Chapter

14 Dual Nature of Radiation and Matter

Quick Review

➢ **Planck's theory of quantization of energy:**

i. Proposition:

a. Energy is emitted in packets and

b. at higher frequencies, the energy of a packet is large.

ii. Planck assumed that atoms behave like tiny oscillators that emit electromagnetic radiation only in discrete packets of energy $E = nh\nu$, where ν is the frequency of oscillator.

iii. The emissions occur only when the oscillator makes a jump from one quantized level of energy to another of lower energy. This model of Planck formed the basis for explaining the observations of photoelectric effect.

Wave - Particle duality of EM radiations

Photoelectric effect

The phenomenon of emission of electrons from a metal surface when radiation of appropriate frequency is incident on it

Explanation:

i. Einstein proposed that under certain conditions, light behaves as if it was a particle and its energy is released or absorbed in bundles or quanta. He named the quantum of energy of light as photon.

ii. If the frequency of incident radiation is more than the threshold frequency, then the energy ϕ_0 is used by the electron to escape from the metal surface and remaining energy of the photon becomes the kinetic energy of the electron.

Stopping Potential(V_0)

The retarding potential ($-V_0$) for which, photocurrent becomes zero.

$$V_0 = \frac{h\nu}{e} - \frac{\phi_0}{e} = \frac{K.E._{max}}{e}$$

Saturation current(I_0)

Limit of photocurrent at which the increase in I (photocurrent) stops even if V is increased.

Threshold frequency(ν_0)

Minimum value of frequency required for emission of photoelectrons.

Work function (ϕ_0)

Minimum value of energy required for emission of photoelectrons.

The higher the value of work function higher is the value of frequency required to generate photocurrent.

Characteristics of photoelectric effect:

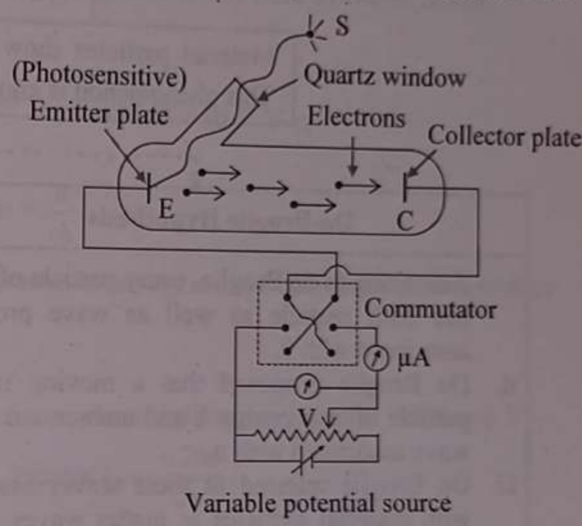
i. For a given photosensitive material, there is no photoelectric emission below the threshold frequency (ν_0). The threshold frequency is different for different metals.

ii. For a given photosensitive material and frequency of incident radiation (above threshold frequency), the photoelectric current is directly proportional to the intensity of incident light.

iii. Above the threshold frequency ν_0, the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiation, but is independent of intensity of incident radiation.

iv. The emission of photoelectron is an instantaneous process. There is no time lag between the irradiation of the metal surface and emission of photoelectrons.

➤ **Experimental setup for photoelectric effect:**



Schematic of experimental set-up for photoelectric effect

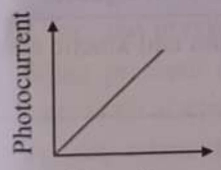
Photoelectric effect

Observations

Effect of intensity

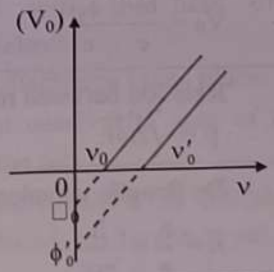
On photocurrent (I)

I ∝ intensity



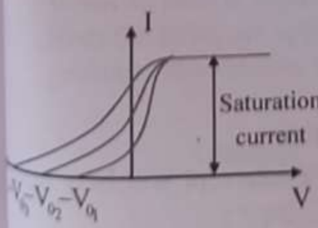
Effect of frequency

On Stopping potential

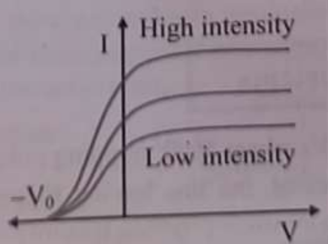


Effect of intensity, frequency and potential

For different frequencies I_0 remains same but V_0 changes.



For different intensities, V_0 remains same but I_0 changes.

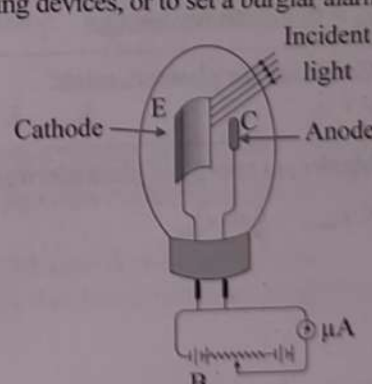


Application

Photocell

i. A device that makes use of the photoelectric effect and converts light energy into electrical energy.

ii. It can be used to operate a counter in counting devices, or to set a burglar alarm.



Schematic of a photocell

Caution

Solar cell is not a photocell. This is because, photoelectric effect is used in photocell but photo-voltaic effect, used in a solar cell.

Einstein's photoelectric equation

i. $K.E._{max} = h\nu - \phi_0$

ii. This implies $K.E._{max}$ depends on the material of emitter plate

Wave - Particle duality of matter

Material particles show wave like nature under certain circumstances. This phenomenon is known as wave-particle duality of matter.

De-Broglie Hypothesis

i. According to de Broglie, every particle of matter has both particle as well as wave properties associated with it.

ii. De Broglie proposed that a moving material particle of total energy E and momentum p has a wave associated with it.

iii. De Broglie referred to these waves associated with material particles as matter waves. Matter waves are also termed as de Broglie waves and De Broglie wavelength is given by,

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}$$

Davisson and Germer experiment

i. The experiment verified the de Broglie hypothesis.

ii. In this experiment nature of electron particles studies with the help of nickel crystal.

iii. Electrons undergo interference and diffraction phenomenon and produce alternate bright and dark rings.

iv. When accelerating potential V = 54 V,
$\lambda = 0.165$ nm (Experimental value)

v. From de Broglie hypothesis,
$\lambda = 0.167$ nm (Theoretical value)

Formulae

1. Energy of photon: $E = h\nu = \frac{hc}{\lambda}$

   [Note: Wavelength (nm) × energy (ev) = 1250
   Wavelength (Å) × energy (eV) = 12500
   i.e., hc = 1250 nm-eV = 12500 Å-eV]

2. Momentum: $p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$

3. Work function: $\phi_0 = h\nu_0 = \frac{hc}{\lambda_0}$

   Where, ν_0 = threshold frequency and
   λ_0 = threshold wavelength

4. Condition for photoemission:

   i. $\nu > \nu_0$ ii. $\lambda < \lambda_0$

5. Maximum energy of photoelectron:

   i. $K.E_{max} = \frac{1}{2} m v_{max}^2$

   ii. $K.E_{max} = h\nu - \phi_0 = h(\nu - \nu_0) = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$

   iii. $K.E_{max} = eV_0$

6. Stopping potential:

   i. $V_0 = \frac{h\nu}{e} - \frac{\phi_0}{e}$ ii. $V_0 = \frac{hc}{e\lambda} - \frac{\phi_0}{e}$

7. Relation between momentum and kinetic energy:
   $p = \sqrt{2mE}$

8. De Broglie wavelength:

   i. $\lambda = \frac{h}{p} = \frac{h}{mv}$ ii. $\lambda = \frac{h}{\sqrt{2mE}}$

   iii. For charged particle: $\lambda = \frac{h}{\sqrt{2meV}}$

   iv. For electron: $\lambda\ (\text{nm}) = \frac{1.228}{\sqrt{V\,(\text{in volts})}}$

Shortcuts

1. Einstein's equation can be written as, $h\nu = \phi_0 + eV_0$ where V_0 is stopping potential.
   Remember, if a question involving a graph is asked, the line having bigger Y-intercept will have higher work function and the slope of the graph will be a constant physical quantity.

2. The slope of the graph between stopping potential and frequency gives the ratio of Planck's constant to electronic charge (h/e).

3. The slope of the graph between kinetic energy and frequency gives the Planck's constant (h) and its X intercept gives the value of threshold frequency.

Whenever calculation in the solution has 'hc' or '$\left(\frac{hc}{e}\right)$' then their values can be used as shown below,

$$hc = 6.63 \times 10^{-34} \times 3 \times 10^{8} = 19.89 \times 10^{-26} \approx 20 \times 10^{-26} \text{ J-m}$$

$$\frac{hc}{e} \approx \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.6 \times 10^{-19}} = 1243.1 \times 10^{-9} \text{ V-m} \approx 1240 \times 10^{-9} \text{ V-m} \approx 12400 \times 10^{-10} \text{ V-m}$$

The equivalent mass of photon while moving is given by, $m = \frac{h}{c\lambda}$.

The de-Broglie wavelength associated with gas molecules varies inversely as the square root of temperature $\left(\lambda \propto \frac{1}{\sqrt{T}}\right)$.

Expression for the wavelength associated with charged particles accelerated through a potential difference V.

Electron: $\lambda_e = \frac{12.27}{\sqrt{V}}$ Å

ii. Proton: $\lambda_p = \frac{0.286}{\sqrt{V}}$ Å

iii. Deuteron: $\lambda_d = \frac{0.202}{\sqrt{V}}$ Å

iv. α-particle: $\lambda_\alpha = \frac{0.101}{\sqrt{V}}$ Å