Chapter 21

PHOTONS

Introduction

- ↳ photons is regarded as a particle of zero rest mass.
- ↳ It travels with speed of light in vacuum.
- ↳ shows both wave and particle nature.
- ↳ No rest mass, dynamic mass
- ↳ In wave, there is transfer of energy only not particle.

Light → wave [interference, Diffraction, polarization]
(Dual nature)
→ particle [photoelectric effect, campton effect.

Quantum theory of Radiation. [Max. Plank's 1901]

↳ According to this theory, [1900 DEC 14]
Radition energy is quantized and is emmitted or absorbed only in discrete (not continuous) values, called quantum

Thus, $E = nhf$; $n = 1, 2, 3 \ldots$
f = frequency of Photon.

↳ Q. Each tiny discrete packets or bundle of radiations that carry certain amount of energy is called photons.

Light → Radiations → They are tiny particles made up of tiny packets of energy called photons.

$$E = hf \quad \text{—— (I)}$$

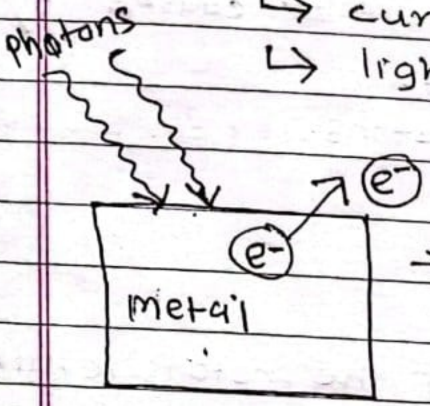
we know, $v = \lambda f$

or, $f = \dfrac{v}{\lambda} = \dfrac{c}{\lambda}$ [$v = c$ for EMW] —— (II)

From (I) and (II) we get

$$E = \frac{h \times c}{\lambda} \qquad h = 6.626 \times 10^{-34} \text{ JS}$$

Photoelectricity ↳ proves particle nature of light.
→ light → photons.
↳ current flowing through light (photons)
↳ light is the cause of current here.



↳ when light enters e^- is out
→ when photons enters to metal surface it sends the e^- completly out of metal's surface.

↳ Easy to remove from Alkali metals
↳ Cesium is the most sensetive photoelectric metal.

History

Max Plank → mentor of Einstein
20-22 years elder than him
↳ Dec 11 1900 AD ⇒ $E = hf$
↓
Birth of Quantum physics.

↳ Later the same theory was paper published by Sir. Einstein in 1905 [Theoritical Apporoch]
↳ Later Sir. R.A. Milikan's experimentally verified it in 1914

1921 → Sir. Einstein Nobel prize
1922 → Bohr's "
1923 → RAM. "

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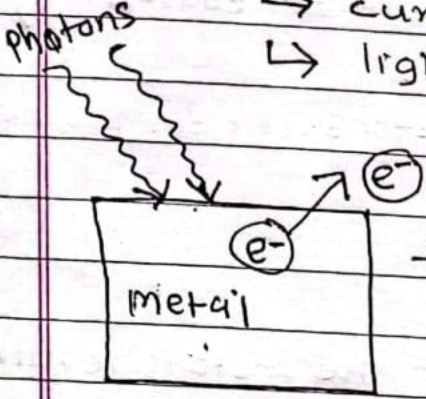

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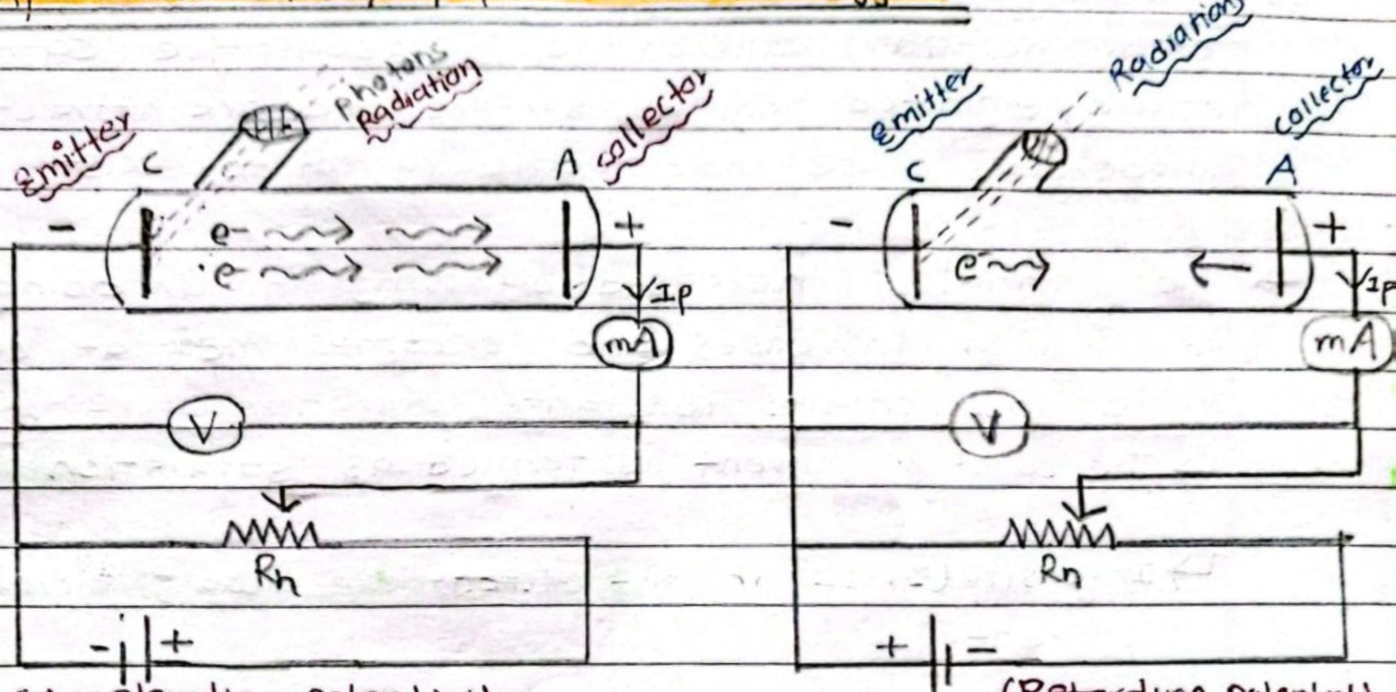
Experimental Study of photoelectric effect.



(Accelerating potential) (Retarding potential)

Fig: Experimental setup for study of photoelectric effect.

Arrangement ;-

→ The experimental setup consists of an evacuated (vacuum) glass tube which cointains photosensative metal as cathode (Emitter). Furthermore it contains another metal which acts as anode (collector) to complete the circuit. The arrangement is equipped with voltmeter (in parallel) and mini Ammeter (in series) to measure voltage and current respectively. Also Rheostat (Rn) is connected to vary potential with external DC source as shown in diagram.

Working :

→ Initially the arrangement acts as accelerating potential. The cathode is connected to -ve potential and anode is connected to +ve potential.

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→ When a monochromatic light (of suitable frequency as filtered by the filter) falls on the photosensative cathode the e^- are emmited from its surface and are attracted by anode. This cause photoelectric current to exist.

→ The potential is increased by using Rh. On doing so the current increases and becomes max at certain value and remains constant. (saturation current) → (I_s)
↳ The constant current is termed as saturation current

↳ Intensity (I) of incident photons can always increase the current.

In the next step,
→ The potentials of metal plate are interchanged. (To check K.E). This cause decrease in photo current.
↳ At certain value retarding potential is made sufficiently large, so that even the fastest e^- fails to get emmitted and this corresponding retarding potential is called Stopping potential / cutoff potential (V_0)
↳ minimum retarding potential which can just stop the emmitted photoelectrons from metal surface and makes photo electric current zero.

↳ K.E & V_0 depends on frequency of incident photons.
Workdone by V_0 = Max K.E of photo electron
$e V_0 = \frac{1}{2} m v^2$

$P = \frac{W}{Q}$

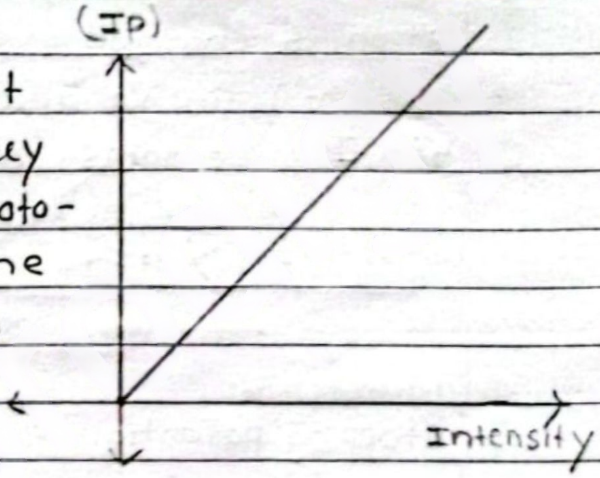
$\therefore W = P \times Q$
↓ ↳ e

Graphs : Observations :

1) Intensity of incident light & photoelectric current (I_p).

→ When intensity of incident light is increased (keeping frequency constant), the emission of photoelectrons is increased. So, the photoelectric current is also increased.

$\boxed{\therefore I_p \propto \text{Intensity}}$

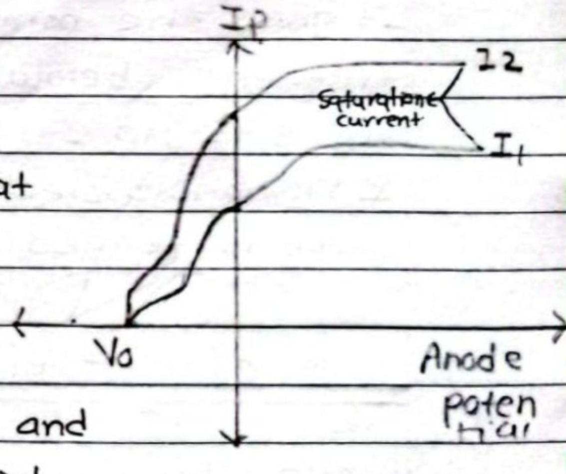


2) Anode potential and photo electric current (I_p)

→ If +ve anode potential is increased, the photo electric current is also increased and becomes constant at a point.

∵ But if −ve anode potential is increased gradually. Then, photo-electric current keeps decreasing and finally becomes zero at certain point.

$\therefore I_p \propto V_0$ (for fix intensity and frequency)



But if the intensity is increased, then there will be no change for V_0 but the saturation current will be changed. Here,

$$I_2 > I_1$$

$$(\text{Intensity})_2 > (\text{Intensity})_2$$

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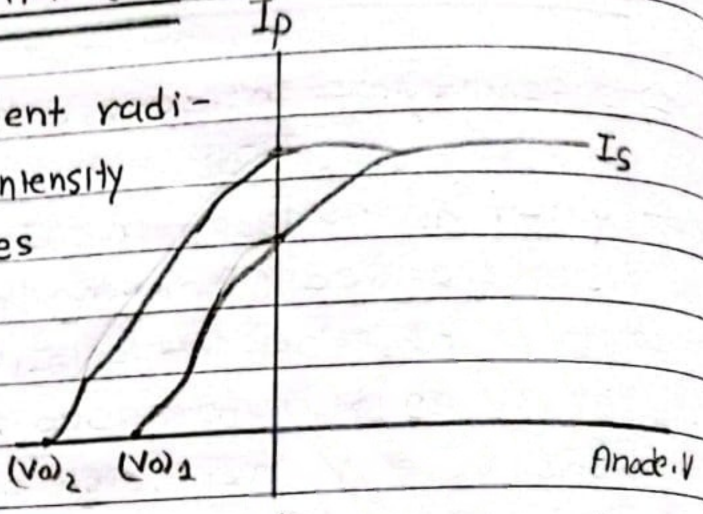
3. Frequency & stopping potential (V_0)

- When the frequency of incident radiation is changed (keeping intensity constant) the V_0 also changes but I_s remains constant.

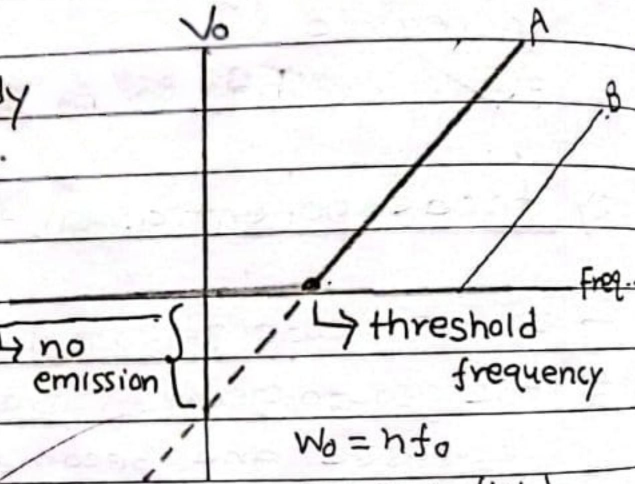
  $|(V_0)_2| > |(V_0)_1|$

  $|F_2| > |F_1|$



- Stopping potential (V_0) is already zero. But frequency is not.

It gives the minimum frequency below which there is no e^- emission & no photo electric effect. Which is termed as threshold frequency.



$W_0 = hf_0$

$(W_0)_B > (W_0)_A$

Laws of photoelectric Emission:

- Photoelectric current (I_p) $\propto$ Intensity of incident light
  - ↳ but independent of frequency
- $V_0 \propto \frac{1}{2} m v^2_{max} \propto$ Frequency
  - ↳ but independent of intensity of light.
- It is instaneous phenomenon within the limits of experimental accuracy. [10^{-9} sec]

Einstein photoelectric equation (1905)

- Sir Albert Einstein gave the photoelectric equations in the paper published in 1905 AD being based on quantum theory given by Max Plank. in 1901 AD. and law of conservation of energy.

- Quantum theory gives the discrete (not continuous) concept of the radiation Each unit of the radiation is called quantum. It's energy is directly porpotional to frequency. and given as $\boxed{E = hf}$ where, $h = 6.626 \times 10^{-34}$ J S

- $\boxed{\text{Total energy of a photon} = \text{Energy to eject most loosely bounded } e^- + \text{K.E of the electron.}}$

i.e. $\boxed{hf = \phi + \frac{1}{2} m v^2 \max.}$ m = mass of e^- $= 9.1 \times 10^{-31}$ kg

or, $hf = hf_0 + \frac{1}{2} m v^2 \max$ —— ①

or, $\frac{1}{2} m v^2_{max} = hf - hf_0$

or, $\frac{1}{2} m v^2_{max} = h \cdot \frac{c}{\lambda} - h \cdot \frac{c}{\lambda_0}$

or, $\frac{1}{2} m v^2_{max} = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$

$v = \lambda F$

$F = v/\lambda$.

$v = c$

- Also, $h(F - F_0) = eV_s$

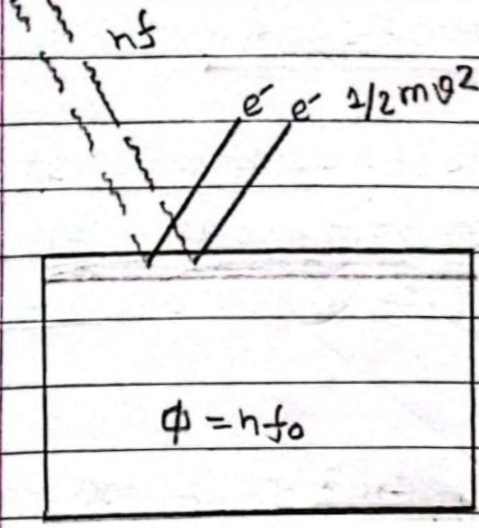
$(K.E)_{max}$ = Workdone by Anode

$= eV_0$ #

K.E = workdone by Anode

$V = \frac{W}{Q}$

$W = VQ$



- Photoelectric effect is one to one phenomenon.
- It is instantaneous phenomenon. (10^{-9} sec)
- I_p depends on intensity of light.
- I_s depends on Intensity of incident photons.
- K.E of liberated e^- depends on frequency of incident photons.
- Frequency of incident photons determines stopping potential (V_0)

Qn) A sodium surface ejects photoelectrons when mercury light of frequency 6.8×10^{14} Hz strikes on it. The work function of Na is 3×10^{-19} J. Find the max kinectic energy needed to eject out the electrons from the metal surface.

- Solution :-

Given that, $f = 6.8 \times 10^{14}$ Hz

$\phi = 3 \times 10^{-19}$ J

$KE_{max} = ?$

we have, $hf = \phi + KE_{max}$

$\therefore KE_{max} = hf - \phi$

$= 6.626 \times 10^{-34} \times 6.8 \times 10^{14} - 3 \times 10^{-19}$

$= 4.5 \times 10^{-19} - 3 \times 10^{-19}$

$= 1.5 \times 10^{-19}$ Joule #

Qn) Alkali metals are most suitable for photoelectric emmission. why?

→ It is because they have losely bounded single electron in their valence shell due to which it is easy to eject out the electron. i.e their work function (ϕ) is less.

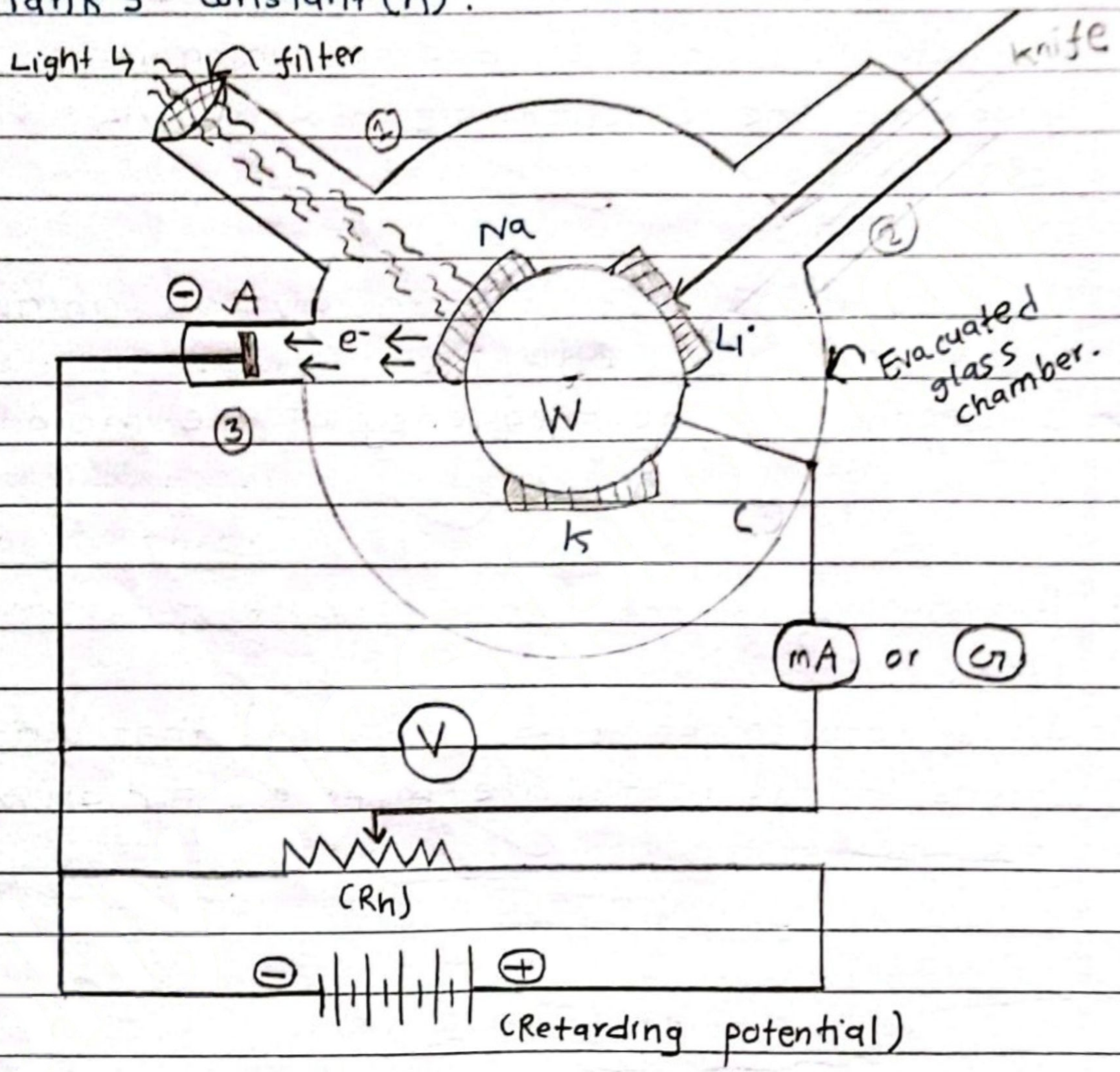
Qn) On what factor does the energy of emmitted photo-electrons depends on?

→ It depends on the frequency of the incident photons.

Qn) The stopping potential is different for different metals. Why?

→ It is because the attractive forces that bind the electrons to the metal are different for diffrent metals

Millikan's Experiment For Verification of Einstein's Photoelectric Equation & Measurement of Plank's Constant (h).



- Robert Andrew Millikan (RAM) in 1914 AD demonstrated an experiment to verify photoelectric laws, equations given by Einstein.
- The arrangement cointains evacuated glass tube/chamber which has rotating wheel equipped with photosensative metals.
- The first limb cointains the light filter for monochromatic incidence. The second limb cointains knife for cleansing purpose. The third limb

cointains anode (collector)

- A sensative voltmeter (in parallel) and galvanometer is used to measure potential and detect current respectively.
- The Rheostat and external DC source is connected as shown in the Figure.

Working:

- When a beam of radiation of suitable frequency falls on alkali metal surface through window ①, photoelectrons are emitted and collected by Anode (A). So, current is detected by Ⓖ
- Further, when retarding potential 'V' is applied to anode gradually increase with the help of Rh, then this potential repels the electron reaching to anode. Here, anode current decreases gradually and becomes zero. Called V_0.

Theory:

As per Einstein's equation,

$$hf = hf_0 + \frac{1}{2} m v^2_{max}.$$

or, $hf = hf_0 + eV_s$

or, $eV_s = hF - hF_0$

or, $\boxed{V_s} = \frac{h}{e}\boxed{F} - \frac{h}{e} F_0$

$K.E = W.D$ by Anode

Also, $V = \frac{W}{Q}$

$\therefore K.E = V \times Q$

$= V_s \times e.$

which is comparable to $y = mx + c$

$y = V_s$ $\quad$ $x = F$

$m = \frac{h}{e}$ $\quad$ $c = -\frac{h}{e} F_0$ → y-intercept

slope of line

→ $m = \tan\theta$

$\tan\theta = h/e$

$\therefore \theta = \tan^{-1}\left(\frac{h}{e}\right)$

→ A, B, C are threshold frequency of K, Na and Li respectively.

→ $(f_0)_C > (F_0)_B > (F_0)_A$

Li → 2, 1

Na → 2, 8, 1

K → 2, 8, 8, 1

→ It is easier to remove e^- from K,

$\therefore (\phi)_K < (\phi)_{Na} < (\phi)_{Li}$

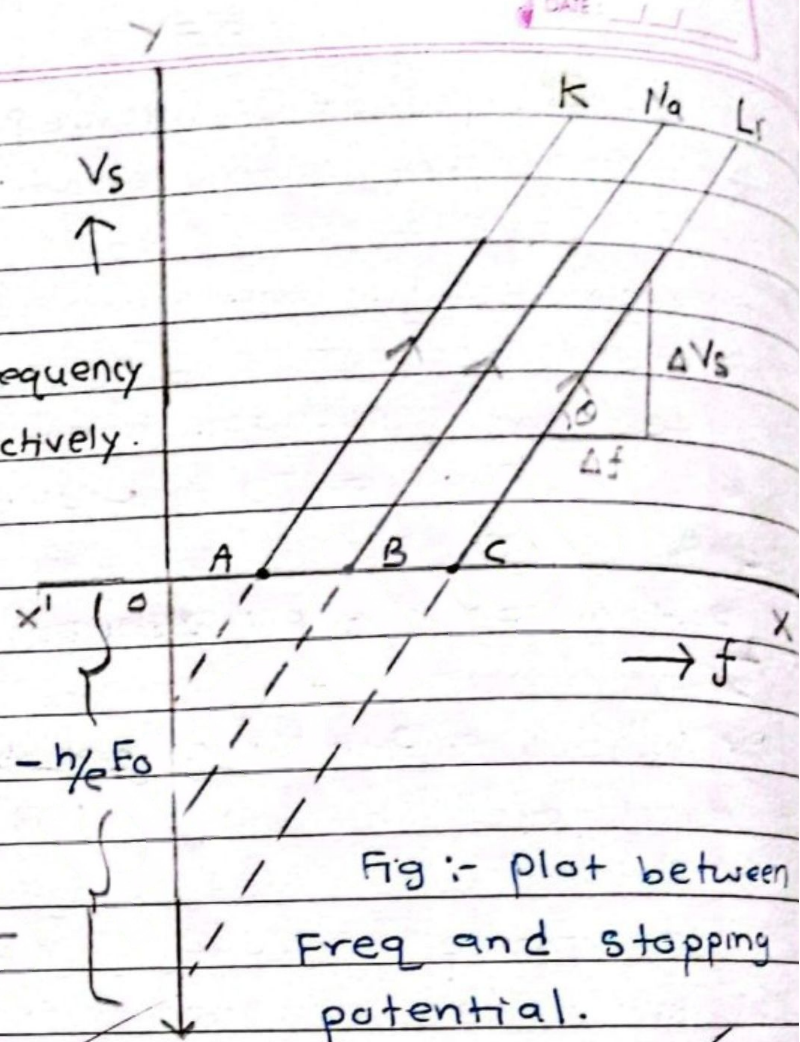


Fig :- plot between Freq and stopping potential.

Determination of plank's constant.

→ Threshold Frequency (F_0) = From graph.

→ c = y-intercept = from graph.

$$c = -\frac{h}{e} f_0$$

$$\boxed{\therefore h = -\frac{ce}{f_0}}$$

$e = 1.6 \times 10^{-19} C$

Method - 2

From slope,

$$\tan\theta = h/e$$

$$\therefore h = e \times \tan\theta$$

$$\therefore \boxed{h = e \times \frac{\Delta V_s}{\Delta F}} \qquad \tan\theta = \frac{p}{b}$$

Determination of work function (ϕ)

→ $\phi = h f_0$

↳ From graph.

Applications / uses of photo-electric Effect.

↳ photoelectric cells are based on photo-electric effect.

Photoelectric cell ↳ device use to convert light energy into electric energy

- → Photoemissive → street lights, electronic devices, traffic signals, etc
- → photo conductive → Light-sensative alarms, lightning control etc.
- → photo voltaic → Solar panels designing

↳ photoemmisive cell is also used to count the no. of person entering stadium, hall, malls etc. i.e counting purpose.

↳ It is used in automatic photographic camera.

↳ It is used for automatic thief alarm, fire alarm etc.

↳ It is used to measure temp. of stars.

Short Questions

1b) What is the reason behind the free electron in metal not emitted out spontaneously? Why external energy is required to eject out such electrons? Discuss.

→ The weaker force of attraction between the nucleus and valance shell electron allows that e^- to move freely within that metal surface but this attractive force always attracts electron towards the nucleus and so these electrons are bound to the atom and cannot be emitted out spontaneously. They need external force to leave metal surface therefore.

c) Light of wavelength 2000Å falls on an aluminium surface. In aluminium 4.2 eV is required just to remove an electron from the surface. What is the KE of:

i) the fastest emitted photoelectron?

↳ KE for fastest emmitted e^- = KE_{max}

$$\therefore KE_{max} = hf - \phi$$

$$= h \times \frac{c}{\lambda} - \phi$$

$$= 6.626 \times 10^{-34} \times \frac{3 \times 10^{8}}{2000} - 4.2 \times 1.6 \times 10^{-19}$$

$$= 9.939 \times 10^{-29} - 6.72 \times 10^{-19}$$

$$= 3.219 \times 10^{-19} J$$

$$\approx 2 eV \#$$

ii) The slowest emitted photoelectron.

→ For slowest emitted photoelectron $v = 0$

$$\therefore KE = \frac{1}{2} m v^2 = 0 \#$$

iii) What is the stopping potential?

→ we have, $KE_{max} = eV_0$

$$\therefore V_0 = \frac{KE_{max}}{e} = \frac{3.219\times10^{-19}}{1.6\times10^{-19}}$$

$$\therefore V_0 = 2V \text{ ans. \#}$$

iv) what is the cut off wavelength for aluminium?

→ we have, $\phi = hf_0$

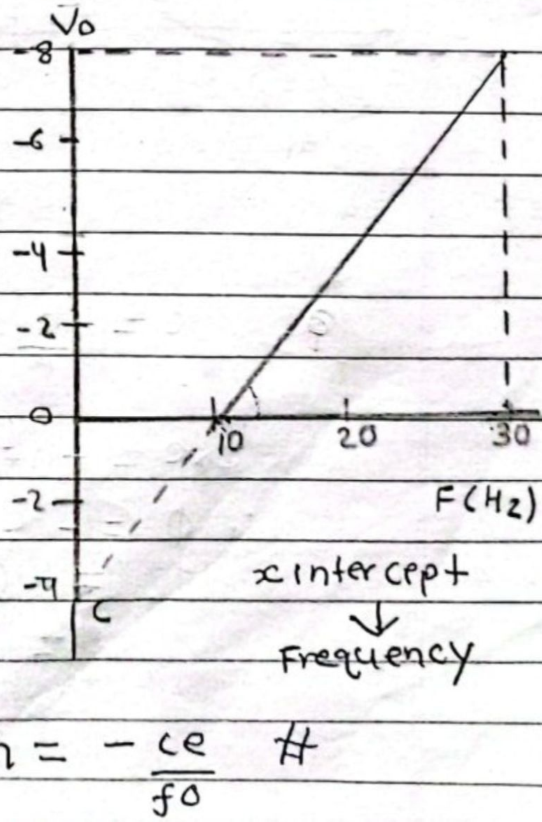
$$\text{or } \phi = h\times\frac{c}{\lambda_0}$$

$$\therefore \lambda_0 = \frac{h\times c}{\phi} = \frac{6.626\times10^{-34}\times3\times10^{8}}{4.2\times1.6\times10^{-19}}$$

$$= 2.958\times10^{-7}\,m$$

$$= 2958\,\mathring{A} \quad [1\mathring{A} = 10^{-10}\,m]$$

2. The given plot is obtained from millikan's experiment during the calculation of Planck's constant:



a) what does the slope of line & its intercept gives? Define them

→ Slope of line and its intercept gives the value of plank's constant.

$$\text{slope } (m) = h/e$$

$$\tan\theta = h/e$$

$$\therefore h = e\times\tan\theta$$

$$= e\times\frac{\Delta V_0}{\Delta F}$$

x intercept
↓
Frequency

$$y\text{ intercept } (c) = -\frac{h}{e}f_0$$

↓
stopping potential

$$\therefore h = -\frac{ce}{f_0} \quad \#$$

on the basis of quantum nature of light, so it clearly explains the particle nature of light.

b) Why photoelectric effect cannot be explained on the basis of wave nature of light.

→ According to wave nature of light energy is produced continuously that means on increasing intensity of light their will be no effect on ejection of electrons. Higher intensity of radition should give higher K.E to emitted or ejected electrons But experimentally it is not found.

In photo electric current, we observe one to one interaction between photons and electron.

c) Do X-rays shows the phenomenon of photoelectric effect?

→ Yes, they do, since they have very high energy as compared to light, their $F > F_0$. so they can eject out e^- from metal surface and also provide them sufficient K.E.

d) Is photoelectric effect possible for the any Frequency.

→ No, It is because to eject out e^- from metal surface the Frequency of incident light must be greater than threshold Frequency. (i.e $F > F_0$).

Qn) Light of frequency 5×10^{14} Hz librates electron with energy 1.3×10^{-19} J from a certain metallic surface. What is the wavelength of UV light which librate electron of energy 8.93×10^{-19} J from same surface. [$h = 6.62\times10^{-34}$ Js, $c = 3\times10^{8}$ m/s]

Solution:-

Here, Frequency of light $(f) = 5\times10^{14}$ Hz

$K.E = 1.3\times10^{-19}$ J.

Planks constant $(h) = 6.62\times10^{-34}$ Js

speed of light $(c) = 3\times10^{8}$ m/s

case I) now we have, $E = \Phi + KE$

$$\text{or, } \Phi = E - KE$$
$$= hf - KE$$
$$= 6.62\times10^{-34}\times5\times10^{14} - 1.3\times10^{-19}$$
$$= 2.01\times10^{-19}$$

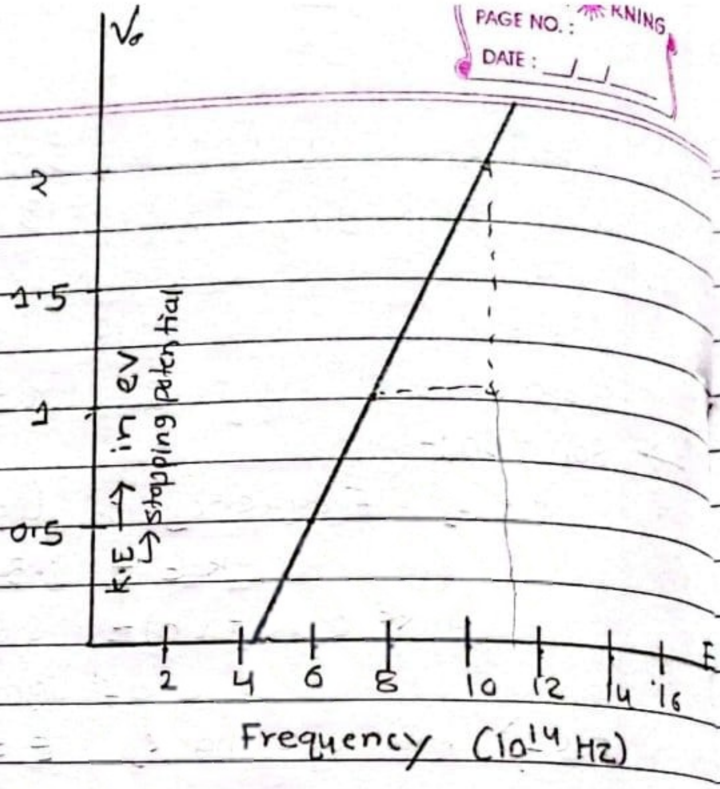
In case II)

The same metal is used thus it work function will be same,

Now, $E = \Phi + KE$

$$hf = 2.01\times10^{-19} + 8.93\times10^{-19}$$
$$6.626\times10^{-34}\times\frac{3\times10^{8}}{\lambda} = 1.094\times10^{-18}$$
$$\therefore \lambda = \frac{1.9878\times10^{-25}}{1.094\times10^{-18}}$$
$$= 2\times10^{-7}\text{ m.}$$

b i) Calculate the threshold frequency and plank's constant on the basis of graph.



→ solution:-

Here,

$F_0 = 4.5 \times 10^{14}$ Hz #

(from graph)

Also, slope $= \frac{h}{e}$

$\frac{\Delta V}{\Delta F} = \frac{h}{e}$

$h = e \times \frac{\Delta V}{\Delta F} = \frac{1.6 \times 10^{-19} \times 2}{5.5 \times 10^{14}} = 5.81 \times 10^{-34}$ JS #

ii) Also determine maximum K.E of emitted photoelectrons corresponding to frequency 10×10^{14} Hz.

→ Solution :-

We have, $hf = \phi + K.E_{max}$

or, $K.E_{max} = hf - \phi$ -------- ①

Here, Plank's constant (h) $= 5.81 \times 10^{-34}$ JS

Frequency (F) $= 10 \times 10^{14}$ Hz

work function $(\phi) = hf_0 = 5.81 \times 10^{-34} \times 4.5 \times 10^{14}$ Hz

Continuing eqn ① we get,

$K.E_{max} = hf - hf_0$

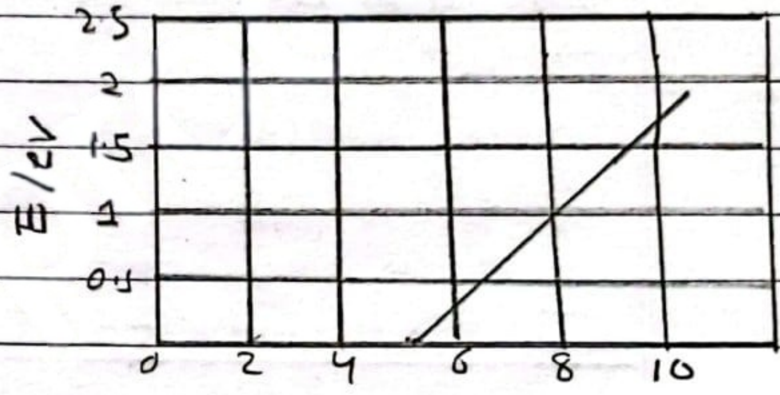
$= h(F - f_0)$

$= 5.81 \times 10^{-34} (10 \times 10^{14} - 4.5 \times 10^{14})$

$= 3.1955 \times 10^{-19}$ J

$= 2$ ev #

9b) Fig- shows maximum KE of the emitted photoelectrons as the frequency of the incident radiation on a sodium plate is varied.



i. Explain why there are no photo electrons emitted when the Frequency of the incident light is less than 5.6×10^{14} Hz.

→ It is because, here threshold frequency is about 5.6×10^{14} Hz and to emit the photo electrons the $hf > hF_0$ i.e. $F > F_0$ the frequency of incident radiation must be greater than threshold frequency.

ii) Calculate the work function for sodium.

→ Solution: Here,

threshold frequency $(F_0) = 5.6 \times 10^{14}$ Hz (By graph)

Plank's constant $(h) = ?$

we have $h -$