UNIT – 5 (BASIC PHY)
(MODERN PHYSICS)

5.1 (PHOTO ELECTRICITY):

Planck's Hypothesis: 1. Light energy can only be emitted and absorbed in discrete bundles called quanta.
2. The quanta of light are called photons.

Properties of Photons:

1. All photons emitted by a source of radiation travel in straight line with the speed of light in vacuum.
2. Energy of a photon is $E = h\nu = \frac{hc}{\lambda}$, where h is Planck's constant. $h = 6.62 \times 10^{-34}$ J-S, ν and λ are frequency and wavelength of photon respectively; c is speed of radiation (light)
3. The frequency of photon does not change as it moves from one medium to the other.
4. Wavelength and speed of photon change as it moves from one medium to the other.
5. Equivalent mass 'm' of a photon of frequency ν is given by Einstein's relation i.e

$$\text{Energy } E (= h\nu) = mc^2$$
$$\text{or, } mc^2 = h\nu, \text{ or } m = \frac{h\nu}{c^2}$$

6. The momentum possessed by photon,

$$p = mc = \frac{h\nu}{c} = \frac{h}{c} \times \frac{c}{\lambda} = \frac{h}{\lambda}$$
$$\therefore \boxed{p = \frac{h}{\lambda}}$$

7. For an X-ray tube operating at an accelerating potential of V volts, the potential energy of the accelerating electrons is converted into energ...

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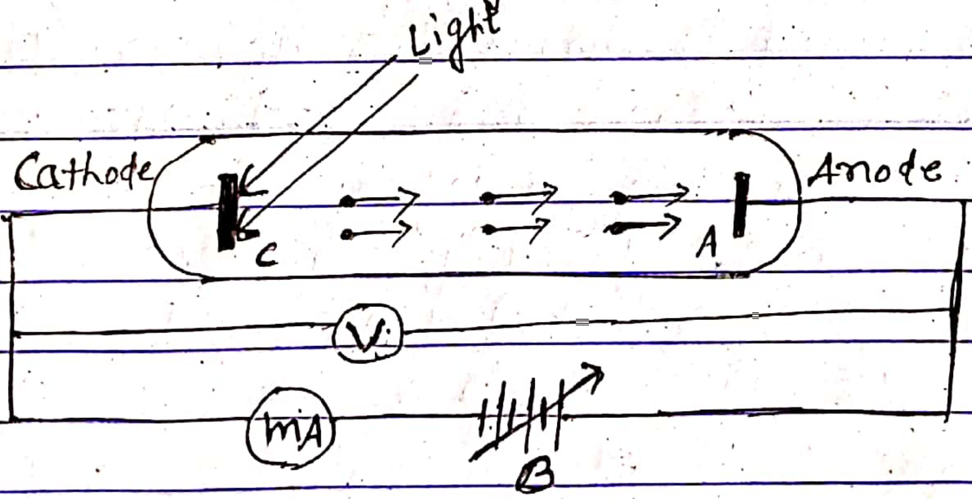
of the radiated photon

$$E = eV = h\nu = \frac{hc}{\lambda}$$

NOTE: The energy of a photon is usually expressed in electron volt (eV), where $1\,eV = 1.6 \times 10^{-19}\,J$.

Photoelectric Effect: When light of sufficiently small wavelength is incident on a photosensitive metal surface like Zinc, Cadmium, selenium, etc; electrons are ejected from the metal. This phenomenon is called the photoelectric effect. The electrons ejected from the metal are called photoelectrons.

Experimental study of the Photoelectric Effect:



This fig. consists of an evacuated glass or quartz tube with two electrodes. The photosensitive surface forms the cathode. A potential difference is maintained between the cathode C and anode A by a variable battery B. The photoelectric current is measured by a milliammeter (mA) while potential difference is measured by a voltmeter V. The tube is evacuated so that emitting surface is not contaminated by collisions with air molecules and electrons also donot lose energy by collisions.

A beam of incident light of suitable frequency acts like a switch and photo electrons are emitted by the cathode. These electrons get accelerated towards the plate A if it is kept at a positive potential with respect to the cathode. A current thus flows in the outer circuit which is called Photo-current.

Photoelectric effect depends upon the following factors :

1. Intensity of incident light
2. frequency of incident light
3. Photosensitivity of the coated metal surface.

* Threshold frequency (ν_0) : "The frequency at which maximum kinetic energy goes to zero is called threshold frequency (ν_0) or cut-off frequency." Below this frequency, no photocurrent is observed. It is different for different photosensitive materials.
* Stopping potential (V_0) ; "The minimum value of negative potential at which photoelectric current becomes zero is called stopping potential or cut-off potential.

Laws of Photoelectric effect :

(i) The rate of emission of electrons is directly proportional to the intensity of the incident light.

(ii) The velocity of the electrons emitted is independent of the intensity of light and depends only upon the frequency (or wavelength) of the light and the nature of the metal. Max. K.E of the emitted photo-electrons varies linearly with the frequency of the incident light.

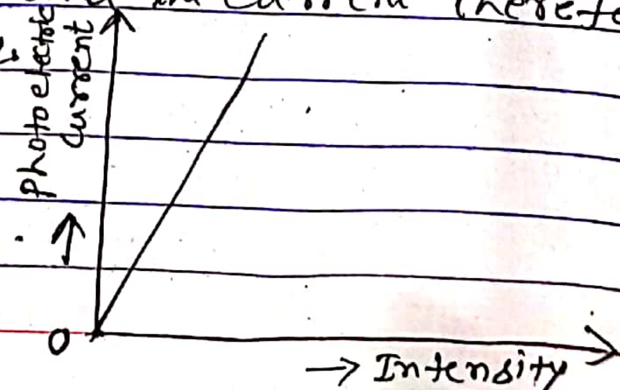
(iii) There exists a minimum frequency known as the threshold frequency for every photo sensitive material at which electron just starts with pratically zero velocity.

(iv) The max. velocity (V_{max}) and hence, the stopping potential (V_0) are independent of the intensity of the incident light but are directly proportional to the frequency of the incident radiation for a given metal.

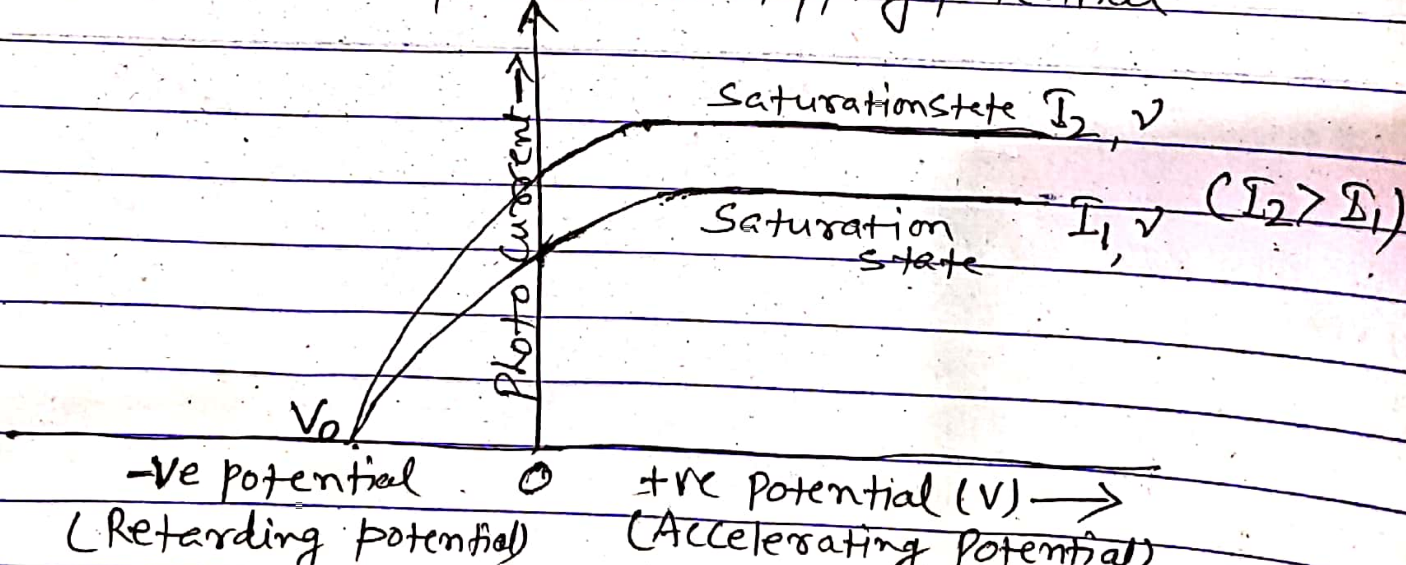
$$K.E_{max} = \frac{1}{2} m V_{max}^2 = eV_0$$

Characteristics of the Photoelectric Effect :-

1. Variation of photocurrent with intensity of incident light : When the intensity of light increases, there is a corresponding increase in the number of photoelectrons and the current therefore increases linearly.

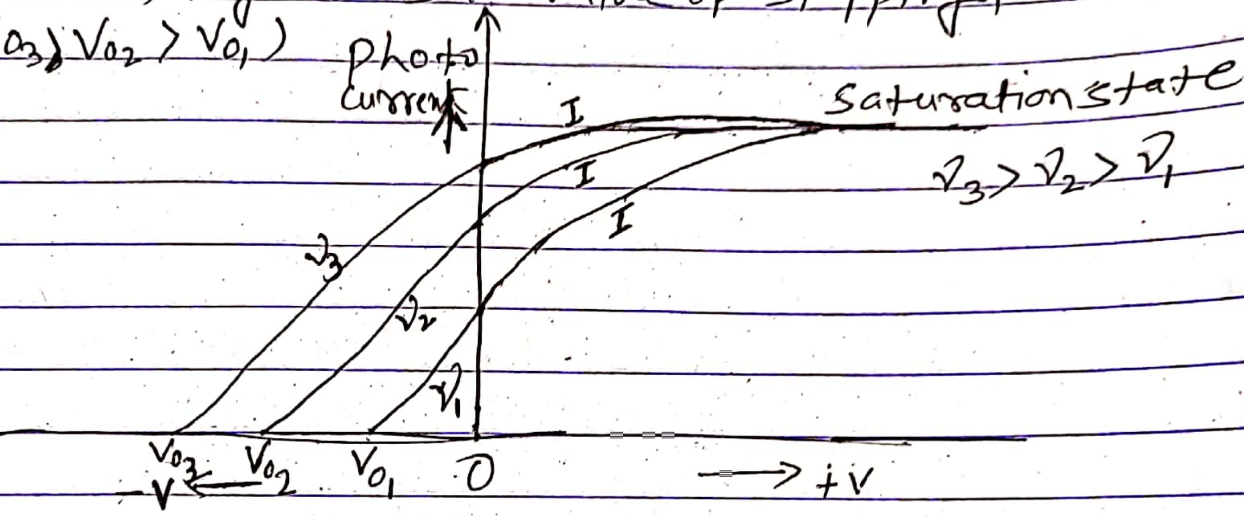


2. Variation of Photo Current with anode potential:
When intensity and frequency of the incident light are kept fixed while potential of anode is varied, it is found that the photo electric current increases with the increase in +ve potential till it reaches a value when photo electric current reaches a saturation value. On the other hand if a -ve potential is applied to plate with respect to cathode and is increased gradually, we find that photo current decreases rapidly and finally becomes zero at a stopping potential (V_0) as shown below. For a higher intensity I_2 ($I_2 > I_1$) of incident radiation, we find that saturation current is higher but stopping potential is same i.e. for a given frequency of the incident radiation stopping potential is independent of the intensity.
In graph OB represents stopping potential.



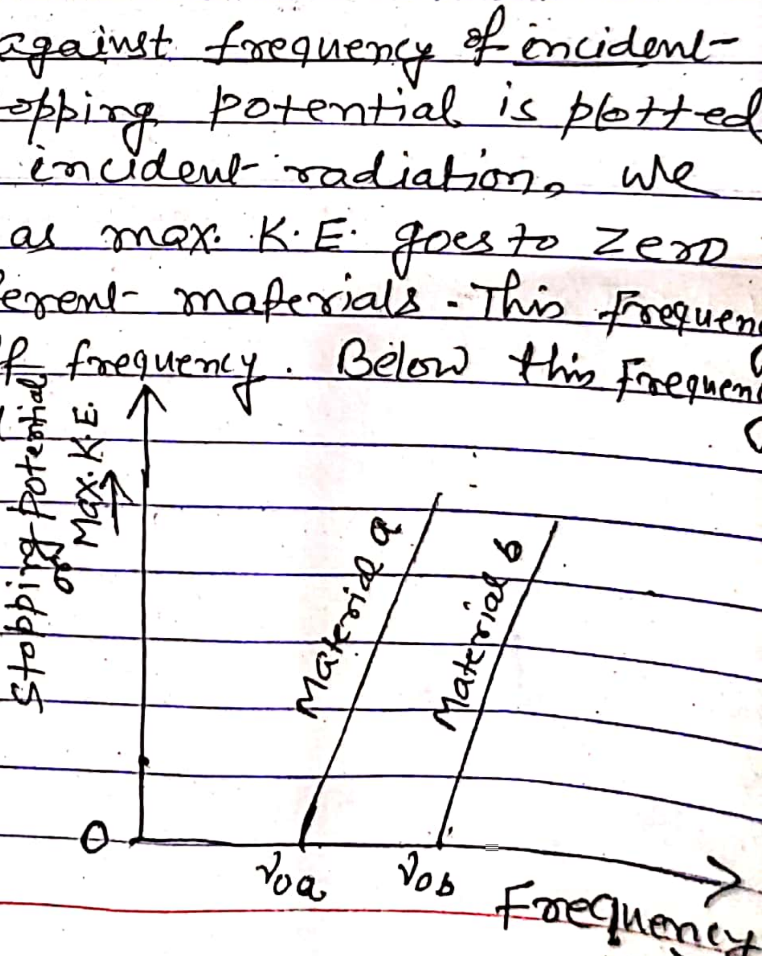
3. Variation of photo current with the frequency of the incident light: Graph shows the variation of photo current with the potential of anode for

various frequencies of incident light (ν_1, ν_2, ν_3---) but at the same intensity. we find that saturation current is same in all the cases but stopping potential is different. Higher is the frequency of the incident radiation, higher is the value of stopping potential ($V_{O_3} > V_{O_2} > V_{O_1}$)

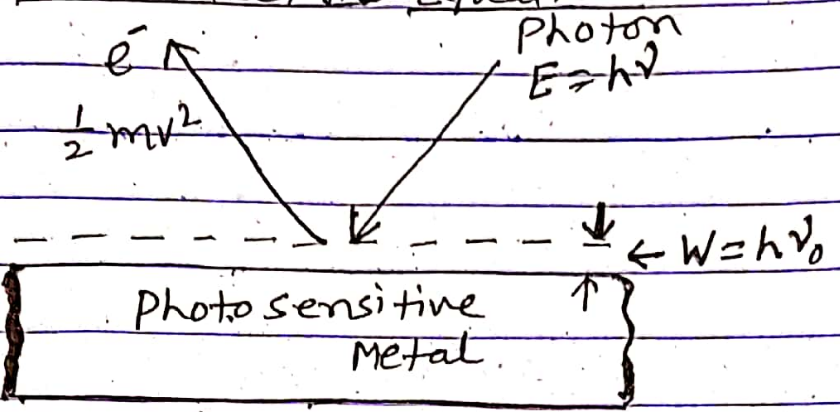


4. <u>Stopping potential against frequency of incident radiation</u> : If stopping potential is plotted against frequency of incident radiation, we get a straight line, as max. K.E. goes to zero is different for different materials. This frequency is called threshold or cutoff frequency. Below this frequency no photo current is observed.

[$\nu_{0a} < \nu_{0b}$, so Material a is more photo sensitive than Material b].



Einstein's Photoelectric Equation :



When a photon of energy $h\nu$ is incident on a metal plate, part of its energy, W is used up in liberating the electrons from the surface of the plate (work function) and the other part in imparting a velocity v to the ejected electrons as shown in the above fig.

∴ Energy of the photon = Work function + K.E. of the electron

$$h\nu = W + \frac{1}{2}mv_{max}^2$$

If ν_0 be the threshold frequency, then $W = h\nu_0$

$$\therefore h\nu = h\nu_0 + \frac{1}{2}mv_{max}^2$$

$$[\ K.E_{max} = \frac{1}{2}mv_{max}^2 = h\nu - h\nu_0 = h(\nu - \nu_0)\ ].$$

Simple Problems

Q.1. The work function of sodium is 2.3 eV. Calculate the threshold frequency and the corresponding wavelength ($h = 6.6 \times 10^{-34}$ Js)

Sol^n → Work function $W = 2.3\ eV = 2.3 \times 1.6 \times 10^{-19}$ J

we know that $W = h\nu_0 = hc/\lambda_0$

$$\therefore \nu_0 = W/h = \frac{2.3 \times 1.6 \times 10^{-19}}{6.6 \times 10^{-34}} = 5.57 \times 10^{14}\ Hz. \text{ Ans}$$

$$\lambda_0 = \frac{c}{\nu_0} = \frac{3 \times 10^8}{5.57 \times 10^{14}} = 5.385 \times 10^{-7}\ m = 5385 Å \text{ Ans}$$

Q2. Light of wavelength 6000Å falls on a photo sensitive plate of work function 1.9 eV. Find (i) energy of the photon in eV (ii) K.E of emitted photo electrons and (iii) Stopping potential ($h = 6.62 \times 10^{-34}$ JS)

Sol: A/Q, $\lambda = 6000Å = 6000 \times 10^{-10}$ m, $W = 1.9$ eV

(i) $E = h\nu = hc/\lambda = 3.31 \times 10^{-19}$ J (after putting the values)

$= 3.31 \times 10^{-19} / 1.6 \times 10^{-19} = 2.07$ eV. A

(ii) K.E, $K = h\nu - h\nu_0 = h\nu - W = E - W = 2.07 - 1.9$

$= 0.17$ eV A

(iii) $K.E = eV_0$, $V_0 = \frac{K.E}{e} = \frac{0.17 eV}{e} = 0.17$ V Ans

Q3. The cut-off voltage in a photoelectric expt. is 1.5V. What is the max. K.E of the photoelectrons emitted

Sol: ∵ $V_0 = 1.5$ V, $K.E_{max} = eV_0$

$= 1.6 \times 10^{-19} \times 1.5 = 2.4 \times 10^{-19}$ J

$= 2.4 \times 10^{-19} / 1.6 \times 10^{-19} = 1.5$ eV

Q4: In an expt. on photo electric effect, the slope of the cut-off voltage versus frequency of incident light is found to be 4.2×10^{-15} Vs. Estimate value of Planck's con

Sol: From Einstein's photo electric equation,

$eV_0 = h(\nu - \nu_0) = h\nu - h\nu_0$

or, $V_0 = \frac{h}{e}\nu - \frac{h}{e}\nu_0$. [This is like a straight line equation $y = mx + c$, $m = \text{slope} = \tan\theta = \frac{h}{e}$]

∴ Slope of curve is $\frac{h}{e} = 4.2 \times 10^{-15}$ Vs

∴ $h = e \times 4.2 \times 10^{-15} = 1.6 \times 10^{-19} \times 4.2 \times 10^{-15}$

$= 6.72 \times 10^{-34}$ JS Ans.

Solve these problems

1. The threshold frequency for a certain metal is 3.3×10^{14} Hz. If light of frequency 8.2×10^{14} Hz is incident on the metal, predict the cut-off voltage for photo electric emission.

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Hint: $V_0 = \frac{h}{e}(\nu - \nu_0) = 2.02$ Volt Ans.

2. The work fn for a certain metal is 4.2 eV. Will this metal give photoelectric emission for incident radiation of wave length 300 nm?

[Hint: $\nu_0 = \frac{W}{h} = 1.015 \times 10^{15}$ Hz.
$\nu = c/\lambda = 1 \times 10^{15}$ Hz, $\nu < \nu_0$, $\therefore$ photo emission will not take place.]

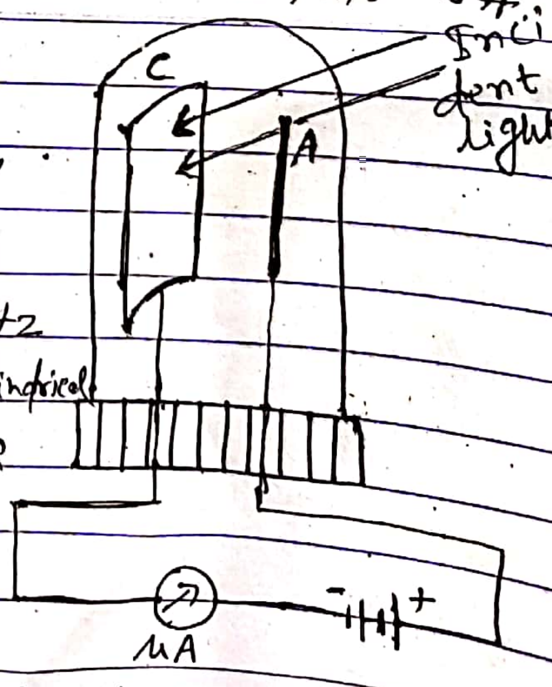
3. A monochromatic source of light operating at 200 W emits 4×10^{20} photons per sec. Find the wavelength of light.

Sol:- The energy of each photon $= \frac{200 J/s}{4 \times 10^{20}/s} = 5 \times 10^{-19}$ J.
$\lambda = hc/E = 4 \times 10^{-7}$ m $= 400$ nm.

4. The photoelectric cut-off voltage in a certain photoelectric expt. is 1.5 V. What is the max. K.E of photo electrons emitted?

Sol: $V_0 = 1.5$ V, K.E$_{max} = eV_0 = 1.5$ eV $= 1.5 \times 1.6 \times 10^{-19}$ J
$= 2.4 \times 10^{-19}$ J Ans.

Photoelectric Cell



Construction:

This fig. consists of a cathode 'C' and anode 'A' enclosed in a highly evacuated glass or quartz bulb. The cathode is a semi-cylindrical plate of metal coated with a photo-sensitive material of low work function such as silver oxide. The anode is in the form of a wire so that it does not obstruct the light falling on the cathode.

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Working : When light of frequency higher than the threshold frequency for the cathode surface, falls on the cathode, photoelectrons are emitted. For anode voltage of +10V and higher, current saturation is achieved and a current in the outer circuit which can be measured by a micro-ammeter.

Applications of photoelectric cell :

(i) Used to switch ON and OFF the automatic switches of street light.

(ii) Used to operate controls in electronic devices such as televisions, computers etc.

(iii) Used in counting devices.

(iv) Used to record daylight in meteorology.

(v) Used in industry to locate minor flaws (defect) or holes in metal sheets.

(vi) Used in reproduction of sound in cinematography.

(vii) Used in controlling temperature of furnaces and chemical reactions.

—x—

MCQ

1. Planck constant has the same dimensions as
(a) Force x time (b) Force x distance (c) Force x speed
(d) Force x distance x time. Ans (d).

2. Two photons having
(a) equal wavelengths have equal linear momenta
(b) equal energies have equal linear momenta
(c) ~~equal frequencies have equal linear momenta~~
(d) equal linear momenta have equal wavelengths.
Ans (d)

3. The work function of a metal is $h\nu_0$. Light of frequency ν falls on this metal. The photo electric effect will take place only if.
(a) $\nu \geq \nu_0$ (b) $\nu > 2\nu_0$ (c) $\nu < \nu_0$ (d) $\nu < \nu_0/2$
Ans: (a)

4. Light of wavelength λ falls on a metal having work function hc/λ_0. Photoelectric effect will take place only if (a) $\lambda \geq \lambda_0$ (b) $\lambda \geq 2\lambda_0$ (c) $\lambda \leq \lambda_0$ (d) $\lambda < \lambda_0/$
Ans: (C)

5. If the frequency of light in a photoelectric expt. is doubled, the stopping potential will
(a) be doubled (b) be halved (c) become more than double (d) become less than double. Ans (C)

6. A point source of light is used in a photo-electric effect. If the source is removed farther from the emitting metal, the stopping potential
(a) will increase (b) will decrease (c) will remain constant (d) will either increase or decrease.
Ans: (C)