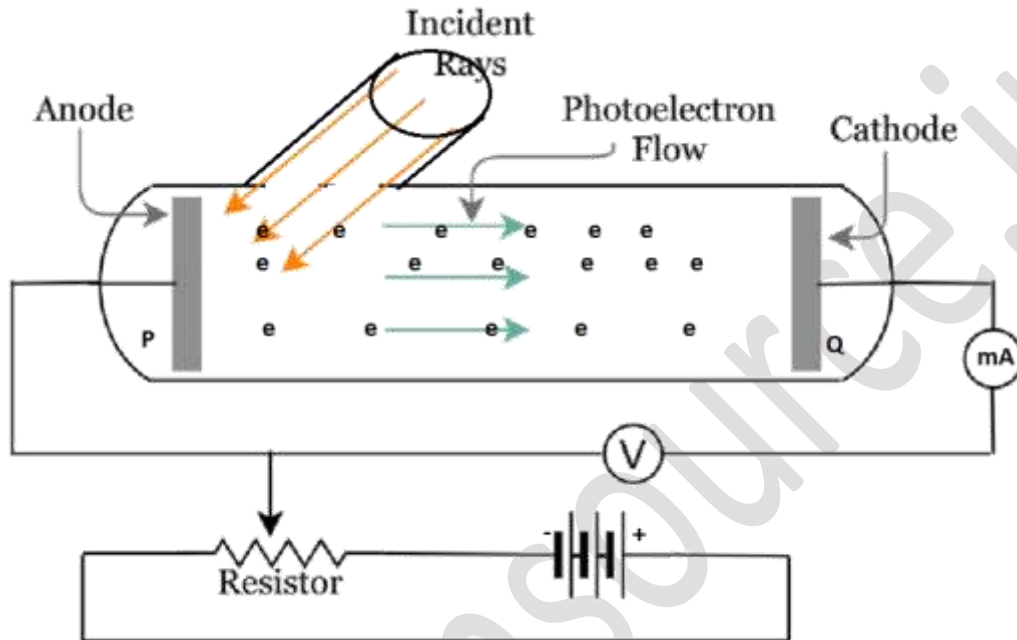
**Photoelectrons:** Electrons emitted from the metal surface due to incident light.

**Photoelectric current:** Electric current constituted by photoelectrons.

**(d) Experimental Study of Photoelectric effect: -**

- In the given set up, when light radiations of suitable frequency fall on plate P, photoelectrons are emitted from P.
- If plate Q is at zero potential w.r.t. P, then very small current flows in the circuit because only some electrons of high kinetic energy are reaching to plate Q.
- If plate Q is kept at positive potential w.r.t. P, then current starts flowing through the circuit because more electrons are able to reach upto plate Q.

- As the positive potential of plate **Q** increases, current through the circuit increases but after sometime constant current flows through the circuit even, if positive potential of plate **Q** is still increasing because at this condition, all the electrons emitted from plate **P** are able to reach upto plate **Q**. This constant current is called **saturation current**.

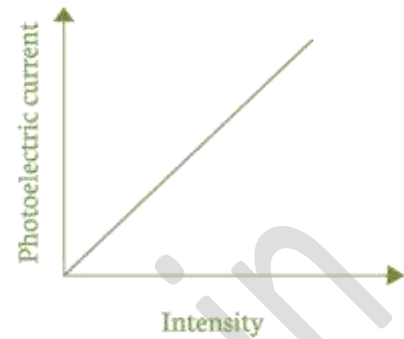


- To increase the photoelectric current further, we will have to increase the intensity of incident light. To decrease the photoelectric current, plate **Q** is maintained at negative potential w.r.t. **P**. As the anode **Q** is made more and more negative, fewer electrons will reach the cathode and the photoelectric current decreases.
- At a particular negative potential of plate **P**, no electron will reach the plate **Q** and the current will become zero. This negative potential is called **stopping potential**, denoted by  $V_0$ . Obviously, the kinetic energy of fastest electron as it reaches the anode is zero, i.e.,  $eV_0 = K_{\max}$

**(a) Effect of intensity of incident light on the photoelectric current: -**

The photoelectric effect is a phenomenon where electrons are emitted from a material when it is exposed to light. The number of electrons is emitted from the material depends upon the intensity of incident light. The intensity of the incident light refers to the amount of light energy per unit area falling on the material.

- 1. Increasing Intensity:** Higher intensity light means more photons are striking the material per unit time and area. This leads to a greater number of photoelectrons being emitted, thereby increasing the photoelectric current.
- 2. Decreasing Intensity:** Lower intensity light results in fewer photons hitting the material, reducing the number of emitted photoelectrons and consequently decreasing the photoelectric current.



This shows that the **photoelectric current  $\propto$  Intensity of incident light.**

**(b) Effect of potential on photoelectric current: -**

When light of suitable frequency (**greater than the threshold frequency**) falls on the photo sensitive electron photoelectrons are emitted. These electrons get accelerated towards the electrode which is at positive potential w.r.t. the photosensitive electrode and give the current called photoelectric current. fixed frequency and fixed intensity of incident light, this photoelectric current increases with the increase in applied positive potential on collector plate.

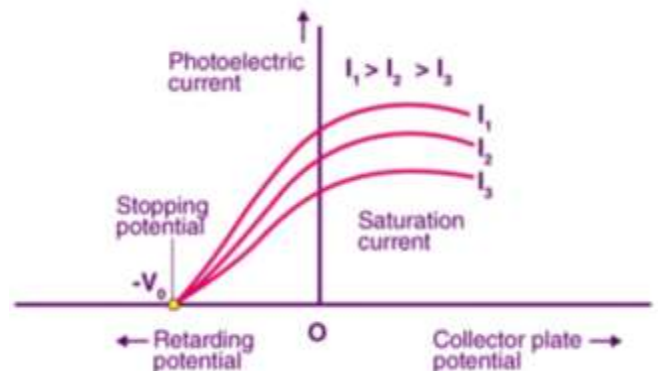
When all the photoelectrons emitted by electrode reach Collector plate, the photoelectric current has the maximum value. This maximum current is **known as saturation Current**. Saturation current will not increase with the increase in positive potential because number of photoelectrons emitted is equal to the number of photoelectrons reaching the collector plate. Now the potential on collector plate is decreased such that it attains negative potential with respect to electrode The negative potential applied to collector plate is increased to a certain value  $V_o$ , for which no photoelectrons reach the collector plate. Thus, at this potential, photoelectric current is zero.

The minimum negative potential ( $V_o$ ) applied to the collector plate for which photoelectric current becomes zero is called **cut off potential or stopping potential**.

*The maximum kinetic energy  $\frac{1}{2}mv_{max}^2$  of photo electron must equal to the energy acquired by an electron passing through a potential difference  $V_o$ .*

$$\frac{1}{2}mv_{max}^2 = eV_o$$

$$\text{K.E.}_{max} \propto V_o$$



- (i) Saturation current depends upon the intensity of the incident radiation.
- (ii) For a given beam of incident radiation, the intensity of incident radiation does not affect the stopping potential.
- (iii) Emitted photoelectrons may have different kinetic energies. Maximum kinetic energy of emitted photoelectrons does not depend upon intensity of incident radiation.

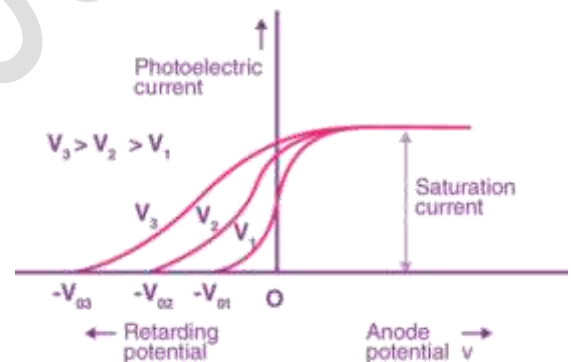
### (c) Effect of frequency of incident light

The intensity of incident light is kept constant but the frequency of incident light is changed so that in each case the saturation current is exactly the same.

Now for a given frequency ( $\nu_1$ ) of the incident light, the positive potential at collector plate is decreased to zero. It is found that the photo-electric current decreases. Now, the collector plate negative potential which is increased till the photoelectric current becomes zero. Let this value of negative potential be  $V_{01}$ .

The experiment is repeated with the incident light of same intensity but of different frequency ( $\nu_2 > \nu_1$ ). It is found that now, the stopping potential is higher than  $V_{01}$  than  $V_{02}$ .

- (i) We find that the value of stopping potential depends upon the frequency of the incident light.
- (ii) The value of saturation current does not depend upon the frequency of the incident radiation.



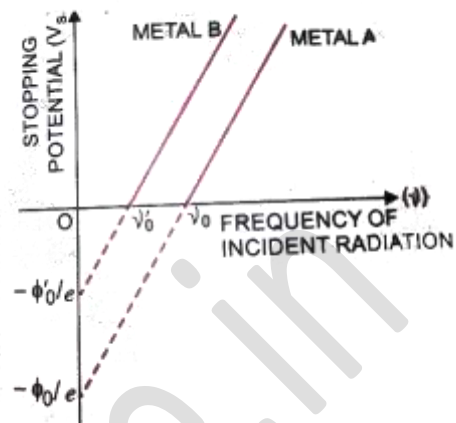
### (e) Graph between frequency and stopping potential: -

#### 1. Threshold Frequency ( $\nu_0$ ):

- There is a minimum frequency known as the threshold frequency ( $\nu_0$ ) or cutoff frequency.
- Below this threshold frequency, no photoemission occurs, even if the intensity of the incident radiation is high.
- The threshold frequency varies for different materials and depends on the nature of the substance emitting the photoelectrons.
- Materials with higher work functions have higher threshold frequencies.

## 2. Stopping Potential ( $V_0$ ):

- Stopping potential ( $V_0$ ) is the potential required to stop the emission of photoelectrons.
- The graph shows that there is a non-zero stopping potential even when the incident frequency is at the threshold frequency ( $\nu_0$ ).
- This implies that no photoemission occurs below the threshold frequency, but once the threshold is reached, photoelectrons are emitted with kinetic energy, resulting in a non-zero stopping potential.



## 3. Linear Relationship:

- The graph between the stopping potential ( $V_0$ ) and the incident frequency shows a straight line.
- This linear relationship indicates that the stopping potential varies linearly with the incident radiation frequency.
- The greatest kinetic energy of photoelectrons is directly proportional to the incident radiation frequency, regardless of its intensity.

## 4. Different Materials (Metals A and B):

- The graph in Figure represents two different materials, A and B.
- The linear relationship between stopping potential and incident frequency differs for these materials.
- The specific nature of the material affects how stopping potential varies with incident frequency.

## (f) Laws of Photoelectric Emission: -

### 1. Direct Proportionality to Intensity:

- The photoelectric current or the number of photoelectrons ejected per second is directly proportional to the intensity of the incident light.
- This law indicates that increasing the intensity of the incident light leads to a proportional increase in the photoelectric current.

### 2. Saturation Current and Stopping Potential:

- For a given material and frequency of incident radiation, the saturation current is found to be proportional to the intensity of incident radiation.

- However, the stopping potential (the potential required to stop the emission of photoelectrons) is independent of the intensity of the incident light.

### 3. Threshold Frequency:

- For a given material, there exists a minimum frequency of incident radiation below which no emission of photoelectrons occurs.
- This minimum frequency is known as the threshold frequency. Photoelectric emission only happens when the incident frequency is equal to or greater than this threshold frequency.

### 4. Independence of Maximum Kinetic Energy on Intensity:

- Above the threshold frequency, the maximum kinetic energy of the emitted photoelectrons (or the equivalent stopping potential) is independent of the intensity of the incident light.
- This implies that while increasing the intensity may increase the number of photoelectrons emitted, it does not affect their individual kinetic energies.

### 5. Instantaneous Process:

- The photoelectric emission is described as an instantaneous process. There is a very small-time lag, less than  $10^{(-9)}$  seconds, between the incidence of radiation and the emission of photoelectrons.
- This suggests that photoelectrons are emitted promptly upon exposure to incident radiation, supporting the particle-like nature of light.

## (g) Photo electric effect and Wave Nature of the light: -

### 1. Intensity and Kinetic Energy:

- According to the wave theory of light, the electric field component of light increases with the intensity of the light.
- If the photoelectric effect were to follow wave theory, the kinetic energy acquired by photoelectrons should increase with the intensity of incident light.
- However, the observed photoelectric effect contradicts this, as the maximum kinetic energy of photoelectrons remains the same for different intensities of light.

### 2. Threshold Frequency:

- Wave theory suggests that electrons should be emitted from a metal surface when exposed to intense light, without any specific requirement for a minimum or threshold frequency.

- The photoelectric effect, on the other hand, clearly shows that photoemission occurs only when the frequency of the incident light is equal to or greater than a specific threshold frequency.

### 3. Time Delay:

- In wave theory, energy is distributed uniformly over the wavefronts of incident light. This implies that each electron would need time to accumulate enough energy to be emitted.
- However, the photoelectric effect is an instantaneous process, where electrons are emitted as soon as light falls on the metal surface, without any significant time delay.

In summary, the wave theory of light, which treats light as a continuous wave, fails to explain the photoelectric effect's fundamental aspects, such as the threshold frequency requirement, the independence of kinetic energy on intensity, and the instantaneous nature of photoelectron emission.

#### (h) Einstein's photoelectric equation: -

As per Einstein, an incident photon energy  $h\nu$  ejects electron from a metal having work function,  $\phi_0 = h\nu_0$  and imparts kinetic energy,  $K.E. = \frac{1}{2}mv^2$  to it.

#### (a) Energy Distribution of Incident Photon:

- According to Einstein, light is composed of discrete packets of energy called photons or quanta.
- The energy ( $E$ ) of each photon is given by Planck's equation:  $E = h\nu$ , where  $h$  is Planck's constant and  $\nu$  is the frequency of the incident light.

#### (b) Photon Interaction with Metal Surface:

- When a photon with energy  $h\nu$  falls on a metal surface, Einstein proposed that the energy of the photon is utilized in two ways:
  - Part of the energy is used by an electron to overcome the surface barrier and come out of the metal. This portion of energy is equal to the work function ( $\phi_0$ ) of the metal.
  - The remaining energy imparts velocity to the emitted photoelectron, contributing to its kinetic energy, which is given by  $K.E. = \frac{1}{2}mv^2$

**(c) Law of Conservation of Energy:**

- The law of conservation of energy, the energy of the incident photon ( $h\nu$ ) is equal to the sum of the work function and the kinetic energy of the emitted electron.
- Mathematically,  $h\nu = \varphi_0 + \frac{1}{2}mv^2$  .....(1)

**(d) Threshold Frequency Condition:**

- If the frequency ( $\nu$ ) of the incident light is just equal to the threshold frequency ( $\nu_0$ ), the emitted photoelectron will have zero kinetic energy.
- In this case, the equation becomes  $h\nu_0 = \varphi_0 + 0$  or  $h\nu_0 = \varphi_0$ .....(2)
- This expression represents the work function ( $\varphi_0$ ) of the metal.

Using the value of equation (2) in (1)

$$h\nu = \varphi_0 + \frac{1}{2}mv^2$$

$$h\nu = h\nu_0 + \frac{1}{2}mv^2$$

$$h\nu - h\nu_0 = \frac{1}{2}mv^2$$

$$h(\nu - \nu_0) = \frac{1}{2}mv^2$$

This equation shows that the kinetic energy  $\frac{1}{2}mv^2 \propto$  frequency  $\nu$ .

**(e) Laws of Photoelectric emission on the bases of Einstein's photoelectric equation: -****1. Frequency Below Threshold ( $\nu < \nu_0$ ):**

- If the incident frequency ( $\nu$ ) is less than the threshold frequency ( $\nu_0$ ), the kinetic energy ( $\frac{1}{2}mv^2$ ).
- From photoelectric equation ( $h\nu - h\nu_0 = \frac{1}{2}mv^2$ ) will be negative.
- Negative kinetic energy is not possible, as kinetic energy cannot be negative. This observation confirms that photoelectric emission does not occur if the frequency of incident light is below the threshold frequency.

**2. Direct Proportionality to Intensity:**

- Each photon can emit only one electron from the metal surface.
- The number of photoelectrons emitted per second is directly proportional to the intensity of the incident light, which is related to the number of photons present in the incident light. This supports the concept that the photoelectric current is proportional to the intensity.

### 3. Frequency and Kinetic Energy Relationship:

- From the photoelectric equation ( $h\nu - h\nu_0 = \frac{1}{2}mv^2$ ), it is evident that the kinetic energy ( $\frac{1}{2}mv^2$ ) of the emitted photoelectron increases with the increase in the frequency ( $\nu_0$ ) of the incident light.
- This observation is consistent with the photoelectric effect, where higher frequency light results in photoelectrons with greater kinetic energy.

### 4. Instantaneous Nature of Photoelectric Emission:

- Photoelectric emission is attributed to elastic collisions between photons and electrons in the substance.
- The absence of a significant time lag between the incidence of a photon and the emission of a photoelectron supports the idea that the process of photoelectric emission is instantaneous.

#### (i) Particle Nature of Light: The Photon: -

##### 1. Photoelectric Effect:

- The photoelectric effect demonstrated that light exhibits characteristics of particles. When light falls on a material surface, it can eject electrons from that material.

##### 2. Light Quanta and Photons:

- The concept of light quanta, or packets of energy associated with particles, was introduced. These packets are called photons.

##### 3. Energy of a Photon:

- The energy (**E**) of a photon is related to its frequency ( **$\nu$** ) and wavelength ( **$\lambda$** )
- through the equation  $E = h\nu = \frac{hc}{\lambda}$ , where  $h$  is Planck's constant and  $c$  is the speed of light.

##### 4. Momentum of a Photon:

- The momentum (**p**) of a photon is given by  $p = \frac{E}{c}$ , which can also be expressed as  $p = \frac{h\nu}{c}$  or  $p = \frac{h}{\lambda}$ . This equation relates the momentum of a photon to its energy and wavelength.

These concepts contribute to the understanding of light behaving as both waves and particles. The photon model helps explain phenomena like the photoelectric effect and provides a quantum perspective on the nature of light.

**Properties of Photon: -**

**a) A photon travels with a speed of light in a vacuum (i.e.,  $3 \times 10^8 \text{ ms}^{-1}$ ):**

Photons, being massless, always travel at the speed of light in a vacuum.

**b) A photon has zero rest mass (i.e.,  $m=0$ ):**

Photons are massless particles, and they do not have a rest mass. This is a fundamental property that distinguishes them from particles with mass.

**c) Photons travel in a straight line:**

Photons propagate in straight lines unless influenced by external factors like gravitational fields or other interactions.

**d) Wavelength of the photon changes in different media, so the velocity of a photon is different in different media:**

The speed of light in a medium is given by  $v = \frac{c}{n}$ , where  $n$  is the refractive index of the medium. The wavelength of light in a medium is different from its wavelength in a vacuum.

**e) Photons do not have any charge, so they are electrically neutral:**

Photons are electrically neutral; they do not carry any electric charge.

**f) Photons are not deviated by magnetic fields:**

Photons, being chargeless, do not experience a force from magnetic fields.

**g) Photons are not deflected by electric fields:**

Photons, being chargeless, do not interact with electric fields in the classical sense.

**h) Photons may show diffraction under given conditions:**

Photons, like waves, can exhibit diffraction under certain conditions, demonstrating their wave-particle duality.

**(x) Total energy and total momentum of photons remain conserved when photons collide with matter. All photons having the same frequency have the same energy and momentum irrespective of the intensity of the radiation:**

In interactions involving photons, the total energy and momentum are conserved. Photons of the same frequency have the same energy and momentum, regardless of the intensity of the radiation.

## ⇒ Wave Nature of Particles: (de-Broglie Hypothesis):-

According to de-Broglie, a wave is associated with moving material which controls the particle in every respect. The wave associated with moving material particle is called matter wave or de-Broglie wave and whose wave length is called **de-Broglie wavelength**.

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

$h$  = Planck's constant

$m$  = mass of particle

$v$  = Velocity of particle.

According to Planck's quantum theory

$$E = h\nu = \frac{hc}{\lambda} \quad \text{--- (i)} \quad [c = \nu\lambda \Rightarrow \nu = \frac{c}{\lambda}]$$

According to Einstein's theory

$$E = mc^2 \quad \text{--- (ii)}$$

from (i) and (ii)

$$\frac{hc}{\lambda} = mc^2$$

$$\lambda = \frac{hc}{mc^2}$$

$$\boxed{\lambda = \frac{h}{mc}} \quad \text{or} \quad \boxed{\frac{h}{p} = \lambda} \quad [p = mc]$$

where,  $p = mc$  is momentum of a photon.

if a material particle of mass ( $m$ ) is moving with velocity ( $v$ ). Then momentum of the particle ( $p = mv$ )

$$\text{i.e. } \boxed{\lambda = \frac{h}{p} = \frac{h}{mv}}$$

which is the expression for de-Broglie wavelength.

⇒ Relation between de-Broglie wavelength ( $\lambda$ ) and Temperature

From kinetic theory of matter, the average kinetic energy of a particle at a given temperature ( $T$ ) Kelvin is given by

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

$k$  = Boltzmann Constant

if a particle of mass  $m$ , moving with velocity ( $v$ ) then its K.E.

$$K = \frac{1}{2} mv^2 \Rightarrow \begin{aligned} mv^2 &= 2K \\ m^2v^2 &= 2mK \\ (mv) &= \sqrt{2mK} \end{aligned}$$

Momentum of particle is

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

$$p = \sqrt{2m \left( \frac{3}{2} kT \right)}$$

$$\boxed{p = \sqrt{3mkT}}$$

Now de - Broglie wavelength

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

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

⇒ De - Broglie wavelength of an electron :-

Let an electron of charge ( $e$ ) having mass ( $m$ ) be accelerated from rest through a potential difference ( $V$ ), then gain K.E.

$$K.E = \frac{1}{2} m v^2 \quad \text{--- (i)}$$

$$\text{work done on electron} = eV \quad \text{--- (ii)}$$

from (i) and (ii)

$$\frac{1}{2} m v^2 = eV$$

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

momentum is given by

$$p = m v$$

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

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

$$\boxed{p = \sqrt{2meV}}$$

Now wavelength associated

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

$$\lambda = \frac{h}{\sqrt{2eVm}} \quad (m = \text{mass of electron})$$

$$h = 6.63 \times 10^{-34}, \quad e = 1.6 \times 10^{-19} \text{ C}, \quad m = 9.1 \times 10^{-31} \text{ kg}$$

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 1.6 \times 10^{-19} \times 9.1 \times 10^{-31} \times (V)}}$$

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

$$\lambda = \frac{12.27}{\sqrt{V}} \text{ \AA}$$

$$\lambda = \frac{1.227}{\sqrt{V}} \text{ nm}$$