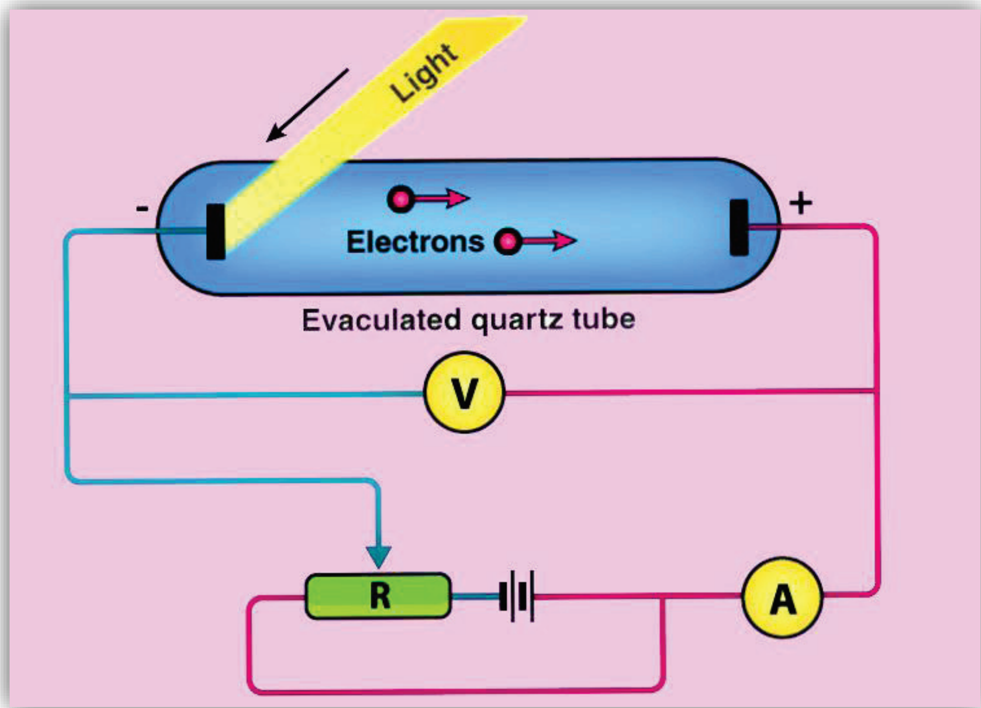
Dual Nature of Radiation and Matter



Dual Nature of Radiation and Matter

Photoelectric effect

Electrons are the common constituents of all atoms and hence of all materials. The electrons inside a material are held by electrostatic forces, so that they cannot by themselves come out of the material. By supplying proper energy from outside, some of the electrons in a material can be made to come out, and this phenomenon is known as *electron emission.* The minimum energy required to remove an electron from a material is called the *work function*, of that material.

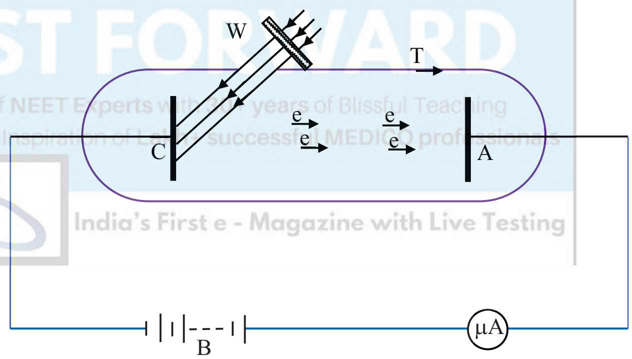
Types of Electron Emission

According to the free electron theory of metals, a large number of loosely bound electrons exist in a metal. Thus, electrons can be liberated from a metal surface by any one of the following methods.

1. The process of emission of electrons from the surface of a metal by heating it is called **thermionic emission.**
2. The process of emission of electrons from the surface of a metal by using radiation of suitable frequency (UV, Visible, IR etc.,) of suitable frequency is called **photoelectric emission.**
3. The process of emission of electrons from the surface of a metal, using an electric field is called **field emission** or **cold emission.**
4. The process of emission of electrons from the surface of a metal, using a beam of accelerated charged particles is called **secondary emission.**

Photoelectric effect is the phenomenon of emission of electrons from a surface when radiation of suitable frequency falls on it.

T = Evacuated tube
C = Photo cathode
A = Collector plate
W = quartz window
B = Voltage source
μA = microammeter

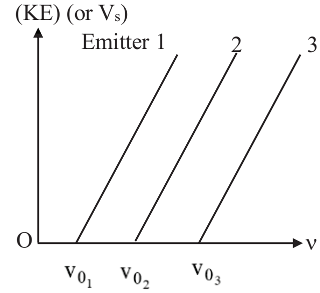


Experimental results

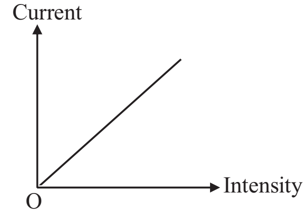
1. **For a given material (photosensitive cathode), there is a frequency of radiation, below which photoelectric emission does not take place, whatever may be the intensity. This minimum frequency is called threshold frequency (ν_0), with respect to that material.**

   The wavelength corresponding to the threshold frequency is called the limiting wavelength (λ_0).
   For photoelectric effect to take place, $\nu_{incident} > \nu_0$ and hence $\lambda_{incident} < \lambda_0$.
2. **Photoelectric effect is almost instantaneous.**

3. **When the frequency of radiation incident on a photoemission surface is increased above the threshold frequency, the kinetic energy of the photoelectrons increases linearly.**
A graph of maximum kinetic energy of the emitted photoelectrons versus the frequency of radiation is a straight line.
The slope is same for all emitters and thus, a set of parallel straight lines is obtained.

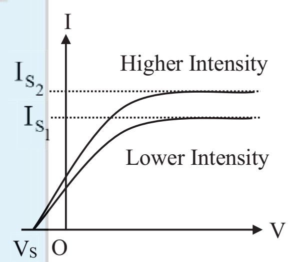


4. **When $\nu > \nu_0$, if the intensity of the incident radiation is increased, the number of photoelectrons liberated and hence the photoelectric current increases.**



5. **If the collector potential with respect to the emitter is reduced to zero, current does not reduce to zero. If the collector potential is made negative with respect to the emitter and then increased, the current decreases. At a particular negative potential (V_s), the photoelectric current becomes zero. This potential is called stopping potential.**
Kinetic energy is eV is numerically equal to stropping potential in volt.

6. **As the collector potential (+V w.r.t. emitter) is increased, the photoelectric current (I) increases gradually to a certain constant value called the saturation current (I_s).**



Einstein's explanation of photoelectric effect

Assumed that a beam of light is composed of discrete packets of energy called **photons**, which travel with the velocity of light. The energy of a photon is given by

$$\boxed{E = h\nu = \frac{hc}{\lambda}}$$

where $h \rightarrow$ Planck's constant $= 6.625 \times 10^{-34}$ J s

$\nu \rightarrow$ frequency of incident light (in hertz)

$c \rightarrow$ speed of light in free space $= 3 \times 10^{8}\, \text{m s}^{-1}$

$\lambda \rightarrow$ wavelength of light incident on the photosensitive surface (in metre).

A metal has a large number of free electrons. Though these electrons are free to move within the metal, they cannot come out of the metal surface. A certain minimum energy is required to pull them out. This is called the **workfunction.**

Hence, the energy equation can be written as,

$$\begin{bmatrix}\text{Energy of the} \\ \text{incident photon}\end{bmatrix} = \begin{bmatrix}\text{photoelectric} \\ \text{workfunction}\end{bmatrix} + \begin{bmatrix}\text{maximum kinetic energy of} \\ \text{the photoelectron}\end{bmatrix}$$

$$h\nu = W + \frac{1}{2}mv_{max}^2 \quad \Rightarrow \frac{1}{2}mv_{max}^2 = h\nu - W \quad \Rightarrow (KE)_{max} = E - W$$

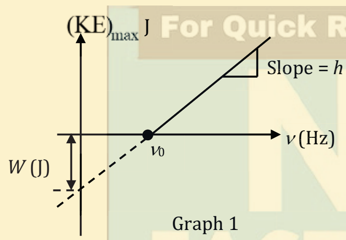
where m = mass of an electron, v_{max} = maximum velocity of the photo electron and W is the work function, of the material.

This equation is called **Einstein's photoelectric equation**.

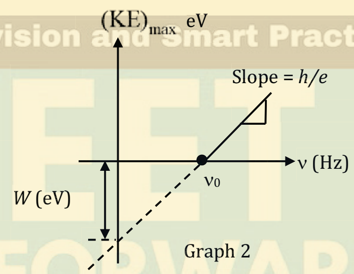
Einstein's photo electric equation can be also written as

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

- **For quick calculation**, $E = \frac{hc}{e\lambda} = \frac{6.625\times10^{-34}\times3\times10^{8}}{1.6\times10^{-19}\times\lambda\times10^{-10}} \cong \frac{12400}{\lambda(\overset{0}{A})}eV = \frac{1240}{\lambda\ (nm)}eV$
- Similarly, work function = $W \cong \frac{12400}{\lambda_0(\overset{0}{A})}eV = \frac{1240}{\lambda_0\ (nm)}eV$
- $v_{max} = \sqrt{\frac{2eV_s}{m}} = \sqrt{\frac{2\times1.6\times10^{-19}\times V_S}{9.1\times10^{-31}}} \cong 6\times10^5\sqrt{V_S}\ m\,s^{-1}$
- Physical significance of various geometrical terms used in the following graphs.



Graph 1



Graph 2

Geometrical terms	Graph 1	Graph 2
Abscissa	Frequency in Hz	Frequency in Hz
Ordinate	$(KE)_{max}$ in J	$(KE)_{max}$ in eV
Slope	h	h/e
x-intercept	Threshold frequency ν_0	Threshold frequency ν_0
y- intercept (negative)	W in J	W in eV $\equiv V_s$ in volt

Photocells

A photocell device which converts light energy into electrical energy. Three major types are:

(i) Photoemissive cell

(ii) Photovoltaic cell (used as a source of emf)

(iii) Photoconductive cell

Applications of photocells

Photocells have several applications. For example,

1. In cinematography for reproduction of sound.
2. In television cameras for converting optical images into electrical signals.
3. In exposure meters fitted to cameras (combination of a photocell and galvanometer).
4. For automatic switching, depending on the presence or absence of light.