SHORT NOTES: CLASS 12

CHAPTER 11: DUAL NATURE OF RADIATION AND MATTER

DISCOVERY	DISCOVERER
Cathode rays	William Crookes(1879)
X-rays	Roentgen(1895)
Electrons	J.J. Thomson (1897)

Millikan: measured experimentally charge to mass (specific charge, e/m) ratio and predicted that q = ne. e/m of electron = 1.76×10^{11} C/Kg

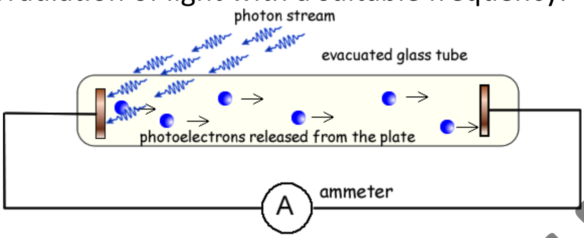
Light has a dual nature: Wave nature- wave theory of light**,**

Particle nature- Quantum theory of light: photoelectric effect by Hertz, Compton Effect by Compton and Stark effect by Stark

According to the **quantum theory of light**, light consists of packets of energy that travel in a straight line with the speed of light. Each packet of energy is called a photon or quantum of light (**$E = h\nu = hc/\lambda$**) where h is Planck's constant and $h = 6.6 \times 10^{-34}$ Js.

Free electrons: loosely bound electrons

Work Function, φ: It refers to the minimum amount of energy required to take out one electron from the metal surface. This energy can be supplied through various sources, such as a strong electric field or irradiation of light with a suitable frequency.



Photoelectric Effect: The phenomenon of emission of photoelectrons from the surface of metal, when a light beam of suitable frequency is incident on it, is called the photoelectric effect. The emitted electrons are called photoelectrons and the current so produced is called photoelectric current.

Hertz's Observation: The phenomenon of photoelectric emission was discovered in 1887 by Heinrich Hertz during his electromagnetic wave experiment. In his experimental investigation on the production of electromagnetic waves by means of a spark across the detector, the loop was enhanced when the emitter plate was illuminated by ultraviolet light from an arc lamp.

Lenard's Observation: Lenard observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube enclosing two electrodes, current flows. As soon as the ultraviolet radiations were stopped, the current flow also stopped. These observations indicate that when ultraviolet radiations fall on the emitter plate, electrons are ejected from it, which are attracted toward the positive plate by the electric field.

Terms Related to Photoelectric Effects:

a) **Free Electrons:** In metals, the electrons in the outer shells (valence electrons) are loosely bound to the atoms; hence they are free to move easily within the metal surface but cannot leave the metal surface. Such electrons are called free electrons.

b) **Electron Emission**: The phenomenon of emission of electrons from the surface of a metal is called electron emission.
Photoelectric Emission: It is the phenomenon of emission of electrons from the surface of a metal when light radiations of suitable frequency fall on it.

c) **Work Function**: The minimum amount of energy required to just eject an electron from the outer most surface of metal is known as work function of the metal.

$$\textbf{Work function, } \varphi \textbf{ (or W)} = h\nu_o = \frac{hc}{\lambda}$$

Where, ν_o and λ_o are the threshold frequency and threshold wavelength respectively.

d) **Cut-off Potential (V_o):** For a particular frequency of incident radiation, the minimum negative (retarding) potential V_0 given to plate for which the photoelectric current becomes zero, is called cut-off or stopping potential.

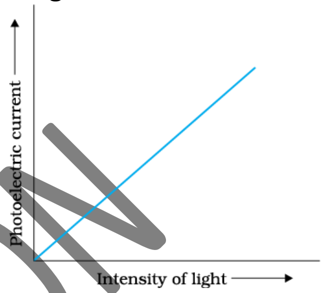
K.E.$_{max}$ = eV$_o$ => $\frac{1}{2} mv^2_{max} = eV_o$

e) **Cut-off Frequency (ν_o):** The minimum frequency of light that can emit photoelectrons from a material is called threshold frequency or cut-off frequency of that material.

f) **Cut-off Wavelength (λ_o):** The maximum wavelength of light which can emit photoelectrons from a material is called the threshold wavelength or cut-off wavelength of that material.

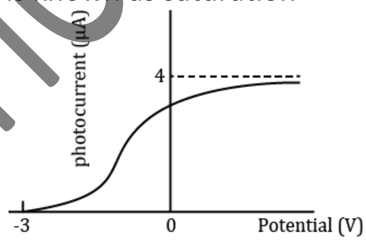
EFFECT OF INTENSITY OF LIGHT ON PHOTO CURRENT: For a fixed frequency of incident radiation, the photoelectric current increases linearly with an increase in the intensity of incident light.

- Zn, Cd, and Mg respond to UV light as they have short wavelengths and high work function.
- Li, Na, K, Rb, Cs are sensitive to visible light, emit photoelectrons in visible light and have very low work function.

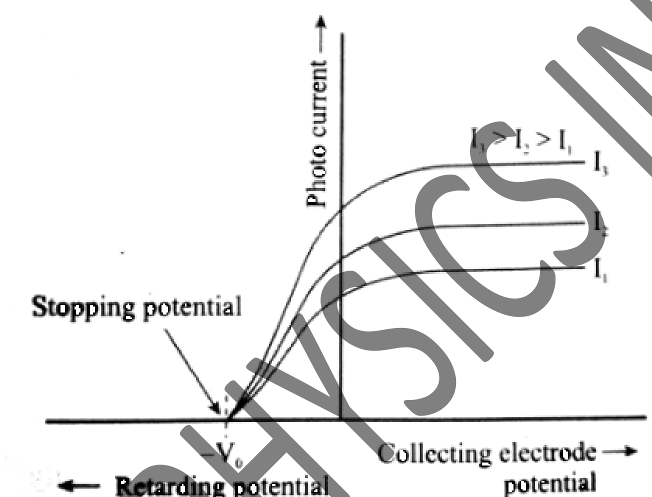


EFFECT OF POTENTIAL ON PHOTOELECTRIC CURRENT: For a fixed frequency and intensity of incident light, the photoelectric current increases with an increase in the potential applied to the collector.

When all the photoelectrons reach plate A, the current becomes maximum it is known as saturation current. A higher intensity of radiation produces a higher value of photocurrent. When all the photoelectrons reach plate A, the current becomes maximum it is known as saturation current. For the negative potential difference, as the absolute value of the potential difference increases, the value of the photocurrent decreases and becomes zero at the stopping potential (also called cut-off potential or retarding potential).



Photoelectric current is zero, whenever no electron, even the fastest photoelectrons cannot reach plate A.



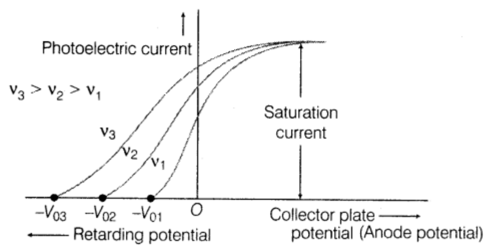
HOW IS INTENSITY, CURRENT & STOPPING POTENTIAL RELATED?

Note:

- The saturation photoelectric current is proportional to the intensity of incident radiation. Saturation current α Intensity
- Changing the intensity of incident radiation does not affect the stopping potential.
- Kinetic energy is independent of intensity.

EFFECT OF FREQUENCY OF INCIDENT RADIATION ON STOPPING POTENTIAL

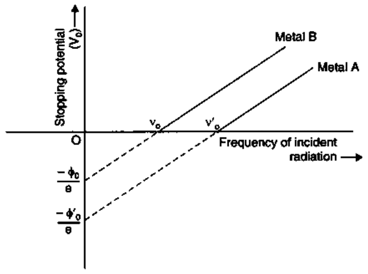
As, the **frequency of radiation (ν) increases, the stopping potential (V_o) increases.** An increase in the frequency of the incident light will increase the kinetic energy of the emitted electrons, therefore greater retarding potential is needed to stop them. We take radiations of different frequencies but of the same intensity. For each radiation, we study the variation of photoelectric current against the potential difference between the plates.



Note:

- The saturation photoelectric current is frequency-independent.
- The value of stopping potential is more negative for radiation of higher incident frequency.
- UV radiations can produce photoelectric emission in Cu.

Stopping potential and the frequency of the incident radiation for two different metals A & B:



- The stopping potential varies linearly with the frequency of the incident radiation.
- The higher the work function for a photosensitive material the greater the value of threshold frequency.

LAWS OF PHOTOELECTRIC EMISSION:

i. For a given material and a given frequency of incident radiation, the photoelectric current (number of photoelectrons ejected per second) is directly proportional to the intensity of the incident light.

ii. For a given material, there exists a certain minimum frequency of the incident radiation below which no emissions of photoelectrons take place. This frequency is called threshold frequency.

iii. Above the threshold frequency, the maximum kinetic energy of the emitted photoelectron is independent of the intensity of incident light but depends only upon the frequency (or wavelength) of the incident light.

iv. The photoelectric emission is an instantaneous process. The time lag between the incidence of radiations and emission of photoelectrons is very small, less than even 10^{-9} s.

EINSTEIN'S PHOTOELECTRIC EQUATION: ENERGY QUANTUM OF RADIATIONS

Consider a photon of radiation of frequency ν, incident on a photosensitive metal surface.
The energy of the photon is given by $E = h\nu$
The energy of the incident photon is spent in two ways:

i. 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 of the metal.

ii. The rest of the energy of the photon is used in imparting the maximum kinetic energy to the emitted photoelectron.

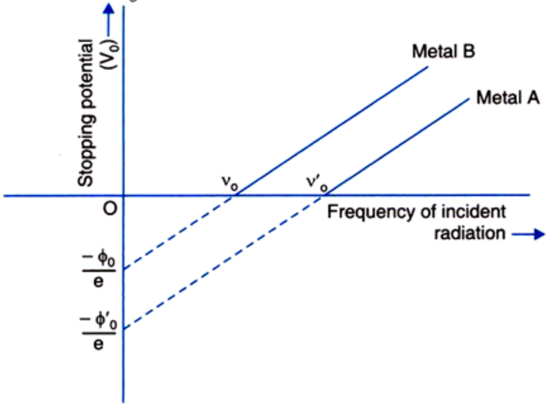
If v_{max} is the maximum velocity of the emitted photoelectron and m is its mass, then
Max. K.E. of the photoelectrons, $K_{max} = \frac{1}{2} mv^2_{max}$
Therefore, $h\nu = \varphi_o + \frac{1}{2} mv^2_{max}$ where, Φ_o = work-function: $\Phi_o = h\nu_o$
$K_{max} = \frac{1}{2} mv^2_{max} = h\nu - h\nu_o = h(\nu - \nu_o)$

RELATION BETWEEN CUT OFF POTENTIAL, FREQUENCY OF THE INCIDENT PHOTON AND THRESHOLD FREQUENCY/WAVELENGTH:

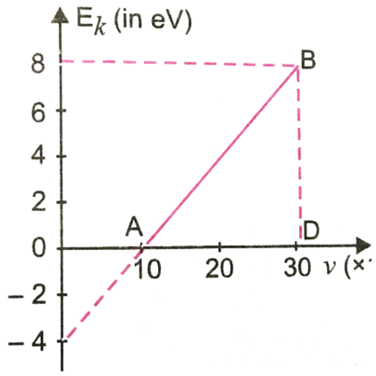
Max. K.E. of the photoelectrons, $K_{max} = h(\nu - \nu_o)$
If V_o is the cutoff potential or stopping potential and e is the charge on an electron. then
$K_{max} = eV_o$
Therefore, $eV_o = h(\nu - \nu_o) = h(\frac{c}{\lambda} - \frac{c}{\lambda o}) = hc\,(\frac{1}{\lambda} - \frac{1}{\lambda o})$
For photoelectric emission, $\lambda < \lambda_o$ and $\nu > \nu_o$

GRAPHS:

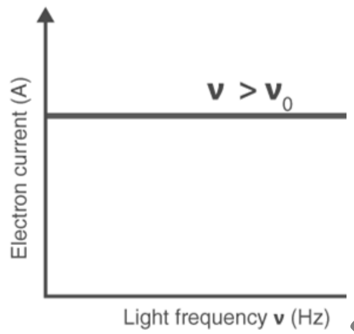
a) Frequency and stopping potential graph:



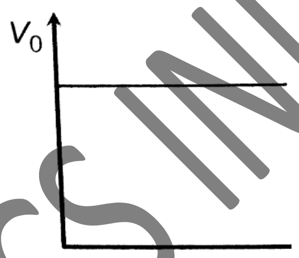
b) Frequency and maximum kinetic energy graph:



c) Frequency and photoelectric current graph:



d) Intensity and stopping potential graph:



e) Time and photoelectric current graph: