7.1 Electron Emission: The phenomenon, in which electrons are ejected from metallic surface when adequate amount of energy is supplied to it, is called electron emission. Electron emission may be of following type,

(i) **Thermionic Emission:** Emission of electrons by heating a metal. Emitted electrons are called *thermions or thermo-electrons*.

(ii) **Field Emission or Cold Cathode Emission:** When a metal surface is subjected to very high electric field (10^3-10^8 V/m) *electrons* are emitted from metal surface.

(iii) **Photoelectric Emission:** Electrons are emitted from metal surface when electromagnetic radiation of suitable frequency falls on it. Emitted electrons are called *photoelectrons*.

(iv) **Secondary Emission:** When fast moving electrons strikes to metal surface, electrons are emitted such electrons are called *secondary electrons*.

Work Function (ϕ_o): *The minimum amount of energy required by an electron to just escape it from the metal surface is called work function.* Work function of metal depends on,

(i) Nature of the metal. (ii) The conditions of its surface

$$\phi_o = h\nu_o$$

ν_o - the threshold frequency of incident radiation, h- Plank's constant

Work function is minimum for *Cesium* metal and maximum for *Platinum* metal.

7.2 Photoelectric Effect: The phenomenon in which electrons are emitted from a metallic surface, when high energy electromagnetic radiation falls on it is called photoelectric effect.

7.2.1 Hertz's Experiment: The phenomenon of photoelectric effect was first discovered by Heinrich hertz in 1887 while performing an experiment for the production of EM-wave. He observed that when U-V light falls on the metal surface electrons are emitted.

7.2.2 Hallwach's and Lenard's Observations:

Wilhelm Hallwach's and Philipp Lenard study the photoelectric effect during1886-1902.The experimental arrangement consists of an evacuated glass/quartz tube which encloses a photosensitive (Zn) plate C(emitter) and another metal plate A(collector). The two plates are connected to high tension battery. The battery maintains the potential difference between the plates C and A, that can be varied. The polarity of the plates C and A can be reversed by a device called *commutator*. When monochromatic radiations of suitable frequency falls on the plate C, electrons are emitted which are collected by plate A, so the current produced called *photoelectric current*. The potential difference between the emitter and collector plates is measured by a voltmeter (V) whereas the resulting photoelectric current flowing in the circuit is measured by a microammeter (μA).

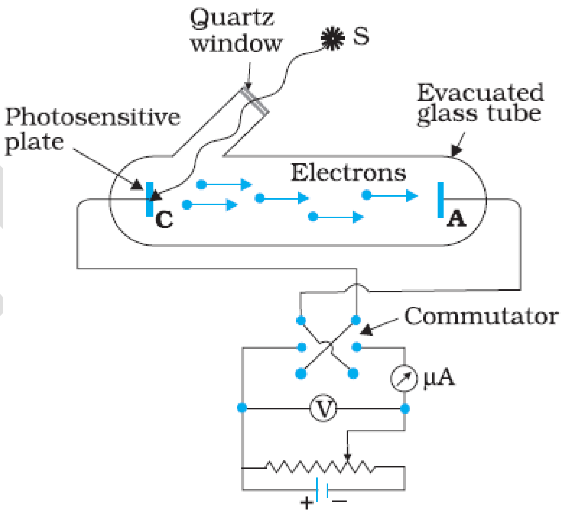


FIGURE 11.1 Experimental arrangement for study of photoelectric effect.

(i) Effect of intensity of light on photoelectric current: When collector (A) is maintained at positive potential and emitter C at negative then at constant suitable frequency (above *threshold frequency*) *photoelectric current ((number of photoelectrons emitted)) is directly proportional to intensity of incident radiation*. Intensity of radiation

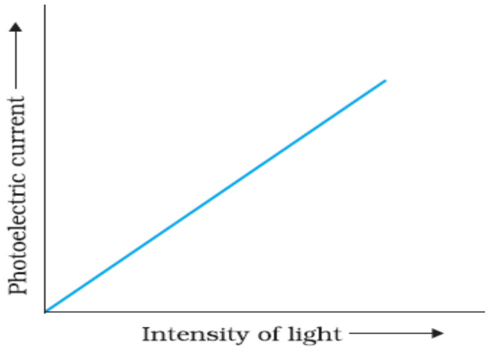


FIGURE 11.2 Variation of Photoelectric current with intensity of light.

means amount of energy falling on a surface per unit time per unit area (Unit-W/m^2).

(ii) Effect of Potential on photoelectric current: When Plate A is maintained positive and plate C is negative, for fixed intensity and for constant frequency. The *photoelectric current increases with the increases in accelerating potential* till a stage is reached when the photoelectric current become maximum and does not increases further with increases in the accelerating potential. This maximum value of current is called *Saturation Current.*

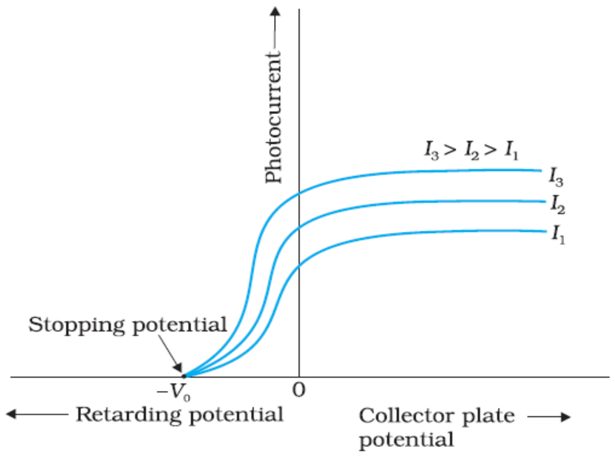


FIGURE 11.3 Variation of photocurrent with collector plate potential for different intensity of incident radiation.

If we apply negative potential on plate A with respect to plate C, and increase its magnitude gradually then the photoelectric current decreases rapidly and become zero. *The value of negative/retarding potential at which the photoelectric current becomes zero is called* ***Cut-Off or Stopping Potential*** **(V_0)**. Photoelectric current becomes zero because the stopping potential is sufficient to attract even the most energetic photoelectrons to emit, with the maximum kinetic energy (K_{max}), so that

$$K_{max} = e\,V_0$$

If we increase the intensity of incident radiation at same frequency (above threshold value) the values of saturation current also increases due to increase in number of photoelectrons emitted while, stopping potential and maximum kinetic energy of photoelectrons is independent of this intensity.

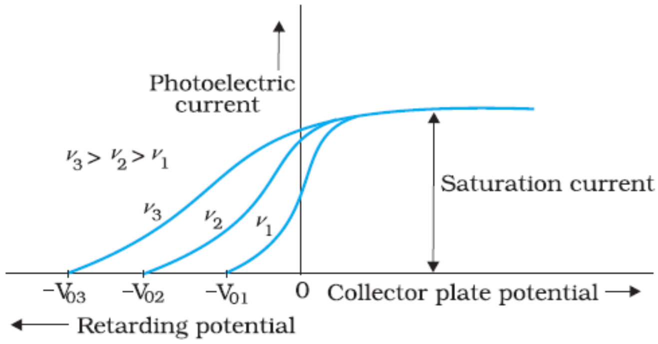


FIGURE 11.4 Variation of photoelectric current with collector plate potential for different frequencies of incident radiation.

(iii) Effect of frequency of incident radiation on stopping potential:
At constant intensity of radiation *the value of stopping potential increases with increase in frequency* of incident radiation, while there is no change in saturation current.
The minimum value of frequency of incident radiation which is just capable of ejecting an electron from metal surface is called ***Threshold/Cut–off Frequency,*** *below this frequency photoelectric emission stops.*

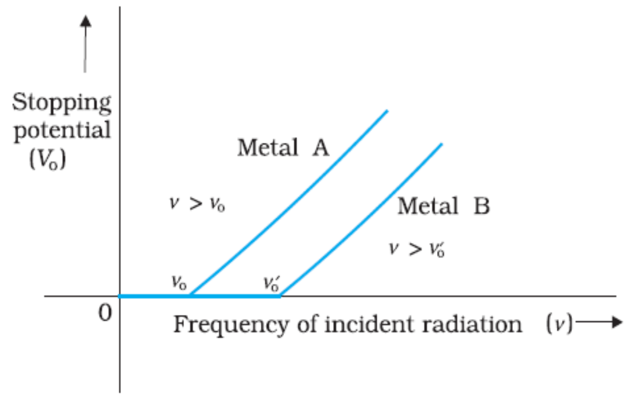


FIGURE 11.5 Variation of stopping potential V_0 with frequency ν of incident radiation for a given photosensitive material.

Graph between the frequency of incident radiation and corresponding stopping potential:
This graph reveals following observation and *Conclusion,*
(i) Stopping potential increases linearly with frequency ν of the incident radiation for a given photosensitive material ---*The maximum*

kinetic energy of the photoelectrons varies linearly with the frequency of incident radiation, but is independent of its intensity.

(ii) There exists a certain minimum cut-off frequency for which the stopping potential is zero ---- *For a frequency ν of incident radiation, lower than the cut-off frequency ν_o, no photoelectric emission is possible even if the intensity is large.*
(iii) For two different metals A and B the threshold frequency are different.

7.2.3 Law of Photoelectric Emission: On the basis of above experiment it is observed that,
(i) For a given photosensitive material and frequency of incident radiation (above the threshold frequency), the *photoelectric current is directly proportional to the intensity of light and saturation current is directly proportional to the intensity of incident radiation*.
(ii) For a given photosensitive material, there exists a *threshold frequency below which no photoelectrons are emitted*; however high is the intensity of incident radiation.
(iii) Above the threshold frequency, the stopping potential or equivalently the maximum kinetic energy of the photoelectrons is directly proportional to the frequency of incident radiation, but is independent of its intensity.
(iv) The photoelectric effect is instantaneous process.

7.3 Photoelectric Effect and Wave Theory of Light:
(i) According to the wave picture of light, the free electrons at the surface of the metal (over which the beam of radiation falls) absorb the radiant energy continuously. The greater the intensity of radiation, greater will be energy absorbed by each electron. No matter what the frequency of radiation is. A threshold frequency, therefore, should not exist. These expectations of the wave theory directly contradict observations (i),(ii) and (iii).
(ii) According to wave theory of light energy transferred by radiation to electrons is not goes to a particular electron but it distributed uniformly to all electrons. Therefore it takes time to collect energy required of ejection of electron but experimental observation shows that there is no time lag.

Thus, wave picture is unable to explain the most basic features of photoelectric emission.

7.4 Einstein's Photoelectric Equation: In 1905, Albert Einstein (1879-1955) proposed that **(Assumption of Einstein theory),**
(i) Photoelectric emission does not take place by continuous absorption of energy from radiation. Radiation energy is built up of discrete units called *quanta of energy of radiation*. Each quantum of radiant energy has energy hν, where *h* is Planck's constant and ν the frequency of light.
(ii) Photoelectrons are emitted as a result of interaction between photon of incident radiation and an electron of photosensitive metal.
(iii) Each photon interacts with one electron. The energy (E= hν) of the incident photon is used up in two parts,
 (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 ϕ_o of the metal.
 (b) The remaining energy of the photon is used in imparting kinetic energy to the ejected electron.

From conservation of energy,
Energy of incident photon = Max.KE.of photon + work function (ϕ_o)

$$h\nu = K_{max} + \phi_o$$
$$K_{max} = \tfrac{1}{2} mv^2_{max.} = h\nu - \phi_o$$

If ν_o is the threshold frequency of incident photon then its energy ($\phi_o = h\nu_o$) is just sufficient to free the electron.

$$\boxed{K_{max} = \tfrac{1}{2} mv^2_{max.} = h\nu - h\nu_o = h(\nu - \nu_o)}$$ This is known as Einstein's photoelectric eq^n.

Explanation of Photoelectric Effect on the basis of Einstein's photoelectric equation,

(i) **Explanation of effect of intensity:** With increase in intensity of light (no. of photon increases) number of photoelectrons increases which increases photoelectric current.

(ii) **Explanation of the threshold frequency:** If $\nu < \nu_o$ i.e. the frequency of incident radiation (ν) is less than the threshold frequency (ν_o). The photoelectric emission does not occur.
If $\nu > \nu_o$ is the frequency of incident radiation is more than the threshold frequency then the maximum kinetic energy of the electrons increases.

(iii) **Explanation of time lag:** There is no time lag between the incidence of photon and the emission of a photoelectron(less than 10^{-9} s).

Determination of Planck constant and work function from graph between stopping potential and frequency of incident radiation:

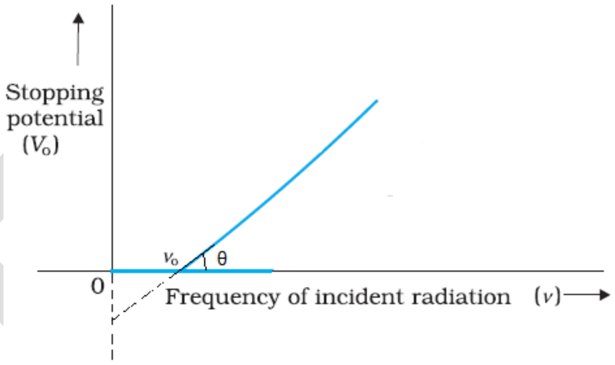
According to Einstein's photoelectric equation,

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

$K_{max} = eV_o = h\nu - h\nu_o$

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

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



Comparing this equation with standard equation of straight line,

$y = \mathbf{m}\, x + C$

$V_o = \frac{\boldsymbol{h}}{\boldsymbol{e}}\ \nu\ -\ \frac{\phi_o}{e}$

Slope of the graph = m = tan θ = V_o/ν = (h/e)

$\boldsymbol{h = e \tan\theta}$

7.5 Dual Nature of Radiation: Radiation has dual nature and can be explained on the basis of two theories,

(i) **Wave theory of radiation:** According to this theory radiation is an electromagnetic wave, which travels with speed 3×10^8m/s. Some phenomenon like interference, diffraction and polarisation can be explained on the basis of wave theory.

(ii) **Quantum theory of radiation/light:** According to this theory radiation is composed of particle which moves in straight line with very high speed. Phenomenon like reflection, refraction, photoelectric effect, Compton Effect can be explained on the basis of this.

7.6 Particle Nature of Light: The Photon

(i) The photon picture of electromagnetic radiation as follows:
(ii) When radiation interacts with matter, it behaves as, that it is made up of particles called photons.
(iii) Rest mass of photon is zero while dynamic or kinetic mass is $m = \frac{h\nu}{c^2} = \frac{h}{c\lambda}$
(iv) Each photon has energy and momentum, and moves with speed of light *c*.
(v) All photons of light of same frequency (ν) or same wavelength (λ), have the same energy ($E = h\nu = hc/\lambda$) and momentum ($p = h\nu/c = h/\lambda$), whatever the intensity of radiation may be. By *increasing the intensity of light of given wavelength, there is only an increase in the number of photons per second crossing a given area*, with each photon having the same energy. Thus, *photon energy is independent of intensity of radiation.*
(vi) Photons are electrically neutral and are not deflected by electric and magnetic fields.

(vii) In a photon-particle collision (such as 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.

7.7 Dual Nature of Matter: In 1924, Louis Victor de-Broglie hypothesised that material particle in motion should display wave like properties as well as matter. He reasoned that nature was symmetrical and that the two basic physical entities – matter and energy, must have symmetrical character. If radiation shows dual aspects, so should matter. The waves associated with material particles in motion are called matter or de Broglie waves and their wave length is called De-Broglie wave length.

de–Broglie's wave equation: Considering photon *as a wave*, energy of photon from Panck's quantum theory is given by, $E=h\nu$ --------------- (i)

Considering photon *as particle* of mass m, its energy is given by Einstein's mass- energy relation,

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

Comparing equation (i) and (ii),

$$h\nu = mc^2$$

Put $\nu = c/\lambda$, $\quad h\frac{c}{\lambda} = mc^2$

So, wavelength associated with photon is, $\boldsymbol{\lambda = \frac{h}{mc} = \frac{h}{p}}$ {linear momentum $p=mc$}

According to de-Broglie's the above equation is a general formula and applicable for material particles like electrons, protons, neutrons etc.

If v is speed of moving particle, then wavelength associated with matter wave is given by,

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

If **K** is kinetic energy of moving particle then wavelength associated is given by,

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

If a charge particle (e) of mass m is accelerated by a by potential difference V then wavelength associated with produced matter wave is given by,

K = eV V- applied potential different

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

h – Planks constant =$6.63\text{x}10^{-34}$j/s, m– mass of electron = $9.1\text{x}\ 10^{-31}$kg, e = $1.6 \text{ x } 10^{-19}$ C

$$\boldsymbol{\lambda} = \frac{6.63 \text{ x } 10^{-34} \text{ J/s}}{\sqrt{\mathbf{2}\text{x } (9.1 \text{ x } 10^{-31} \text{ kg}) \text{ x } (1.6 \text{ x } 10^{-19} \text{ C}) \ \mathbf{V}}}$$

$$\boldsymbol{\lambda = \frac{12.3}{\sqrt{V}}\ A^{\circ}}$$

We may conclude from de-Broglie's equation,

(i) The wave length (λ) of a moving particle is inversely proportional to its momentum (p).

(ii) If v = 0 then λ =∞ this implies that waves are associated with material particles only when they are in motion.

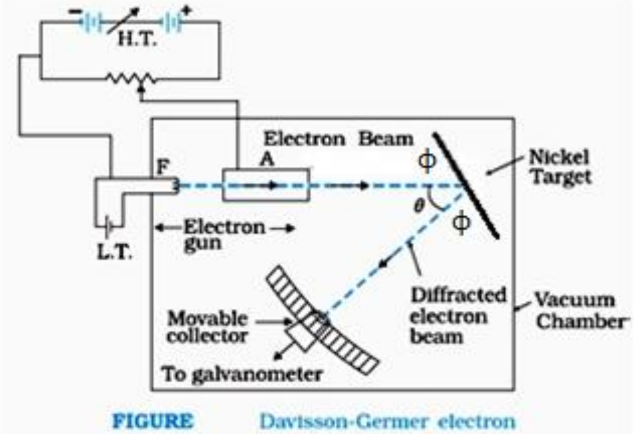


FIGURE Davisson-Germer electron diffraction arrangement.

7.8 Davisson and Germer Experiment:

The *wave nature of electrons* was first experimentally verified by C.J. Davisson and L.H. Germer in 1927 .Davisson and Germer designed a experimental arrangement. An electron beam is produced by an *electron gun* by applying a suitable potential difference. Electron beam is directed against the face of Ni crystal. The electron scatters in different direction by the Ni atom are collected by movable electron detector. We measure electron intensity (scattered) as a function of scattering angle ϕ. This experiment is repeated for various accelerating potential V.

A strong peak is obtained at 54 volt and scattering angle $\theta = 50^o$

From figure, $\phi + \theta + \phi = 180^o$

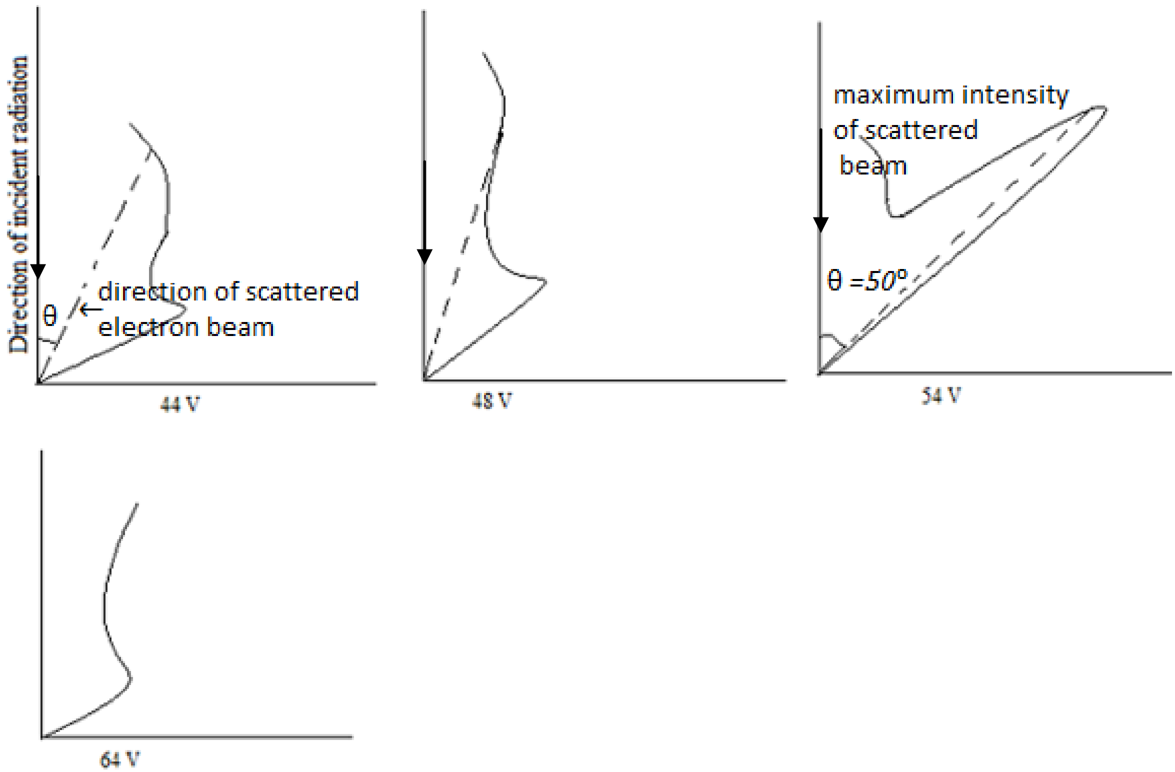
$2\phi = 180^\circ - \theta = 180^\circ - 50^\circ = 130^\circ$

$\phi = 65^o$

ϕ = glancing angle (angle between the scattered beam of electron with plane of atom of crystal)

According to De-Broglie's hypothesis, wavelengths of electron accelerated through a potential V volt is given by, here V = 54 volt

$$\lambda = \frac{12.3}{\sqrt{V}} = \frac{12.3}{\sqrt{54}} = 1.66\ A^\circ$$



From Bragg's law, for first order maxima diffraction pattern

$$2d \sin\phi = n\lambda$$

d = 0.911 is inter-atomic spacing of Ni crystal n =1 (for first order diffraction maximum)

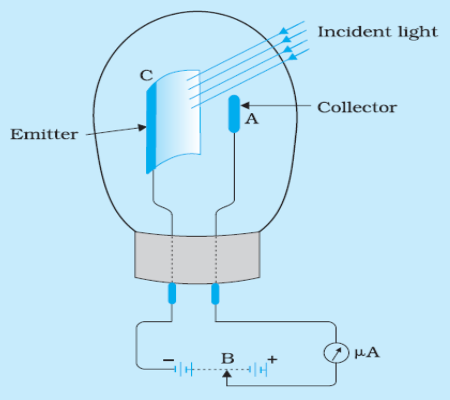
$\lambda = 2 \times 0.911 \times \sin 65^o$

$= 2 \times 0.911 \times \sin 65^o = 2 \times 0.911 \times 0.906 = \mathbf{1.65\ A^o}$

Thus experimental measured wavelength associated with moving particle is close to that estimated from De-Broglie's hypothesis, so it verify De-Broglie's hypothesis of wave nature of moving particles.

Photocell:

A photocell is a technological application of the photoelectric effect. It is a device whose electrical conducting properties are affected by light. It is also sometimes called an *electric eye*. When light of suitable wavelength falls on the emitter C, photoelectrons are emitted. A photocell converts a change in intensity of illumination into a change in photocurrent. Photocells are used in photographic cameras, automatic door opener, burglar alarm.



A photo cell

Some Conceptual Questions:

1. Electrons are emitted from a photosensitive surface when it is illuminated by green light but electron emission does not take place by yellow light. Will the electrons be emitted when the surface is illuminated by: (i) red light, and (ii) blue light?
   Ans: For red No, for blue yes
2. Can non-metals show photoelectric effect?
   Ans: Yes. If em-wave have high energy.
3. What is the charge on metal in the photoelectric experiment?
   Ans: positive (loss in electron)
4. What determines the maximum velocity of photoelectrons?
   Ans: frequency of incident radiation
5. A proton and a α-particle are accelerated, using the same potential difference. How are the de Broglie wavelengths λ_p and λ_s related to each other?
   Ans: $\sqrt{8}$: 1
6. Do all the electrons that absorb a photon come out of photoelectrons?
   Ans: No, most electron get scattered inside metal, a few are able to come out of the surface of the metal.
7. A particle is dropped from a height *H*. How de-Broglie wavelength associated with particle is related to height H.
   Ans: $\lambda \propto 1/\sqrt{H}$
8. A source of light is placed at a distance of 50cm from a photocell and the cut-off potential is found to be V_0. If the distance between the light source is made 25 cm, what will be the cut-off potential? Justify your answer.
   Ans: On changing the distance between the source and the photocell, *only the intensity of light falling on the photocell change* (I α $\frac{1}{r^2}$) and the frequency of incident light (i.e., the maximum KE of emitted electrons) does not change. Since cut-off potential depends upon frequency of incident light (and not upon intensity) hence the cut-off potential will remain the same, i.e., v_0.
   On decreasing the distance r to half, the intensity of radiation falling on photocell will increase to four times and as such the photocurrent will also increase to four times.
9. Every metal has a definite work function, why do photoelectrons not come out with the same energy of incident radiation if incident radiation is monochromatic? Why is there an energy distribution of photo electrons?
   Ans: Work function is the minimum amount of energy required by an electron to escape from the metallic surface; this energy corresponds to highest energy level of conduction band. All the electrons in metal do not belong to these categories; they occupy a continuous band of energy levels. So for the same monochromatic incident radiation, electrons knocked off from different levels come out with different energies, hence photoelectrons have energy distribution.
10. Name an experiment which shows wave nature of electrons. Which phenomenon was observed in this experiment using an electron beam?

Ans: Davisson and Germer Experiment show wave nature of electrons. The phenomenon of diffraction of electron beam was observed in this experiment.

11. How does the work function influence the kinetic energy of electrons liberated during the photoelectric emission?

Ans: Increase in work function decreases kinetic energy.

12. Explain briefly the reasons why wave theory of light is not able to explain the observed features of photoelectric effect.

Ans: Wave theory of light is not able to explain the observed features of photoelectric effect because,

(i) According to wave theory, the kinetic energy of photoelectrons must depend on the intensity of incident light; but according to experimental observations, the kinetic energy of photoelectrons does not depend on the intensity of incidents light.

(ii) According to wave theory, the light of any frequency can emit electrons from metallic surface provided the intensity of light be sufficient to provide necessary energy for emission of electrons, but according to experimental observations, the light of frequency less than threshold frequency cannot emit electrons; whatever the intensity of incident light may be.

(iii) According to wave theory, the energy transferred by light waves will not go to a particular electron, but it will be distributed uniformly to all electrons present in the illuminated surface. Therefore, electrons will take some time to collect the necessary energy for their emission. The time for emission will be more for light of less intensity and vice versa. But experimental observations show that the emission of electrons take place instantaneously after the light is incident on the metal; whatever the intensity of light may be.

13. Are matter waves electromagnetic? Why?

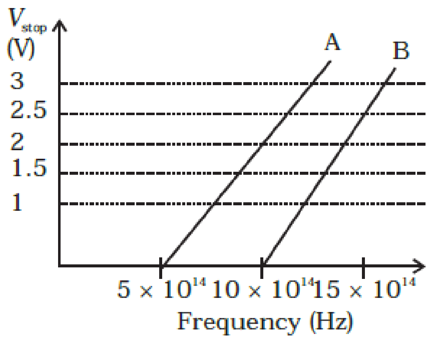
Ans: No, because em-waves are produced by accelerated charge particles, whereas matter waves are produced due to motion of particles irrespective of charge on it.

14. Why do the photoelectrons have variable K.E.?

15. There are materials which absorb photons of shorter wavelength and emit photons of longer wavelength. Can there be stable substances which absorb photons of larger wavelength and emit light of shorter wavelength.

16. Explain why the saturation current in photoelectric effect experiments with light of one frequency and intensity is independent of anode potential?

Ans: In the state of saturation current, all the electrons emitted from the cathode (for the given frequency and intensity) reach the anode and constitute the current. Further increase in anode potential will not increase the number of emitted photoelectrons and thus the current will not change.



17. A student performs an experiment on photoelectric effect, using two materials A and B. A plot of V_{stop} *vs* ν is given in Fig.

(i) Which material A or B has a higher work function?

(ii) Given the electric charge of an electron $= 1.6 \times 10^{-19}$ C, find the value of *h* obtained from the experiment for both A and B.