UNIT 7

PHOTOELECTRIC EFFECT

- The photoelectric effect is the phenomenon of emission of electrons by a metallic surface under the action of light.
- Observation of the experiments on photoelectric effect:
  - The emission of photoelectrons is instantaneous.
  - The number of photoelectrons emitted per second is proportional to the intensity of the incident light.
  - The maximum velocity with which electrons emerge is dependent only on the frequency and not on the intensity of the incident light.
  - There is always a lower limit of frequency called threshold frequency below which no emission takes place, however high the intensity of the incident radiation may be.

Einstein's Photoelectric Equation

- According to Einstein, photon energy is utilized for two purposes.

  Partly for getting the electron free from the atom and away from the metal surface. This energy is known as the photoelectric work function of the metal and is represented by ϕ_0.

  The balance of the photon energy is used up in giving the electron a kinetic energy of $\frac{1}{2}mv^2$

  $$h\upsilon = \phi_0 + \frac{1}{2}mv^2$$

  In the case the photon energy is just sufficient to liberate the electron only, the kinetic energy of the electron is zero.

  i.e., $h\upsilon_0 = \phi_0$.

  where υ_0 is the threshold frequency and ϕ_0 is the work function. If the frequency of incident light is less than υ_0, no photoelectric emission takes place.

  Kinetic energy of photoelectrons is

  $$\Delta KE = h\upsilon - h\upsilon_0 = h(\upsilon - \upsilon_0)$$

  $$= hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) = 12400\left(\frac{1}{\lambda(\text{Å})} - \frac{1}{\lambda_0(\text{Å})}\right) \text{eV}$$

Work Function

- The minimum amount of work or energy necessary to take a free electron out of a metal against the attractive forces of surrounding positive ions inside metals is called the work function of the metal.

  $\phi_0 = h\upsilon_0$, where υ_0 is the threshold frequency.
- An electron can undergo collisions with other electrons, protons or macroscopically with the atom. In this process it will fritter away its energy. Therefore, electrons with KE ranging from 0 to KE_{max} will be produced.

Illustration 1

A beam of light has three wavelengths 4144 Å, 4972 Å and 6216 Å with a total intensity of 3.6×10^{-3} W m^{-2} equally distributed among the three wavelengths. The beam falls normally on an area 1.0 cm^2 of a clean metallic surface of work function 2.3 eV. Assuming that there is no loss of light by reflection and that each energetically capable photon ejects one electron, calculate the number of photo-electrons liberated in 2 seconds.

Soln.: Three different wavelengths are incident on metal surface, so first determine which is (are) capable of ejecting photo-electrons.

For photo-emission, $\lambda \le \lambda_0$. Given: $\phi_0 = 2.3$ eV

$$\phi_0 = hc/\lambda_0$$

$$\Rightarrow \lambda_0 = \frac{hc}{\phi_0} = \frac{6.63\times10^{-34}\times3\times10^8}{2.3\times1.6\times10^{-19}} = 5404 \text{ Å}$$

$\Rightarrow$ only wavelengths 4144 Å and 4972 Å will cause photo-emission (6216 Å > λ_0)

Intensity of each incident wavelength

$$= 3.6\times\frac{10^{-3}}{3} = 1.2\times10^{-3} \text{ W/m}^2$$

[∵ I is distributed equally among three wavelengths]

Number of electrons emitted per second,

$$n/\text{sec} = \frac{IA}{hc/\lambda}$$

$$n/\text{sec}(\lambda = 4144 \text{ Å})$$

$$= \frac{(1.2\times10^{-3})\times(10^{-4})\times4144\times10^{-10}}{6.63\times10^{-34}\times3\times10^8} = 2.5\times10^{11}$$

$$n/\text{sec}(\lambda = 4972 \text{ Å})$$

$$= \frac{(1.2\times10^{-3})\times(10^{-4})\times4972\times10^{-10}}{6.63\times10^{-34}\times3\times10^8} = 3\times10^{11}$$

$\Rightarrow$ total electrons emitted/sec $= 5.5 \times 10^{11}$

$\Rightarrow$ total electrons emitted in 2 seconds $= 11 \times 10^{11}$

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

Illustration 2

The work function of caesium metal is 2.14 eV. When light of frequency 6×10^{14} Hz is incident on the metal surface, photoemission of electrons occurs. What is the :
(a) maximum kinetic energy of the emitted electrons,
(b) stopping potential, and
(c) maximum speed of the emitted photo-electrons?

Soln.: Here,

$\phi_0 = 2.14$ eV, $\upsilon = 6 \times 10^{14}$ Hz

(a) $K_{max} = h\upsilon - \phi_0$

$= 6.63 \times 10^{-34} \times 6 \times 10^{14}\,\text{J} - 2.14\,\text{eV}$

$$= \frac{6.63 \times 6 \times 10^{-20}}{1.6 \times 10^{-19}}\,\text{eV} - 2.14\,\text{eV}$$

$= 2.48 - 2.14 = 0.34$ eV.

(b) As $eV_0 = K_{max} = 0.34$ eV

$\therefore$ Stopping potential, $V_0 = 0.34$ V.

(c) $K_{max} = \frac{1}{2} m v_{max}^2 = 0.34$ eV

$= 0.34 \times 1.6 \times 10^{-19}$ J

$$\text{or} \quad v_{max}^2 = \frac{2 \times 0.34 \times 1.6 \times 10^{-19}}{m}$$

$$= \frac{2 \times 0.34 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}} = 119560.4 \times 10^6$$

or $v_{max} = 345.8 \times 10^3\,\text{m s}^{-1} = 345.8\,\text{km s}^{-1}$.

WAVE PARTICLE DUALITY

- Despite their wave nature, electromagnetic radiations, have properties alike to those of particles. Electromagnetic radiation is an emission with a dual nature *i.e.* it has both wave and particle aspects. In particular, the energy conveyed by an electromagnetic wave is always carried in packets whose magnitude is proportional to frequency of the wave. These packets of energy are called photons.
- Energy of photon is $E = h\upsilon$ where h is Planck's constant, and υ is frequency of wave.

According to de Broglie,

- As wave behaves like material particles, similarly matter also behaves like waves. According to him, a wavelength of the matter wave associated with a particle is given by $\lambda = \frac{h}{p} = \frac{h}{mv}$, where m is the mass and v is velocity of the particle.
- If an electron is accelerated through a potential difference of V volt,

  then $\frac{1}{2} m_e v^2 = eV$ or $v = \sqrt{\frac{2eV}{m_e}}$

  $\therefore \lambda = \frac{h}{m_e v} = \frac{h}{\sqrt{2eVm_e}}$

  (It is assumed that the voltage V is not more than several tens of kilovolt)

Illustration 3

Sun gives light at the rate of 1400 W m^{-2} of area perpendicular to the direction of light. Assume λ (sunlight) = 6000 Å. Calculate the
(a) number of photons/sec arriving at 1 m^2 area at that part of the earth, and
(b) number of photons emitted from the sun/sec assuming the average radius of earth's orbit is 1.49×10^{11} m.

Soln: $I = 1400$ W/m^2 ; $\lambda = 6000$ Å

(a) Energy of the photon, $E = h\upsilon = \frac{hc}{\lambda}$

($c = 3 \times 10^8$ m/sec)

Let n be the number of photons received/sec per unit area.

$$n = \frac{IA}{E_{Photon}} = \frac{(1400 \times 1) \times (6000 \times 10^{-10})}{6.63 \times 10^{-34} \times 3 \times 10^8}$$

$= 4.22 \times 10^{21}$.

(b) Total energy emitted per second = power (watt)

$$n/\text{sec} = \frac{\text{Power of sun (W)}}{E/\text{photon}}$$

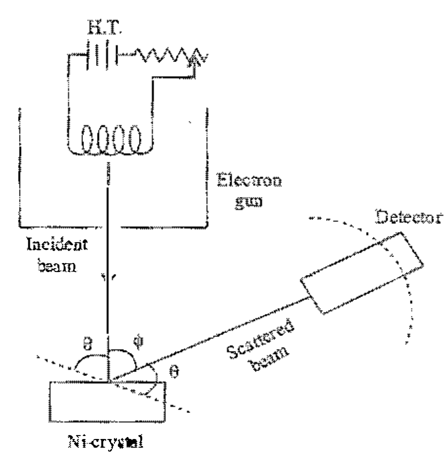
$$= \frac{I \times (4\pi R^2) \times (6000 \times 10^{-10})}{6.63 \times 10^{-34} \times 3 \times 10^8}$$

(R is the average radius of earth's orbit)

$= 1.178 \times 10^{45}$

Davisson and Germer Experiment

- Davisson and Germer experiment proves the concept of wave nature of matter particles. In a crystal lattice, the interatomic distance between the layers and de Broglie wavelengths of an electron are nearly of same order. So, diffraction of electron beam can be observed through crystals. This experiment uses an electron gun to produce fine beam of electrons which can be accelerated to any desired velocity by applying suitable voltage across the gun.
- A fine beam of electrons is made to fall on the surface of nickel crystal. The electrons are scattered in all directions by the atoms of the crystal. The intensity of the electron beam, scattered in a given direction, is measured by the electron detector, which can be rotated, on a circular scale.



Experimental set up