Chapter 11
Dual Nature of Radiation and Matter

11.1 Introduction

- It was found that at low pressure ,when an electric field is applied to the gas in the discharge tube, a fluorescent glow appeared on the glass opposite to cathode. These cathode rays were discovered, in 1870, by William Crookes who later, in 1879, suggested that these rays consisted of streams of fast moving negatively charged particles.
- By applying mutually perpendicular electric and magnetic fields across the discharge tube, J. J. Thomson determined experimentally the speed and the specific charge [charge to mass ratio (e/m)] of the cathode ray.
- In 1887, it was found that certain metals, when irradiated by ultraviolet light, emitted negatively charged particles having small speeds. Also, certain metals when heated to a high temperature were found to emit negatively charged particles. The value of e/m of these particles was found to be the same as that for cathode ray particles.

These observations thus established that all these particles, although produced under different conditions, were identical in nature. J. J. Thomson, in 1897, named these particles as electrons, and suggested that they were fundamental, universal constituents of matter.In 1913, the American physicist R. A. Millikan performed oil-drop experiment and measured the charge of electron as 1.602×10^{-19} C. Millikan's experiment established that electric charge is quantised.

11.2 Electron emission

If an electron attempts to come out of the metal, the metal surface acquires a positive charge and pulls the electron back to the metal. The electron can come out of the metal surface only if it has got sufficient energy to overcome the attractive pull.

Work Function

The minimum energy required to eject an electron from the metal surface is called work function. The work function is denoted by ϕ_0 .

- Work function is measured in electron volt (eV).
- ϕ_0 depends on properties of metal and nature of its surface.

- One electron volt is the energy gained by an electron when it has been accelerated by a potential difference of 1 volt.

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

TABLE 11.1 WORK FUNCTIONS OF SOME METALS

Metal	Work function ϕ_o (eV)	Metal	Work function ϕ_o (eV)
Cs	2.14	Al	4.28
K	2.30	Hg	4.49
Na	2.75	Cu	4.65
Ca	3.20	Ag	4.70
Mo	4.17	Ni	5.15
Pb	4.25	Pt	5.65

The work function of platinum is the highest ($\phi_0 = 5.65$ eV) while it is the lowest ($\phi_0 = 2.14$ eV) for caesium.

The minimum energy required for the electron emission from the metal surface can be supplied to the free electrons by any one of the following physical processes:

(i) Thermionic emission

By suitably heating, the free electrons will get sufficient thermal energy to escape from the metal surface.

(ii) Field Emission

By applying a very strong electric field (of the order of 10^8 V/m) to a metal, electrons will get sufficient energy to escape from the metal, as in a spark plug.

(iii) Photo-electric emission

When light of suitable frequency incident on a metal surface, electrons are emitted from the metal surface. These photo(light)-generated electrons are called photoelectrons.

11.3 Photoelectric Effect

Hertz's observations

The phenomenon of photoelectric emission was discovered in 1887 by Heinrich Hertz (1857-1894).

He observed that when light falls on a metal surface, the electrons escaped from the surface of the metal into the surrounding space.

Hallwachs' and Lenard's observations

Lenard (1862-1947) observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube enclosing two electrodes (metal plates), current flows in the circuit.
Hallwachs, in 1888, connected a negatively charged zinc plate to an electroscope and found that negatively charged particles were emitted from the zinc plate under the action of ultraviolet light.

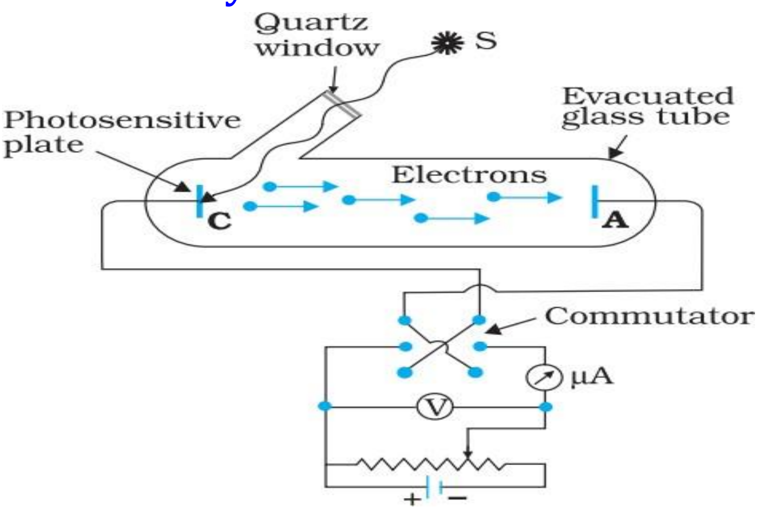
It was found that zinc, cadmium, magnesium, etc., responded only to ultraviolet light, having short wavelength, to cause electron emission from the surface.

However, some alkali metals such as lithium, sodium, potassium, caesium and rubidium were sensitive even to visible light.

Photoelectric Effect

The phenomenon of emission of electrons when photosensitive substances are illuminated by light of suitable frequency is called photoelectric effect.

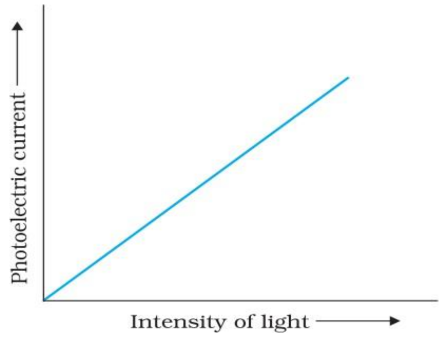
11.4 Experimental Study of Photoelectric Effect



Experimental arrangement consists of an evacuated glass/quartz tube having a photosensitive plate C and another metal plate A. Monochromatic light from the source S of sufficiently short wavelength passes through the window W and falls on the photosensitive plate C (emitter). A transparent quartz window permits ultraviolet radiation to pass through it and irradiate the photosensitive plate C. The electrons are emitted by the plate C and are collected by the plate A (collector), by the electric field created by the battery. The polarity of the plates C and A can be reversed by a commutator. When the collector plate A is positive with respect to the emitter plate C, the electrons are attracted to it. The emission of electrons causes flow of electric current in the circuit.

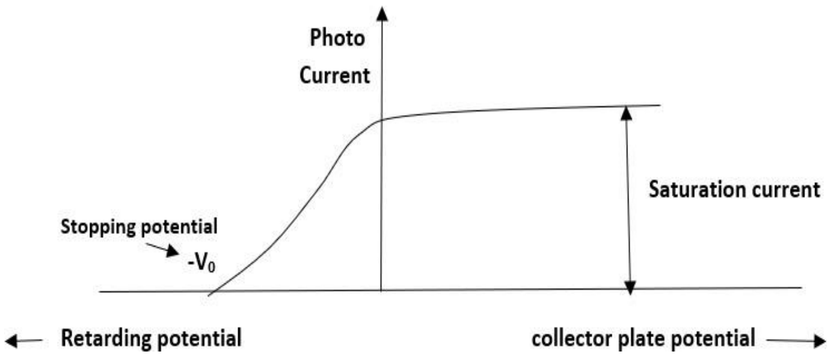
The photoelectric current can be increased or decreased by varying the potential of collector plate A with respect to the emitter plate C. The intensity and frequency of the incident light can also be varied.

1.Effect of intensity of light on photocurrent



When intensity of incident radiation is increased(keeping the frequency of the incident radiation and the accelerating potential fixe), the number of photoelectrons emitted per second increases and hence the photoelectric current also increases.
i.e., the photocurrent increases linearly with intensity of incident light.

2.Effect of potential on photoelectric current



When the positive potential of collector (A) is increased the photoelectric current increases until all the electrons are collected by the collector(A). Then the photocurrent becomes maximum and is called saturation current.

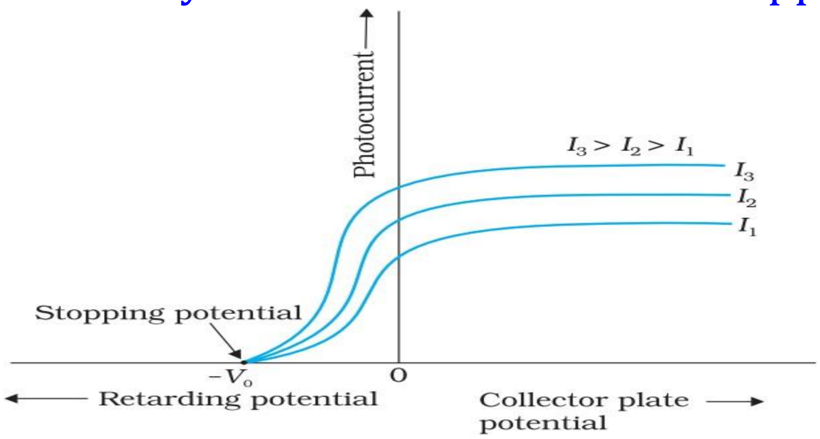
Now the collector is made negative with respect to emitter C. Then the photocurrent decreases with increases in negative potential and finally becomes zero. The minimum negative potential of emitter plate A for which the photocurrent stops or bocomes zero is called the cut off potential or stopping potential (V_0)

At stopping potential,

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

$$\frac{1}{2} m v_{max}^2 = e\,V_0$$

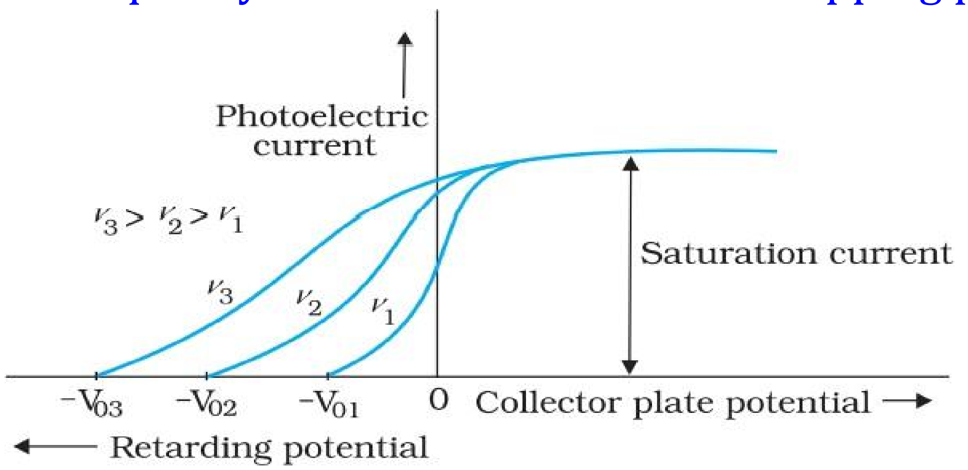
3.Effect of Intensity of incident radiation on stopping potential



The experiment is repeated with incident radiation of the same frequency but different intensities I_1, I_2 and I_3 ($I_3 > I_2 > I_1$).When the intensity of incident radiation is increased ,number of photo electrons emitted per second increases and hence the the saturation current increases. But as the kinetic energy of photoelectrons remains constant and the stopping potential also remains constant.

i.e., for a given frequency of incident radiation, the stopping potential is independent of intensity of radiation.

4.Effect of frequency of incident radiation on stopping potential



The experiment is repeated at same intensity of light radiation but differenr frequencies v_1, v_2 *and* v_3 such that $v_1 > v_2 > v_3$. When the frequency of incident radiation increases, the kinetic energy of photoelectrons increases and hence the stopping potential also increases. But as the intensity does not change , the saturation current will be the same for different frequencies.

i.e., the stopping potential increases with increase in frequency of incident radiation.

Laws of Photoelectric Effect

i. For a given photosensitive material and frequency of incident radiation, the photoelectric current is directly proportional to the intensity of incident light.
ii. For a given photosensitive material and frequency of incident radiation, saturation current is found to be proportional to the intensity of incident radiation whereas the stopping potential is independent of its intensity .
iii. For a given photosensitive material, there exists a certain minimum cut-off frequency of the incident radiation, called the threshold frequency(ν_0) below which no emission of photoelectrons takes place, no matter how intense the incident light is. Above the threshold frequency, the stopping potential or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiation, but is independent of its intensity
iv. The photoelectric emission is an instantaneous process without any apparent time lag.

Threshold Frequency

Threshold frequency is the minimum cut-off frequency of the incident radiation, below which photo emission is not possible, no matter how intense the incident light is.

11.5 Photoelectric Effect and Wave Theory of Light

The phenomena of interference, diffraction and polarisation were explained by the wave picture of light. But the wave picture is unable to explain the most basic features of photoelectric emission.

- According to the wave picture of light, the free electrons at the surface of the metal absorb the radiant energy continuously. The greater the intensity of radiation, the greater should be the energy absorbed by each electron. This is contradictory to the observations of photoelectric effect.
- As large number of electrons absorb energy, the energy absorbed per electron per unit time turns out to be small. It can take hours or more for a single electron to pick up sufficient energy to overcome the work function and come out of the metal. This is contrast to observation that the photoelectric emission is instantaneous.

11.6 Einstein's Photoelectric Equation: Energy Quantum of Radiation

Einstein explained photoelectric effect based on Planck's quantum theory of radiation. When a photon incident on a metal surface, a part of its energy is used as work function and the remaining part is used to give kinetic energy to emitted photoelectrons.

Energy of photon =work function + KE of electrons

$$h\nu = \phi_0 + K_{max}$$

$$K_{max} = h\nu - \phi_0 \text{ ---------------- (1)}$$

This is known as Einstein's photoelectric equation.

At stopping potential V_0

$$K_{max} = eV_0$$

$$eV_0 = h\nu - \phi_0 \text{ ---------------- (2)}$$

At threshold frequency , $\nu = \nu_0$, KE = 0 , $\phi_0 = h\nu_0$

$$K_{max} = h\nu - h\nu_0 \text{ -------------- (3)}$$

Since K_{max} is must be non negative, the photo emission is possible only if $h\nu > \phi_0$, $h\nu > h\nu_0$, $\nu > \nu_0$

where, $\nu_0 = \frac{\phi_0}{h}$

Greater the work function ,greater the threshold frequency.
Below threshold frequency ,photoemission is not possible.

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

$$\frac{1}{2} m v_{max}^2 = h(\nu - \nu_0) \text{ ------------(4)}$$

$c = \nu\lambda$ then $\nu = \frac{c}{\lambda}$, $\nu_0 = \frac{c}{\lambda_0}$

$$\frac{1}{2} m v_{max}^2 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \text{ ----------(5)}$$

where λ_0 is called threshold wavelength.

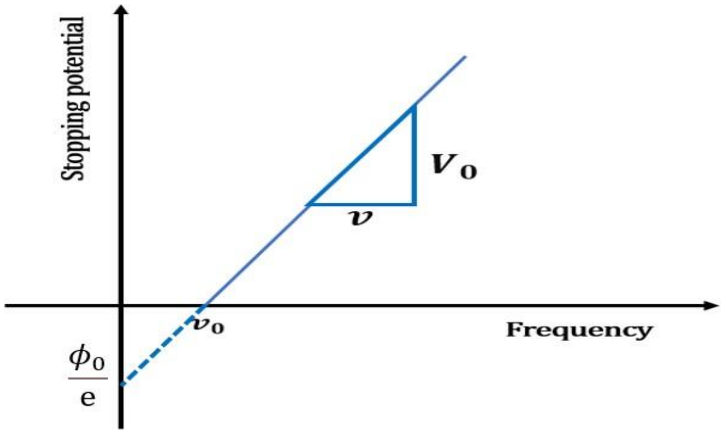
Variation of stopping potential with frequency of incident radiation

At stopping potential V_0 Einstein's photoelectric equation ,

$$eV_0 = h\nu - \phi_0$$

$$V_0 = \frac{h}{e}v - \frac{\phi_0}{e}$$

This equation shows that the graph between stopping potential V_0 and frequency v is a straight line with slope $\frac{h}{e}$ which is a constant independent of nature of material.



From graph , slope $= \frac{V_0}{v} = \frac{h}{e}$

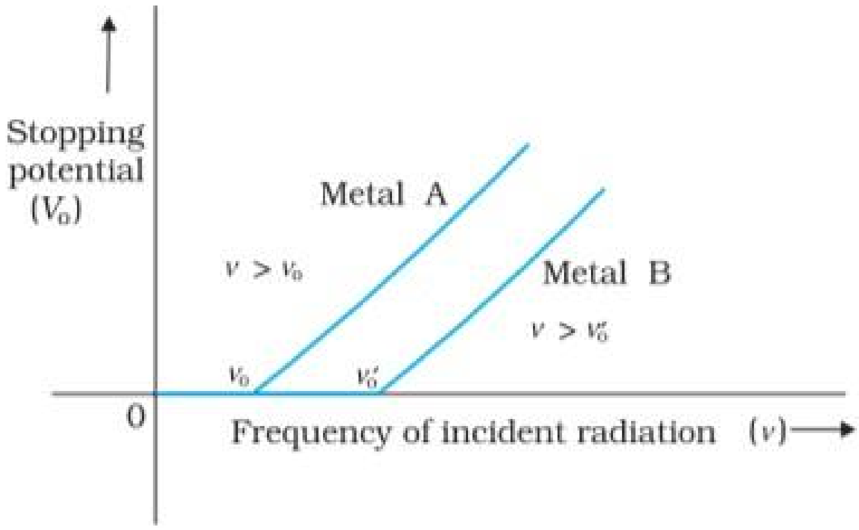
The y- intercept $= \frac{\phi_0}{e}$

The graph shows that

(i) the stopping potential V_0 varies linearly with the frequency of incident radiation for a given photosensitive material.

(ii) there exists a certain minimum cut-off frequency ν_0 for whicthe stopping potential is zero

For two metals A and B these graphs metal A metal B will be parallel straight lines



11.7 Particle Nature of Light –The Photon

1) In the interaction of light with matter , light behaves as if it is made up of particles called photon.

2) Each photon has energy, E=hν and momentum p= hν/c and speed c= 3x 10^8m/s

3) All photons of light of a particular frequency ν, or wavelength λ, have the same energy and momentum p, whatever the intensity of radiation may be.

4) When intensity of light is increased only the number of photons increases, but the energy of photon is independent of intensity of light.

5) Photons are electrically neutral. They are not deflected by electric and magnetic fields.

6) In photon-particle collision 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.

Example

Monochromatic light of frequency 6.0 $\times 10^{14}$ Hz is produced by a laser. The power emitted is 2.0 $\times 10^{-3}$ W.

(a) What is the energy of a photon in the light beam?

(b) How many photons per second, on an average, are emitted by the source?

(a) Each photon has an energy E = h ν = 6.63 $\times 10^{-34}$x6.0 $\times 10^{14}$ Hz

= 3.98 × 10^{-19} J

(b) $N = \frac{P}{E} = \frac{2x10^{-3}}{3.98x10^{-19}} = 5\text{ x}10^{15}$ photons per second

Example

The work function of a metal is 6eV. If two photons each having energy 4 eV strike the metal surface. Will the emission be possible? Why?

No, photo emission is not possible.

Photo emission is possible only if $h\nu > \phi_0$

Here energy of incident photon is less than work function and hence photo emission is not possible.

Example

The work function of caesium is 2.14 eV.

a) Find the threshold frequency for caesium.

b) the wavelength of the incident light if the photocurrent is brought to zero by a stopping potential of 0.60 V.

a) $$v_0 = \frac{\phi_0}{h}$$

$\phi_0 = 2.14 \text{ eV} = 2.14 \times 1.6 \times 10^{-19}$ J

$h = 6.63 \times 10^{-34}$ Js

$$v_0 = \frac{2.14 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}} = 5.16 \times 10^{14} \text{ Hz}$$

b) $$e V_0 = hv - \phi_0$$

$$hv = e V_0 - \phi_0$$

$$h\frac{c}{\lambda} = e V_0 - \phi_0$$

$$\lambda = \frac{hc}{eV_0 - \phi_0}$$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.6 \times 10^{-19} \times 0.6 - 2.14 \times 1.6 \times 10 - 19} = 454 \text{ nm}$$

11.8 Wave Nature of Matter

- The wave nature of light shows up in the phenomena of interference, diffraction and polarisation. On the other hand, in photoelectric effect and Compton effect which involve energy and momentum transfer, radiation behaves as if it is made up of particles – the photons.
- The gathering and focussing mechanism of light by the eye-lens is well described in the wave picture. But its absorption by the rods and cones (of the retina) requires the photon picture of light.

A natural question arises: If radiation has a dual (wave-particle) nature, might not the particles of nature (the electrons, protons, etc.) also exhibit wave-like character?

Louis Victor de Broglie argued that moving particles of matter should display wave-like properties under suitable conditions.

As nature is symmetrical , the two basic physical entities of nature – matter and energy, must have symmetrical character. If radiation shows dual aspects, matter should also exhibit dual nature.

de Broglie Relation -Wavelenth of matter wave

De Broglie proposed that the wave length λ associated with a particle of momentum p is given as

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

where m is the mass of the particle and v its speed.

λ is called de Broglie wavelength.

The dual aspect of matter is evident in the de Broglie relation. Here λ is a wave attribute while the momentum p is a particle attribute. Planck's constant h relates the two attributes.

Why macroscopic objects in our daily life do not show wave-like properties?

The de Broglie wavelength of a ball of mass 0.12 kg moving with a speed of 20 m s^{-1} is ,

$$\lambda = \frac{h}{mv} = \frac{6.6 \, x 10^{-34}}{0.12 \, x 20} = 2.76\text{x}10^{-34} \text{ nm}$$

This wavelength is so small that it is beyond any measurement. This is the reason why macroscopic objects in our daily life do not show wave-like properties. But in the sub-atomic domain, the wave character of particles is significant and measurable.

Example

What is the de Broglie wavelength associated with an electron moving with a speed of 5.4×10^{6} m/s?

$$\lambda = \frac{h}{mv} = \frac{6.6 \, x 10^{-34}}{9.1 \, x \, 10^{-31} x \, 5.4 \, x 10^{6}} = 0.135 \text{ nm}$$

This wavelength is measurable. i.e., in the sub-atomic domain, the wave character of particles is significant and measurable.