THE RADIANT EDUCATION POINT
MRITUNJAY MISHRA
(M.SC PHYSICS)
PHONE NO.- 9643125430, 9643126470

Free electrons

Free electrons in metals. In metals, the electrons in the outer shells of the atoms are loosely bound. They move about freely throughout the lattice of positive ions. Such loosely bound electrons are called *free electrons*.

The free electrons, however, remain confined to the conductor and cannot leave its surface at ordinary temperature. The moment an electron comes out of a metal surface with its negative charge ($-e$), the metal surface acquires an equal positive charge ($+e$) and pulls it back. There is thus a *potential barrier* at the metal surface which the free electrons have to overcome in order to just escape from the metal surface.

Work function

The minimum amount of energy required by an electron to just escape from the metal surface is called work function of the metal.

The work function depends on (*i*) the nature of the metal and (*ii*) the conditions of its surface. It is generally denoted by W_0 (or ϕ_0) and measured in electron volt (eV).

Electron volt

Electron volt. *One electron volt is the kinetic energy gained by an electron when it is accelerated through a potential difference of 1 volt.*

Energy gained by electron

$$= \text{Work done by electric field} = qV$$

$$\therefore \quad 1\text{ eV} = 1.602 \times 10^{-19}\text{ C} \times 1\text{ V}$$

or $$1\text{ eV} = 1.602 \times 10^{-19}\text{ J}$$

Electron volt is a commonly used unit of energy in atomic and nuclear physics.

Electron emission

Electron emission. *The phenomenon of emission of electrons from a metal surface is called electron emission.* For the emission of electrons from the metal surface, the energy of electrons must be higher than the work function of the metal.

1. Thermionic emission. When a metal is heated, its free electrons get sufficient thermal energy and they can overcome surface barrier. This method of removal of electrons is called *thermionic emission* and the emitted electrons are called *thermions or thermo-electrons*.

2. Field emission or cold cathode emission. When a metal surface is subjected to very high electric fields, of the order of 10^3 to 10^8 Vm^{-1}, electrons are emitted from it. This is known as *field* or *cold cathode emission*. This method of electron emission is dangerous and less efficient.

3. Photoelectric emission. It is the process in which electrons are emitted from a metal surface when electromagnetic radiations of sufficiently high frequency are incident on it. The emitted electrons are called *photoelectrons* but their rate of emission is very low.

4. Secondary emission. When fast moving electrons strike a metal surface, they transfer some of their energy to the free electrons of the metal.

The emitted electrons are called *secondary electrons* and this method of removal of electrons is called *secondary emission*.

Photoelectric effect

Photoelectric effect. *When light of suitable frequency illuminates a metal surface, electrons are emitted from the metal surface. The phenomenon is called photoelectric effect.*

The phenomenon of emission of electrons from a metal surface, when electromagnetic radiations of sufficiently high frequency are incident on it, is called photoelectric effect. The photo (light)-generated electrons are called photoelectrons.

Different substances emit photoelectrons only when exposed to radiations of different frequencies. Alkali metals like Li, Na, K, Cs and Rb are *highly photosensitive*. They emit electrons even with visible light. Metals like Zn, Cd, Mg, Al, etc. respond only to ultraviolet light. X-rays can eject electrons even from heavy metals.

Experimental study of Photoelectric effect

Experimental study of photoelectric effect. An extensive study of photoelectric effect was made by *Lenard* and *R.A. Millikan*.

Figure 10.3 shows the experimental arrangement used for the study of photoelectric effect. It consists of an evacuated glass/quartz tube which encloses a photo- sensitive plate *C* and another metal plate *A*. A quartz window *W* is sealed on the glass tube which permits the ultraviolet light to irradiate the plate *C*. The

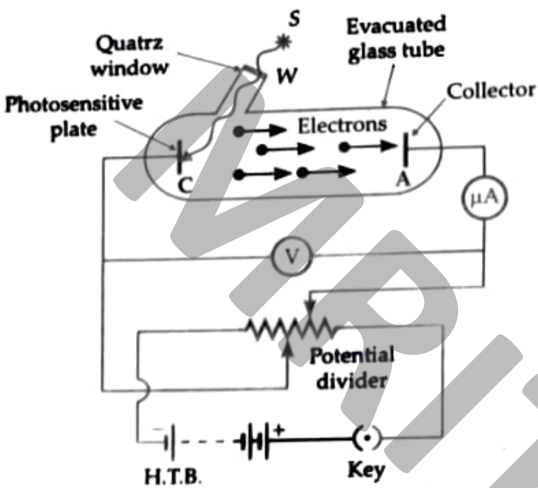

Fig. 10.3 **Experimental arrangement to study photoelectric effect.**

electrons are emitted by the cathode *C* and collected by the plate *A*, called anode or collector. The two electrodes are connected to a high tension battery,

Voltmeter *V* measures the potential difference applied between the two electrodes. When monochromatic radiations of suitable frequency fall on the plate *C*, electrons are emitted which are collected by the plate *A*. So a current, called *photo-electric current*, flows in the outer circuit which is measured by the microammeter μA.

1. Effect of intensity of light on photoelectric current. If we allow radiations of a fixed frequency to fall on plate *P*

then the photoelectric current is found to increase linearly with the intensity of incident radiation, as shown in Fig. 10.4. Since the photoelectric current is directly proportional to the number of photoelectrons emitted

, this implies that *the number of photoelectrons emitted per second is proportional to the intensity of incident radiation*.

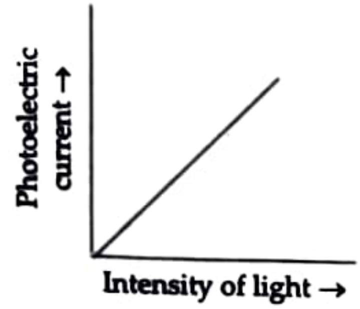

Fig. 10.4 Photoelectric current *vs.* intensity of incident radiation.

2. Effect of potential.

If we increase the positive potential (called *accelerating potential*) on plate *A* gradually, it is found that *the photoelectric current increases with the increase in accelerating potential till a stage is reached when the photoelectric current becomes maximum and does not increase further with the increase in the accelerating potential. This maximum value of the photoelectric current is called the saturation current*. At this stage, all the electrons emitted by the plate *C* are collected by the plate *A*.

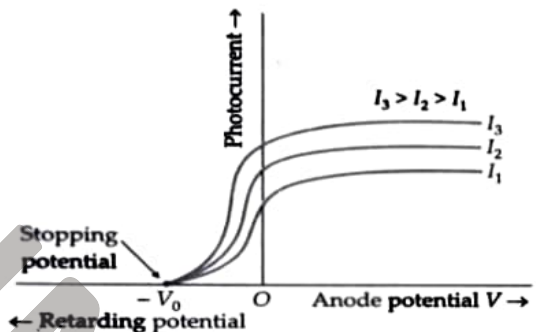

Fig. 10.5 **Variation of photoelectric current with anode potential.**

Now, if we apply a negative potential on plate *A* with respect to plate *C* and increase its magnitude gradually, it is seen that the photoelectric current decreases rapidly until it becomes zero for a certain value of negative potential on plate *A*. *The value of the retarding potential at which the photoelectric current becomes zero is called cut off or* ***stopping potential*** *for the given frequency of the incident radiation*.

. At the stopping potential V_0, when no photoelectrons are emitted, the work done by stopping potential on the fastest electron must be equal to its kinetic energy. Hence

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

where m, e and v_{max} are the mass, charge and maximum velocity of the electrons, respectively.

If we repeat the experiment with incident radiation of the same frequency but of higher intensity I_2 and I_3 ($I_3 > I_2 > I_1$), we find that the values of saturation currents have increased in

while the stopping potential is still the same. Thus, *for a given frequency of incident* *radiation, the stopping potential is independent of its intensity.*

3. Effect of frequency of incident radiation on stopping potential. To study the effect of frequency on photoelectric effect, the intensity of incident radiation at each frequency is adjusted in such a way that the saturation current is same each time when the plate A is at a positive potential. The potential on the plate A is gradually reduced to zero and then increased in the negative direction till stopping potential is reached. The experiment is repeated with radiations of different frequencies.

As shown in Fig. 10.6, the value of stopping potential increases with the frequency of incident radiation. For frequencies $\nu_3 > \nu_2 > \nu_1$, the corresponding stopping potentials vary in the order $V_{03} > V_{02} > V_{01}$. This implies that greater the frequency of the incident radiation, greater is the maximum kinetic energy of the photoelectrons and hence greater is the retarding potential required to stop such electrons completely.

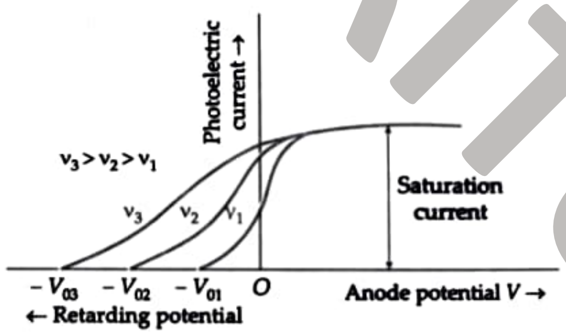

Fig. 10.6 Variation of photoelectric current with anode potential for different frequencies of incident radiation.

If we plot a graph between the frequency of incident radiation and the corresponding stopping potential for different metals, we get straight line graphs, as shown in Fig. 10.7. These graphs reveal the following facts :

(*i*) The stopping potential increases linearly with the frequency ν of the incident radiation for a given photosensitive material.

(*ii*) There exists a certain minimum cut-off frequency for which the stopping potential is zero.

*The minimum value of the frequency of incident radiation below which the photoelectric emission stops altogether is called **threshold frequency**.*

(*iii*) For two different metals A and B, these graphs are parallel straight lines *i.e.*, they have same slope. But the threshold frequencies are different for the two metals.

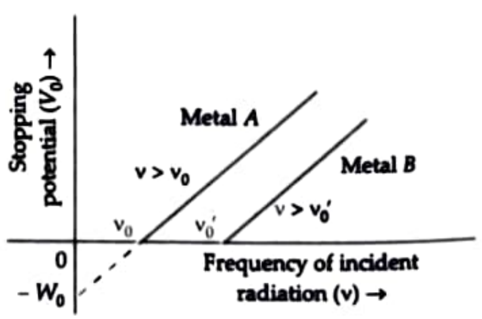

Fig. 10.7 Variation of stopping potential with frequency of incident radiation.

The above observations imply *two* important facts :

(*i*) *The maximum kinetic energy of the photoelectrons increases linearly with the frequency of the incident radiation, but is independent of its intensity.*

(*ii*) *For a frequency ν of the incident radiation less than the threshold frequency ν_0, no photoelectric emission is possible, howsoever large is the intensity of incident radiation.*

Once the frequency of incident light exceeds the threshold frequency, the photoelectric emission starts *instantaneously*, even if the light is very dim. The time interval between the incidence of radiation and the emission of electrons is of the order of 10^{-9} s or ns (nanosecond).

LAWS OF PHOTOELECTRIC EMISSION

Laws of photoelectric emission. On the basis of the experimental results on photoelectric effect, *Lenard and Millikan* gave the following laws of photoelectric emission :

1. *For a given photosensitive material*

   the photoelectric current is directly proportional to the intensity of light.

2. *For a given photosensitive material, there exists a certain minimum cut-off frequency below which no photoelectrons are emitted, howsoever high is the intensity of incident radiation. This frequency is called **threshold frequency**.*

3. *Above the threshold frequency,*

   the maximum kinetic energy of the

photoelectrons is directly proportional to the frequency of incident radiation, but is independent of its intensity.

4. *The photoelectric emission is an instantaneous process.* The time lag between the incidence of light radiation and the emission of photo-electrons is very small, even less than 10^{-9} s.

Failure of classical wave theory

1) If light is a wave then high intensity wave must have high energy and when this wave strike the metal surface, the electron emitted from metal surface must have high energy. But this does not happens in actual experiment. The energy of electron does not depend upon the intensity of light wave

2) If light is a wave, then a high intensity wave of any frequency must eject electrons from the metal surface. But in actual experiment. only a wave of suitable frequency (threshold frequency) was able to eject the electrons.

3) If light is a wave, then the metal surface should take a small time to absorb the energy and eject the electron but in actual Experiment electrons were ejected instantaneously.

Einstein photoelectric effect

Einstein's theory of photoelectric effect. In 1905, *Einstein* explained photoelectric effect on the basis of Planck's quantum theory according to which a light radiation travels in the form of discrete photons. The energy of each photon is $h\nu$, where h is Planck's constant and ν is the frequency of light.

The main points of the Einstein's theory of photo-electric effect are :

1. Photoelectric emission is the result of interaction of two particles – one a photon of incident radiation and the other an electron of photosensitive metal.

2. The free electrons are bound within the metal due to restraining forces on the surface. The minimum energy required to liberate an electron from the metal surface is called work function W_0 of the metal.

3. Each photon interacts with one electron. The energy $h\nu$ of the incident photon is used up in *two* parts :

If

(*a*) a part of the energy of the photon is used in liberating the electron from the metal surface, which is equal to the work function W_0 of the metal, and

(*b*) the remaining energy of the photon is used in imparting kinetic energy to the ejected electron.

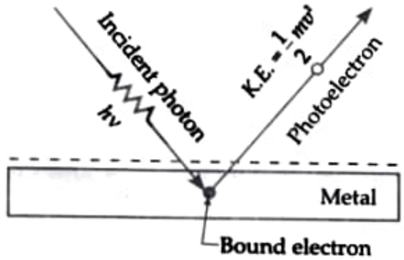

Fig. 10.8 Photoelectric emission.

4. Very few (< 1%) photons, whose energies are greater than W_0, are capable of ejecting the photo- electrons.

By the conservation of energy,

Energy of the incident photon

= Maximum K.E. of photoelectron + Work function

or $$h\nu = \frac{1}{2} mv_{max}^2 + W_0$$

or $$K_{max} = \frac{1}{2} mv_{max}^2 = h\nu - W_0 \quad ...(1)$$

If the incident photon is of threshold frequency ν_0, then its energy $h\nu_0$ is just sufficient to free the electron from the metal surface and does not give it any kinetic energy. So $h\nu_0 = W_0$. Hence

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

Equations (1) and (2) are called *Einstein's photoelectric equations* and can be used to explain the laws of photoelectric effect as follows :

1. Explanation of effect of intensity. The increase of intensity means the increase in the number of photons striking the metal surface per unit time. As each photon ejects only one electron, so the number of ejected photoelectrons increases with the increase in intensity of incident radiation.

2. Explanation of threshold frequency. If $\nu < \nu_0$ *i.e.*, the frequency of incident radiation is less than the threshold frequency, the kinetic energy of photo-electrons becomes negative. This has no physical meaning. So photoelectric emission does not occur below the threshold frequency.

3. Explanation of kinetic energy. If $\nu > \nu_0$, then

$$K_{max} = \frac{1}{2} m v^2_{max} \propto \nu$$

i.e., above the threshold frequency, the maximum kinetic energy of the electrons increases linearly with the frequency ν of the incident radiation. Moreover, the increase in intensity increases only the number of incident photons and not their energy. Hence the maximum kinetic energy of the photoelectrons is independent of the intensity of incident radiation.

4. Explanation of time lag. Photoelectric emission is the result of an elastic collision between a photon and an electron. Thus the absorption of energy from a photon by a free electron inside the metal is a single event which involves transfer of energy in one lump instead of the continuous absorption of energy as in the wave theory of light. Hence there is no time lag between the incidence of a photon and the emission of a photoelectron.

Some basic features of the photon picture of electromagnetic radiation :

1. In the interaction of radiation with matter, radiation behaves as if it is made of particles, called photons.
2. Each photon has energy $E(= h\nu)$ and momentum $p(= h\nu/c = h/\lambda)$, and speed c(= speed of light) in vacuum.
3. All photons of light of a particular frequency ν, or wavelength λ, have the same energy ($E = h\nu = hc/\lambda$) and momentum $p(= h\nu/c = h/\lambda)$, independent of the intensity of the radiation.
4. Photons are electrically neutral and are not deflected by electric and magnetic fields.
5. In a photon-particle (or photon-electron) collision, the total energy and total momentum are conserved. However, the number of photons may not be conserved in a collision. The photon may be absorbed or a new photon may be created.
6. If the intensity of light of a given wavelength is increased, there is an increase in the number of photons incident on a given area in a given time. But the energy of each photon remains the same.

Determination of Planck Constant

Determination of Planck's constant and work function. According to Einstein's photoelectron equation, the maximum K.E. of a photoelectron is given by

$$K_{max} = h\nu - W_0$$

If V_0 is the stopping potential, then

$$K_{max} = eV_0$$

$$\therefore \quad eV_0 = h\nu - W_0$$

or
$$V_0 = \left(\frac{h}{e}\right)\nu - \frac{W_0}{e} \quad \text{...(1)}$$

We compare this equation with the straight line equation,

$$y = mx + c$$

It follows from equation (1) that V_0 versus ν graph is a straight line, as shown in Fig. 10.9.

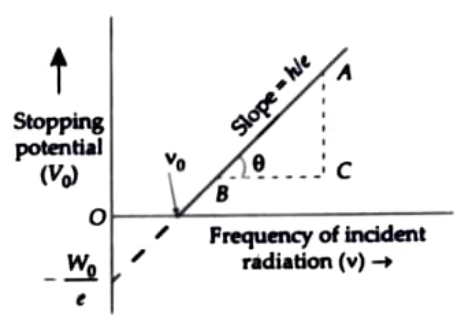

Fig. 10.9 V_0 versus ν graph for a photo-sensitive material.

Clearly, slope of V_0- ν graph $= \frac{h}{e}$

To determine the slope, take two points A and B on the straight line graph. Then

$$m = \tan\theta = \frac{AC}{BC} = \frac{h}{e}$$

$$\therefore \quad h = e \times \frac{AC}{BC} = e \times \text{slope of } V_0\text{- } \nu \text{ graph}$$

Thus, the Planck's constant h can be determined.

Moreover, the intercept on vertical axis $= -\frac{W_0}{e}$

$\therefore$ $W_0 = e \times$ Magnitude of the intercept on vertical axis.

Dual Nature of Radiation

Dual nature of radiation. The phenomena like interference, diffraction and polarisation, etc., can be satisfactorily explained only on the basis of wave nature of light. On the other hand, the phenomena like photoelectric effect, Compton effect, etc., can be explained only in terms of quantum theory of light, *i.e.*, by assuming particle nature of light. This shows that *light radiation has dual nature, i.e.*, it sometimes behaves like a wave and sometimes as a particle.

De-Broglie waves

Dual nature of matter : de-Broglie waves. In 1924, the French physicist *Louis Victor de-Broglie* (pronounced as de Broy) put forward the bold hypothesis that *material particles in motion should display wave-like properties*. His reasoning was based on the following *two* considerations :

1. The two physical quantities which govern all the forms of the physical universe are *mass* and *energy*.

The Einstein's mass-energy relationship :

$$E = mc^2,$$

shows that there is a complete equivalence between *matter* (mass) and *radiation* (energy). There must be a mutual symmetry between matter (mass) and radiation.

2. *Nature loves symmetry*. Since radiation has dual nature, therefore, from symmetry considerations, *de-Broglie* predicted that *matter must also possess dual nature*. Thus the particles like electrons, protons, neutrons, etc., should not only behave like mass points but they should also exhibit wave nature when in motion.

The waves associated with material particles in motion are called matter or de Broglie waves and their wavelength is called de Broglie wavelength.

de-Broglie's wave equation. Considering photon as an em wave of frequency ν, its energy from *Planck's quantum theory* is given by

$$E = h\nu \qquad \text{...(1)}$$

where h is Planck's constant. Considering photon as a particle of mass m, the energy associated with it is given by *Einstein's mass-energy relationship* as

$$E = mc^2 \qquad \text{...(2)}$$

From equations (1) and (2), we get

$$h\nu = mc^2$$

or $$\frac{hc}{\lambda} = mc^2 \qquad \left[\because \nu = \frac{c}{\lambda}\right]$$

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

where λ is the wavelength of the radiation of frequency ν and $p = mc$, is the momentum of the photon. The above equation has been derived for a photon of radiation. According to de Broglie's hypothesis, it must be true for material particles like electrons, protons, neutrons, etc. Hence a particle of mass m moving with velocity v must be associated with a matter wave of wavelength λ given by

$$\lambda = \frac{h}{p} = \frac{h}{mv} \qquad \text{...(3)}$$

This is **de Broglie's wave equation** for material particles. It explains the dual nature of matter as it connects the wave characteristic 'λ' with the particle characteristic 'p'.

From de-Broglie's equation, we find that

1. The wavelength of a moving particle is inversely proportional to its momentum,

i.e., $$\lambda \propto \frac{1}{p}$$

2. If $v = 0$, then $\lambda = \infty$. This implies that waves are associated with material particles only when they are in motion.

3. To be associated with a de Broglie wave, a particle need not have a charge. That is why, de-Broglie waves are also known as matter waves.

4. de-Broglie waves cannot be electromagnetic in nature because electromagnetic waves are only associated with accelerated charged particles.

De-Broglie wavelength of electron

de-Broglie wavelength of an electron. Consider an electron of mass m and charge e. Let v be the final velocity attained by the electron when it is accelerated from rest through a potential difference of V volts. Then kinetic energy gained by the electron equals the work done on the electron by the electric field.

K.E. gained by the electron,

$$K = \frac{1}{2} mv^2 = \frac{p^2}{2m}$$

Work done on the electron $= eV$

$$\therefore \quad K = \frac{p^2}{2m} = eV$$

or

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

Hence the de Broglie wavelength of the electron is

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

Now

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

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

$$= \frac{12.3 \times 10^{-10}}{\sqrt{V}} \text{ m} = \frac{12.3}{\sqrt{V}} \text{ Å}.$$