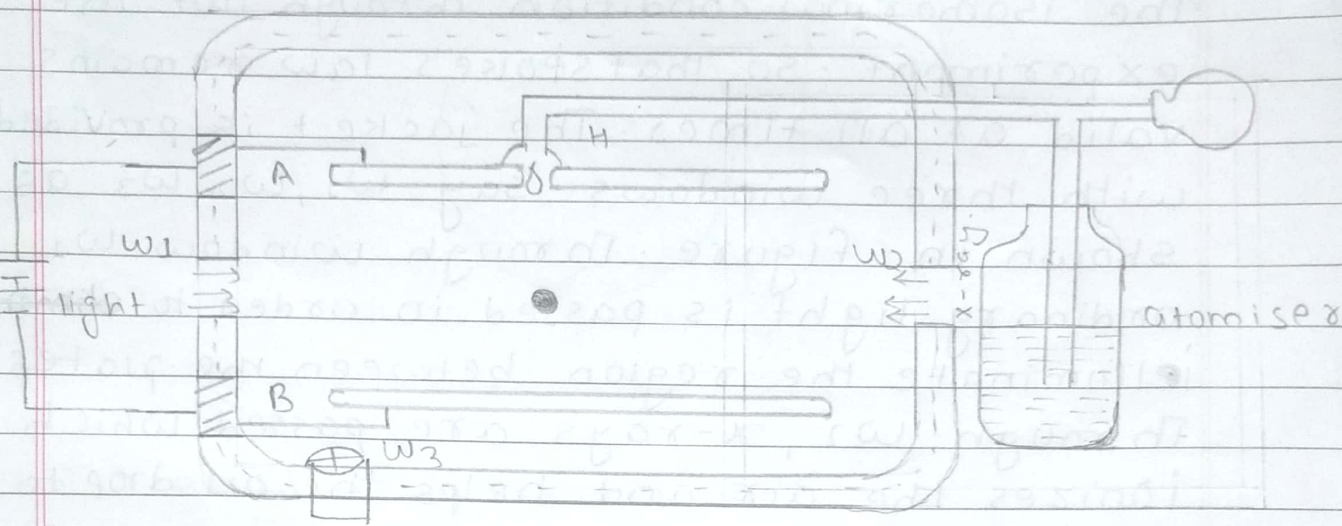
Electrons:

Milikan's oil drop Experiment:



Milikan's oil drop experiment provides basis for quantization of charge. The calculation involves the application of stoke's law in viscosity. This experiment is carried out in two steps:-

1) Motion of the oil drop under the effect of gravity alone.
2) Motion of the oil drop under the combined effect of gravity and electric field.

The experimental setup consists of two metal plates A and B maintained at a positive and negative potential respectively. The metal plate A is provided with a Hole (H), through which the oil drop is spread within the region between the plates and this is done with the help of atomiser. The oil drop so sprayed acquire charge due to friction with air. This apparatus is enclosed by a jacket in which cold water keeps on circulating in order to ensure the isothermal condition through out the experiment. so, that stoke's law remains valid at all times. The jacket is provided with three windows say W_1, W_2, W_3 as shown in figure. Through window W_1 ordinary light is passed in order to illuminate the region between the plates. Through W_2, x-rays are passed which ionizes the air and helps the oil drop to acquire charge if friction alone is insufficient. A microscope provided with a cross wire is fitted to the window W_3 which helps us to determine the terminal velocity of the drop by measuring the distance travelled by it.

Calculations:-

1) Motion under the effect of gravity alone.

Let an oil drop of mass 'm' falls with a terminal velocity v_1. In this situation, the various force acting on the drop are

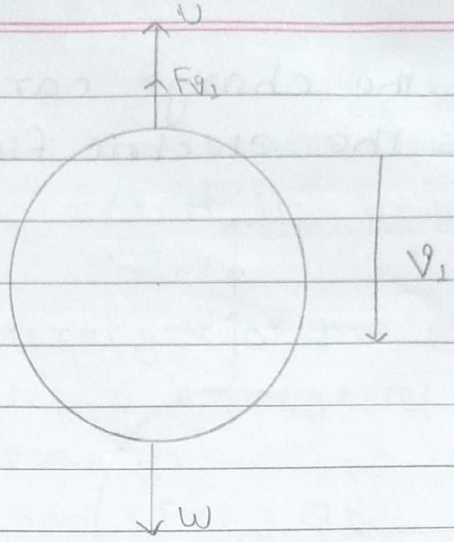
i) weight $W = mg$ in downward direction.

ii) Upthrust $U = V\sigma g$ in upward direction

σ = density of medium (air)

V = volume of fluid displaced.

(iii) Viscous force $F_{v_1} = 6\pi\eta r v_1$ in upward direction.



In equilibrium condition

$$W = F_{v_1} + U$$

$$\text{or, } F_{v_1} = mg - U \quad \text{---(1)}$$

$$\text{or, } 6\pi\eta r v_1 = V\rho g - V\sigma g$$

$$\text{or, } 6\pi\eta r v_1 = \frac{4}{3}\pi r^3(\rho - \sigma)g$$

$$\therefore \quad r = \sqrt{\frac{9\eta v_1}{2(\rho-\sigma)g}} \quad \text{---(2)}$$

2) Motion under the combined effect of gravity and electric field.

Let a negatively charged oil drop falls in the downward direction with terminal velocity (v_2). The various forces acting on the oil drop in this situation are

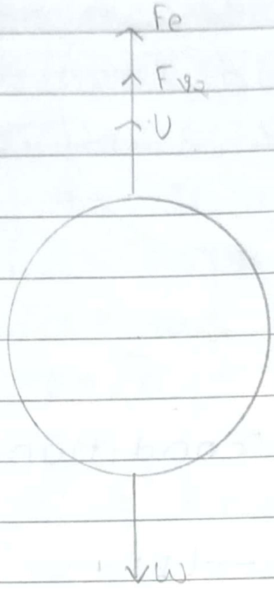
(i) Weight $W = mg$ in downward direction.

(ii) Upthrust $U = V\sigma g$ in upward direction

(iii) viscous force $F_{v_2} = 6\pi\eta r v_2$ in upward direction.

(iv) Electrostatic force $F_e = qE$ in upward direction

Here, q is the charge carried by oil drop.
and E is the electric field strength.



At equilibrium condition;

$mg = F_e + F_{v_2} + U$

or, $F_e = mg - U - F_{v_2}$

or, $F_e = F_{v_1} - F_{v_2}$

or, $qE = 6\pi\eta r(v_1 - v_2)$

or, $q = \frac{6\pi\eta r(v_1 - v_2)}{E}$

This equation gives the total charge carried by the oil drop.

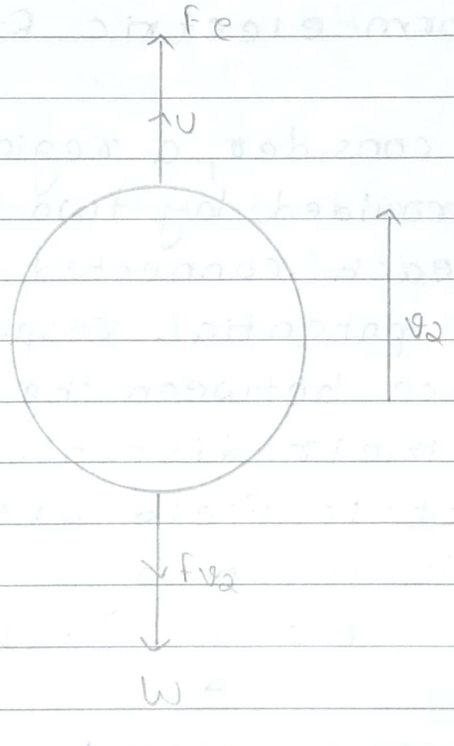
This experiment was carried out for oil drops of different size. Each time it was found that the charge on it was an integer multiple of 1.6×10^{-19}C

i.e : $q = ne$.

In this way, this experiment conformed the quantization of charge.

Note
If the oil drop moves in upward direction viscouse force acted in downward direction.

Let, E be the strength of the electric field. As the drop carries a charge Q, then electrostatic force on oil drop in
Upward direction $(F_e) = QE$
Viscouse force in downward $(F) = 6\pi\eta r v_2$
weight in downward direction, $W = mg$
upthrust in upward direction, $U = V\sigma g$.



At equilibrium condition;

$$F_e + U = F_{v_2} + W$$

$$\text{or, } F_e - F_{v_2} = W - U$$

$$\text{or, } F_e - F_{v_2} = F_{v_1}$$

$$\text{or, } F_e = F_{v_1} + F_{v_2}$$

$$\text{or, } F_e = 6\pi\eta r (v_1 + v_2)$$

$$\text{or, } qE = 6\pi\eta r (v_1 + v_2)$$

$$\therefore q = \frac{6\pi\eta r (v_1 + v_2)}{E}$$

Motion of electron in electric field.

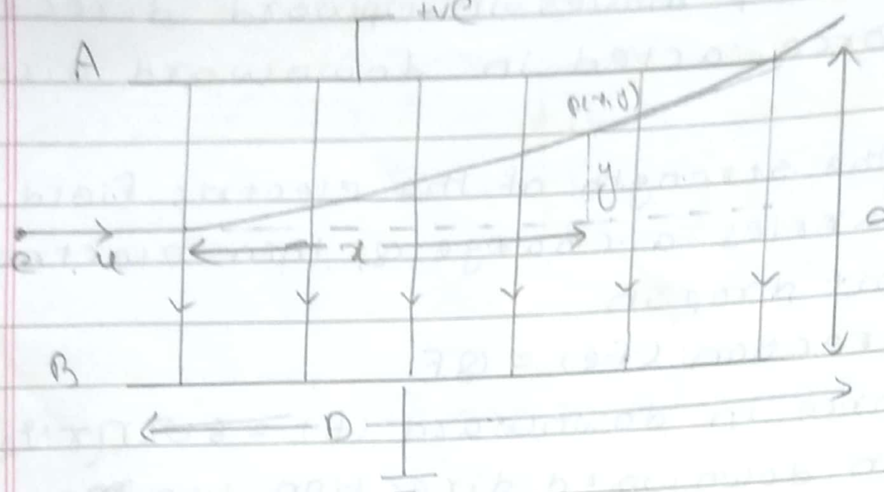


Fig :- Parallel plates arrangement to produce uniform electric field.

Let us consider, a region of uniform electric field provided by two metal plates A and B each connected to a positive and negative potential respectively. The potential difference between the plates be 'V' and 'd' be their distance of separation. The electric field strength within this region is given by

$$E = \frac{V}{d} \quad \text{---} (1)$$

Let an electron enters this region perpendicularly with Horizontal velocity (u). As soon as it reaches the field region, it experiences electrostatic force in upward direction. But it's horizontal velocity tends to move it in a straight path. This results in a tussle between horizontal motion and vertical motion. so that, the electron neigher moves horizontally nor vertically but somewhere between horizontal and vertical tracing a parabolic path.

If F_y be the force experienced in upward direction then from newton second law

$$F_y = m a_y \quad \text{--- (2)}$$

Also, $$F_y = eE \quad \text{--- (3)}$$

from equ(1), (2) and (3), we get

$$a_y = \frac{eV}{md} \quad \text{--- (4)}$$

Let, P(x, y) be the position of the electron at any instant of time 't'. Then horizontal distance travelled is :

$$x = u \times t$$

$$\text{or, } t = \frac{x}{u} \quad \text{--- (5)}$$

Also,
The vertical distance travelled is

$$y = u_y t + \frac{1}{2} a_y t^2 \quad [\because \text{using } s = ut + \frac{1}{2}at^2]$$

Since, initial vertical velocity is zero, we get

$$y = \frac{1}{2} a_y t^2$$

$$\text{or, } y = \frac{1}{2} \frac{eV}{md} \frac{x^2}{u^2} \quad [\text{Using Equ (4) and (5)}]$$

Here, $K = \frac{1}{2} \frac{eV}{mdu^2}$ is constant.

So,

$$y = kx^2$$

This is the equation of parabola. So, the path traced by a charged particle in electric field when projected perpendicular to the field is parabolic in nature.

Resultant velocity (V_R) :-

We know;

$V_x = U_x = U$

and

$$a_y = \frac{V_y - u_y}{t}$$

Since $u_y = 0$

$$\therefore a_y = \frac{V_y}{t}$$

$$\therefore V_y = a_y t$$

$$= \frac{eV}{md} \times \frac{x}{u} \quad \left[a_y = \frac{eV}{md} \text{ and } t = \frac{x}{u}\right] \quad \text{—(i)}$$

When the electron just passes the upper plate, $x = D$, then eq^n(i) can be written as:-

$$V_y = \frac{eV}{md} \times \frac{D}{u} \quad \text{— (ii)}$$

Then

Finally, resultant velocity is given by

$$V_R = \sqrt{V_x^2 + V_y^2}$$

$$= \sqrt{u^2 + \frac{e^2 V^2 D^2}{m^2 d^2 u^2}} \quad \text{— (iii)}$$

Also;

The angle at which the beam emerges from the field is given by

$$\tan\theta = \frac{v_y}{v_x}$$

$$= \frac{eV}{md} \times \frac{D}{u^2}$$

Finally

Gain in K.E is given by

$$\text{gain in K.E} = K.E_f - K.E_i$$

$$= \frac{1}{2} m (v_R)^2 - \frac{1}{2} m u^2$$

$$= \frac{1}{2} m \left[\left(u^2 + \frac{e^2 V^2 D^2}{m^2 d^2 u^2} \right) - u^2 \right]$$

$$= \cancel{\frac{1}{2} m u^2} + \frac{1}{2} \frac{e^2 V^2 D^2}{m d^2 u^2} - \cancel{\frac{1}{2} m u^2}$$

$$= \frac{e^2 V^2 D^2}{2 m d^2 u^2}$$

Thus we can see that the gain in K.E is inversly proportional to mass. This means if an electron and a negatively charged ion enter the uniform ~~magnetic~~ Electric field with same velocity, The K.E gained by electron will be greater.

Doubt.

Motion of Electron in magnetic field:

Let us consider a region of uniform magnetic field which is perpendicularly inward into the plane of paper as shown in figure. An electron of charge e and mass 'm' enters the region of field with velocity v making angle θ with the field.

If the field strength is B, then magnetic force experienced by the electron is

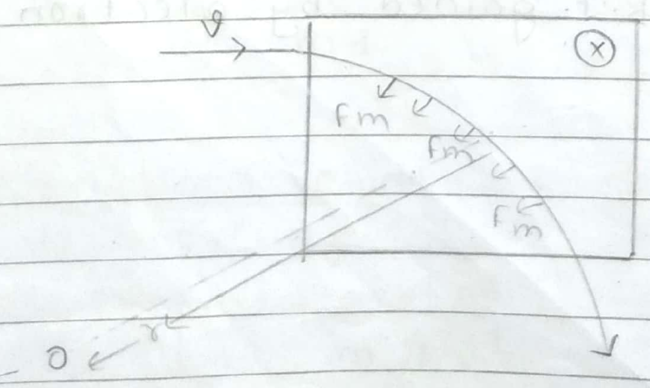
$$F_m = Bev \sin\theta \quad \text{— (1)}$$

Case I :- If θ = 90°

When the electron enters the field perpendicularly, the force is,

$$F_m = Bev \quad \text{— (2)}$$

According to Fleming's left hand Rule, the direction of force experienced by the electron will be in downward direction. This means force and velocity are perpendicular to each other. The result is, charge ~~pra~~ particle traces a circular path as shown in figure.



i.e $\frac{mv^2}{r} = Bev$

$$r = \frac{mv}{Be}$$

This gives the radius of the circle and it depends upon the strength of magnetic field.

Further, Time period $(T) = \frac{2\pi}{\omega} = \frac{2\pi r}{v} = \frac{2\pi}{v} \times \frac{mv}{Be}$

$$\therefore T = \frac{2\pi m}{Be}$$

Thus, time period is independent of speed.

Also, Frequency $(f) = \frac{1}{T} = \frac{Be}{2\pi m}$ //

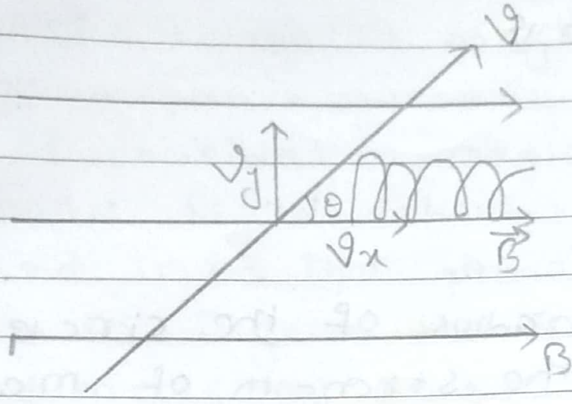
Case II: when $\theta = 0°$ or $180°$

Force experienced by electron $= Bev \sin\theta = 0$

Thus, a charge particle entering the magnetic field parallel or antiparallel experiences no force.

Case III: when θ is other than $90°, 0°$ or $180°$:-

Suppose, an electron enters a uniform magnetic field region making angle θ with the field as shown in figure. The velocity v of the electron can be resolved into two components viz. (they are) $v_x = v\cos\theta$ along horizontal and $v_y = v\sin\theta$ along vertical.



The component v_y is perpendicular to B and tends to move the charge in circular path while the horizontal velocity v_x tends to move the particle along horizontal. Thus, the particle simultaneously moves in a circular and linear path and results in helical path. Now, since the particle moves in a circle due to v_y perpendicular to B, we can have

$$\frac{m v_y^2}{r} = Be v_y$$

$$\Rightarrow r = \frac{m v_y}{Be} = \frac{m v \sin\theta}{Be}$$

Also;

$$\text{time period (T)} = \frac{2\pi r}{v_y} = \frac{2\pi}{v\sin\theta} \cdot \frac{m v \sin\theta}{Be}$$

$$= \frac{2\pi m}{Be}$$

Pitch of helix!

linear distance between two consecutive helix is called pitch of helix. It is denoted by x.

Here, horizontal distance (x) is travelled due to horizontal velocity v_x.

Thus $v_x = \frac{x}{T}$

$$\Rightarrow x = v_x \cdot T = v\cos\theta \cdot \frac{2\pi m}{Be}$$ //

Cross field :-

When electric field and magnetic field are applied simultaneously perpendicular to each other such that a charge particle entering this region perpendicularly passes undeviated then such region is known as cross-field. In such fields, the electrostatics force experienced by a charged particle is equal in magnitude to the magnetic force experienced by it but acts in opposite direction. If v, is the velocity of an electron (e). entering the region of cross-field then magnetic force is equal to electrostatic force

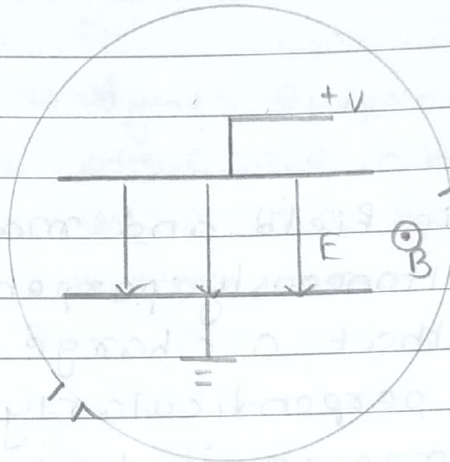
i.e magnetic force = Electrostatic force

or, $Be\!\!\!/ v = e\!\!\!/ E$

$$\therefore v = \frac{E}{B}$$

Thus in a cross field the velocity of charged particle must be equal to the ratio of electric field to magnetic field.

The cross-field arrangement can be provided by two parallel metal plates maintained at different potential and encircled by a circular current carrying conductor as shown in figure.



⊛ J.J Thomson's experiment to determine specific charge (e/m) of electron:-

The charge to mass ratio of an electron is known as it's specific charge. This ratio was calculated experimentally by J.J Thomson and is principally based on the motion of electron in crossfield.

The experimental setup consists of an evacuated glasstube which is provided with a fillament cathode and a cylindrical anode having a hole at it center. Initially, the electrons are ejected from the fillament cathode by heating with the help of current. This ejected electron is accelerated by an anode potential of 'V' volts which then enters the cross-field region through the hole provided in the anode. In doing so, the electrons gains kinetic Energy in the expense of the electrostatic potential energy. If 'v' is the velocity of electron and 'e' be the charge carried by it, then from energy consideration

Electrostatic potential energy = kinetic energy.

or, $eV = \frac{1}{2} m v^2$

or, $\frac{e}{m} = \frac{1}{2} \frac{v^2}{V}$ —— (i)

The cross field arrangement in this experiment is made by two paralley placed metal ~~plate~~ plates maintained at a potential difference of 'V'' volts and separated by distance 'd'. This arrangement is then encircled by a circular conductor carrying current in anticlockwise direction. This experiment is carried out in following steps in order to confirm the cross field arrangement.

1. At first, both the fields are switched off. So that, the electron passes undeviated and strikes at point 'O' of the fluoroscence screen.
2. Now, Only the electric field is switched ON and the electron entering this region suffers a deviation in upward direction and strikes at point 'O'' of the screen.

3. Again, Electric field is switched off and magnetic field only is applied. The electron beam now experiences force in downward direction as defined by fleming's left hand rule and is deviated in the downward direction striking at point 'O'' ' on the screen.
4. Finally, both the electric field and magnetic field are simultaneously applied such that electron entering this region passes undeviated and again strikes at point 'O' of the screen. ~~In~~

In this way the cross field arrangement is confirmed. In such fields the velocity of charge particle is equal to the ratio of electric field to the magnetic field.

i.e $v = \frac{E}{B}$ — (ii)

from equ (i) and (ii), we get

$$\frac{e}{m} = \frac{1}{2}\frac{E^2}{B^2 V} \quad \text{— (iii)}$$

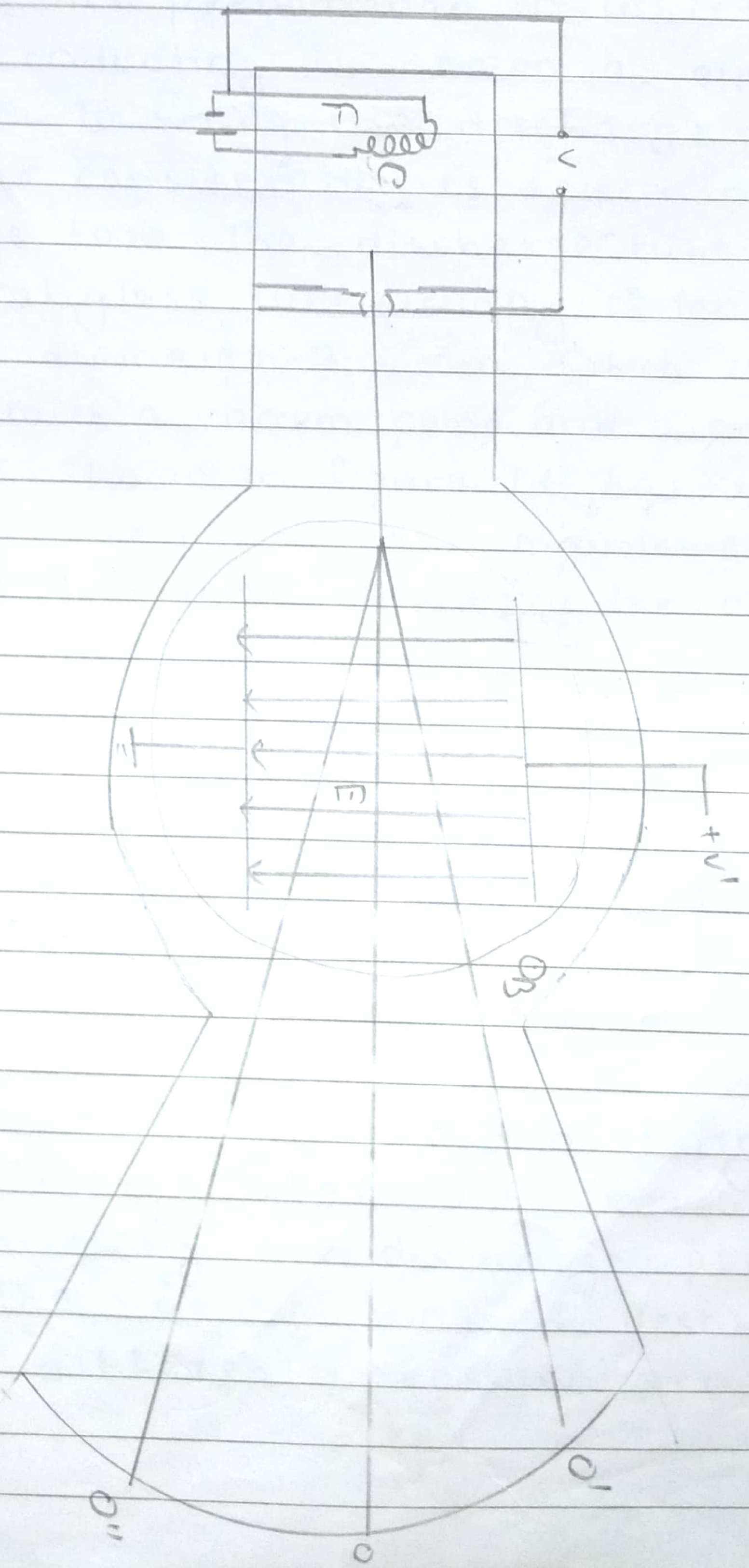
The electric field between the plates is given by

$$E = \frac{V'}{d} \quad \text{— (iv)}$$

So, from (iii) and (iv), we get

$$\frac{e}{m} = \frac{1}{2}\frac{V'^2}{d^2 B^2 V} \quad \text{— (v)}$$

Knowing the value of V', B, V, and 'd' we can calculate, $\frac{e}{m}$. And Experimentally it is found to be 1.76×10^{11} C/kg



Electric discharge through gases:-

At normal condition, Pure and dry gas is bad conductor of electricity. However, the gas can be made conducting when high electric field is applied and the pressure is greately reduced. This phenomenon in which the gas become conducting is known as electric discharge. To study the discharge phenomenon, gas under consideration is taken inside a discharge tube. The discharge tube is a cylindrical glass tube usually of length 30-50 cm and diameter 3-5 cm, which is also provided with a vaccum pump and a pressure gauge as shown in figure. It has two electrodes, a cathode and an anode maintained at a potential difference of the order of KV (10-15 kv)

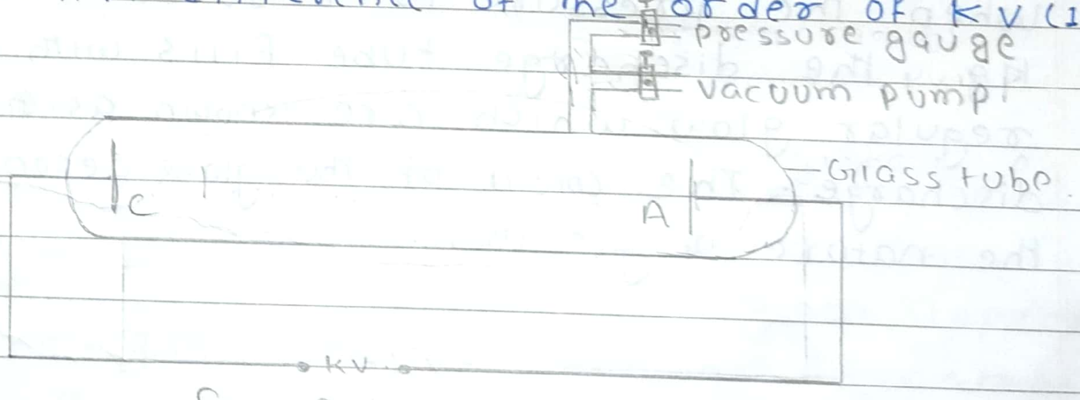
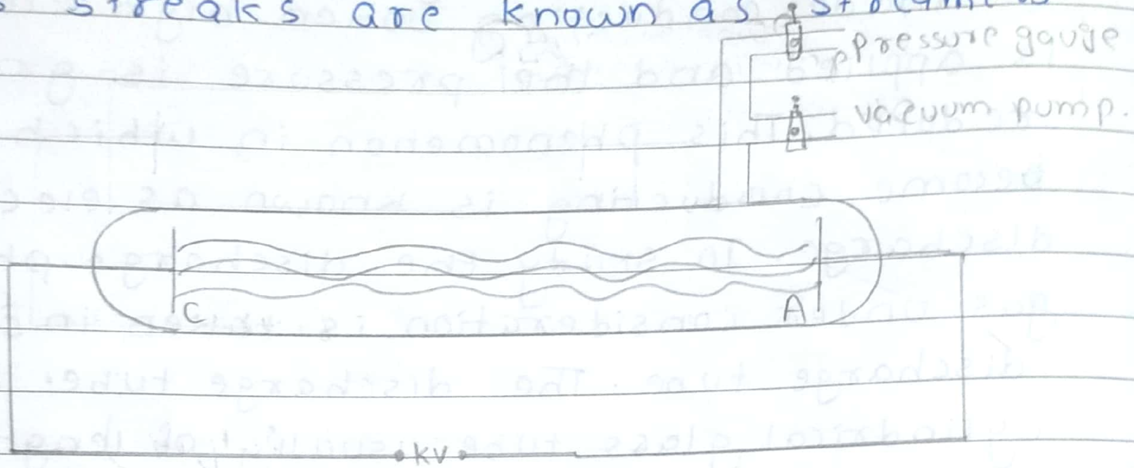


Fig:- Discharge of electricity.

At a pressure above 10 mm of Hg, no discharge occurs. However, when the pressure is reduced to 10mm of Hg the discharge phenomenon begins. The various kind of discharge takes place at different pressure are discussed below:-

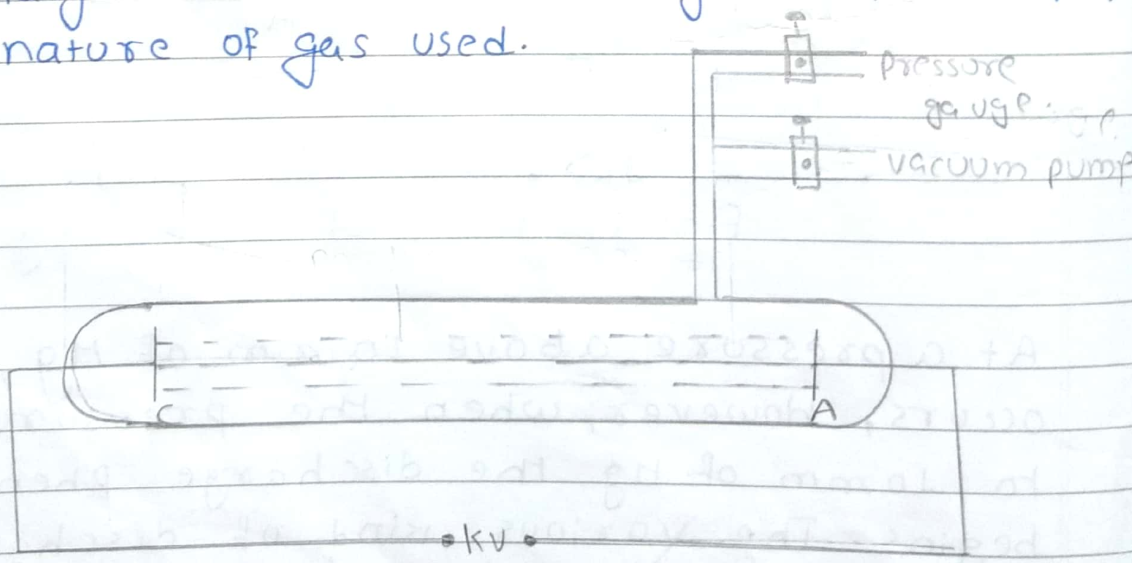
(i) At 10 mm of Hg:-

At this pressure, the discharge begins in the form of luminious streaks with crackling. This streaks are known as Streamers.



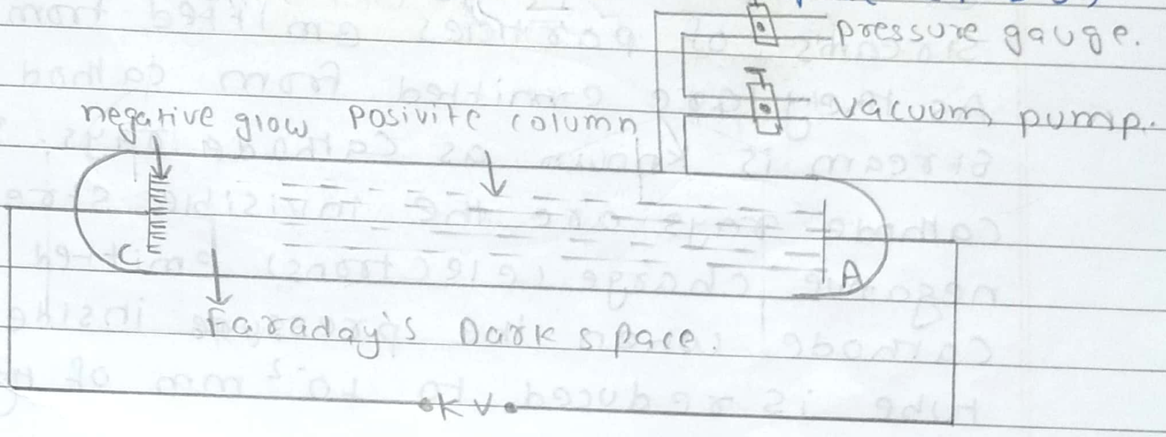
(ii) At 5mm of Hg:-

When the pressure is reduced to 5mm of Hg, the discharge tube fills with a regular glow which are known as Gleisser's discharge. The colour of the glow depends upon the nature of gas used.

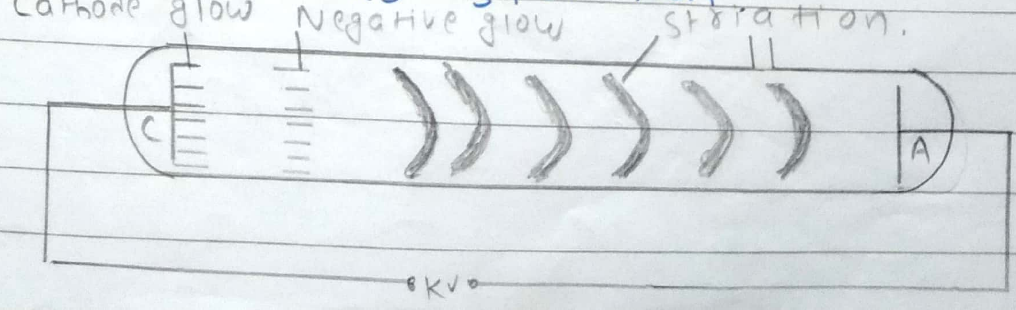


(iii) At 2 mm of Hg.

At this pressure, a glow appears at the cathode known as cathode glow and the regular glow leaves the cathode which extends upto anode. This is known as positive column. The region between negative glow and positive column is a dark space known as Faraday's dark space (F.D.S)



(iv) At 1 mm of Hg:-
When the pressure is reduced to 1 mm of Hg, the negative glow shifts a little further from cathode and a new glow appears at cathode which is known as cathode glow. The space between negative glow and cathode glow is a dark region known crooke's dark space (C.D.S). The positive column now split up into a number of equally spaced bands known as striation.



(v) At pressure of 10^{-2} mm of Hg:

At this pressure all the striations, negative glow, cathode glow, and Faraday's dark space disappear and whole tube is filled with crooke's dark space. The end of the discharge tube opposite to cathode starts to glow. This glow is due to the fluorescence effect produced by hitting of invisible streams of particles emitted from cathode. As they are emitted from cathod, the stream is known as cathode rays. Thus, cathode rays are the invisible streams of negative charge (electrons) emitted from cathode when the pressure inside the tube is reduced to 10^{-2} mm of Hg.

(vi) At pressure of 10^{-4} mm of Hg:

At this pressure, the discharge phenomenon stops due to insufficient concentration of charge carriers.

Photons.
Photoelectric Effect.

Quantum Theory of radiation

According to classical theory, the radition (energy) is emitted or absorbed in continuous manner. However this theory could not explain certain phenomenon such as photoelectric effect compton effect etc.

It was max plank who devised a new theory; known Quantum Theory of radiation while dealing with the study of black body radiation. According to him, the radiation (energy) is absorbed or emitted in the form of tiny packets known as quanta (singular quantum). Each quantum of energy corresponds to 'hf' where h is plank's constant and f is the frequency of ~~energy~~ radiation. later on, Einstein named this quantum of energy as photon. Thus, a quantum of radiation has a number of photons. And total energy of radiation is equal to the integral multiple of the energy carred by each photon. i.e Total Energy = nhf where $n = 1, 2, 3, \ldots$

Thus, the energy carried by a photon is considered the smallest unit of energy known quantum of energy.

Properties of photon:

(i) A photon can be considered as the particle of light

(ii) It moves with velocity of light (i.e 3×10^8 m/s)

(iii) It is never at rest and hence its rest mass is zero.

(iv) It is charge less particle and is not affected by electric and magnetic field.

(v) It has linear momentum given by $p = \frac{h}{\lambda}$, where λ is wavelength of radiation.

Photo-electric effect:-

The phenomenon of emission of electrons from the metal surface when radiation of suitable frequency is incident upon it, is known as photoelectric effect. The electrons thus emitted are known as photoelectrons. It is one to one interaction between photon and electron. During the process, the electron absorbs all of the energy of the photon.

Threshold frequency:-

The minimum frequency that the incident radiation must have, in order to eject the electrons from the metal surface is known as, Threshold frequency. It is denoted by f_0. And it is the property of incident radiation.

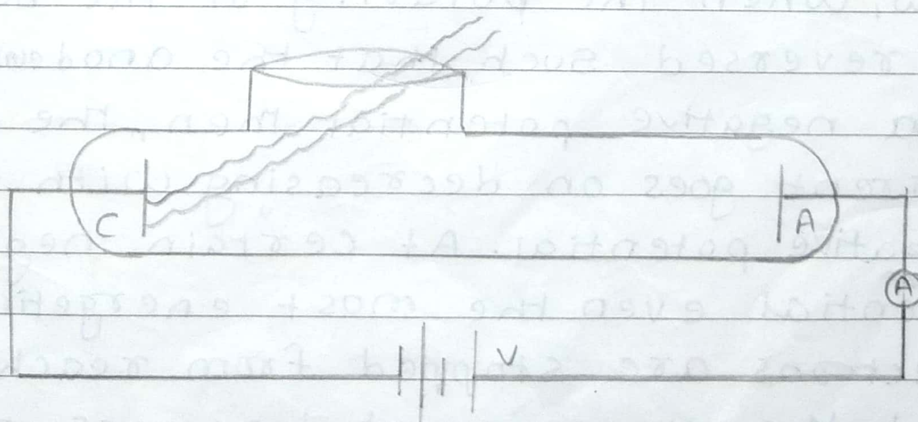
⊛ Threshold wavelength:

The maximum possible wavelength for which the photoelectric effect occurs is known as threshold wavelength. It is denoted by λ_0. This is the longest wavelength of the incident radiation above which no photoelectrons are emitted and corresponds to threshold frequency.

⊛ Work function:-

The minimum energy required to eject photoelectrons from the metal surface is known as work function. It is denoted by 'ϕ'. This is actually the energy with which the electrons are bound to metal surface. This is entirely independent to radiation but is the property of the metal itself

Experimental study of photoelectric effect:-



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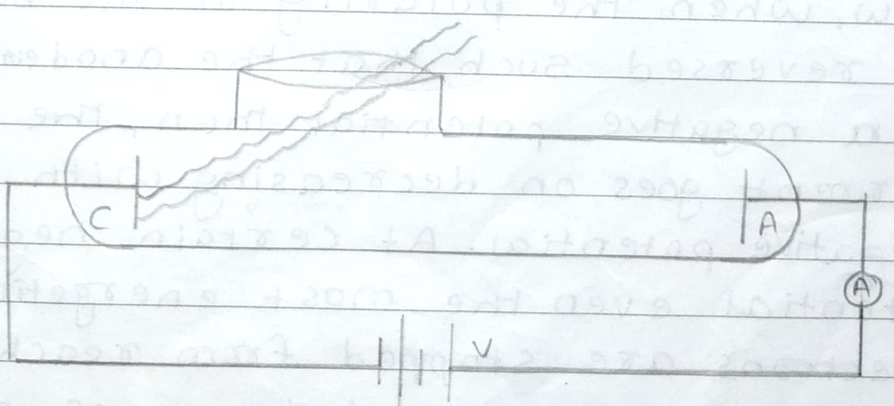


The experimental set up to study the photoelectric effect consists of an evacuated glass tube provided with a cathode (C) and an anode (A) as shown in figure. The cathode material is usually a photo sensative metal especially alkali metals. When radiation of suitable frequency falls on such photosensative metal, electrons are emitted which pile up in the region between cathode, and anode and are known as space charge. When a suitable accelerating potential (V) is applied these electrons move towards anode and move through external circuit to constitute photocurrent (I_p) For constant intensity, the photo current at first increases with accelerating potential and attains a constant value which is known as saturation current. The current is measured by an ammeter provided in the circuit.

Now, when the polarity of the battery is reversed such that the anode (A) is now at a negative potential then, the photo-current goes on decreasing with increasing negative potential. At certain negative potential even the most energetic photo electrons are stopped from reaching to A. and the photocurrent becomes zero. This value of the negative potential for which the photo current becomes zero is known as stopping potential. In this situation, the work done by negative potential to stop the photoelectron is equal to the maximum kinetic energy of the photoelectrons. i.e

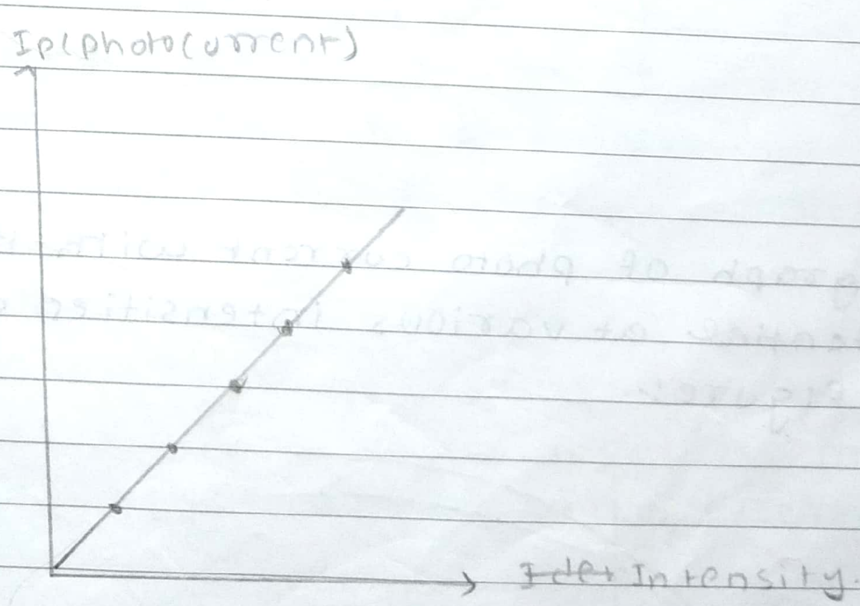
$$K.E_{max} = eV_s$$

$$\frac{1}{2} m v_{max}^2 = eV_s .$$

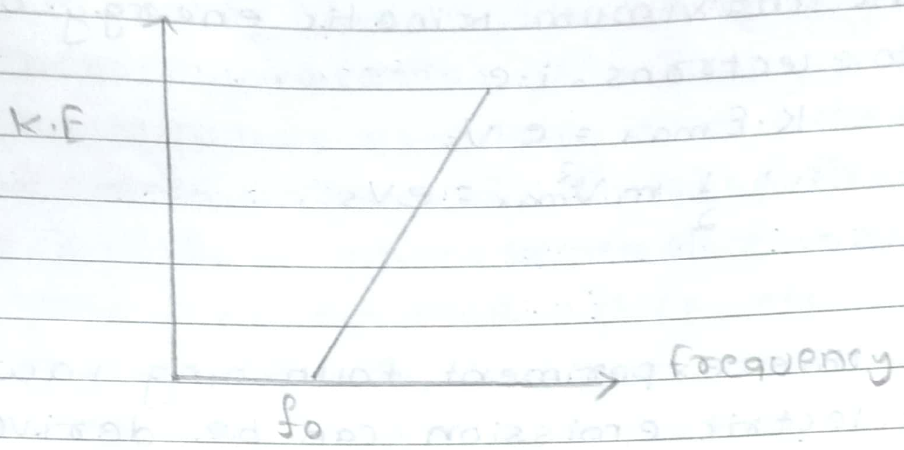
From this experiment, following laws of photoelectric emission can be derived

(i) It is a spontaneous process which occurs almost instantly when radiation of suitable frequency falls upon metal surface.

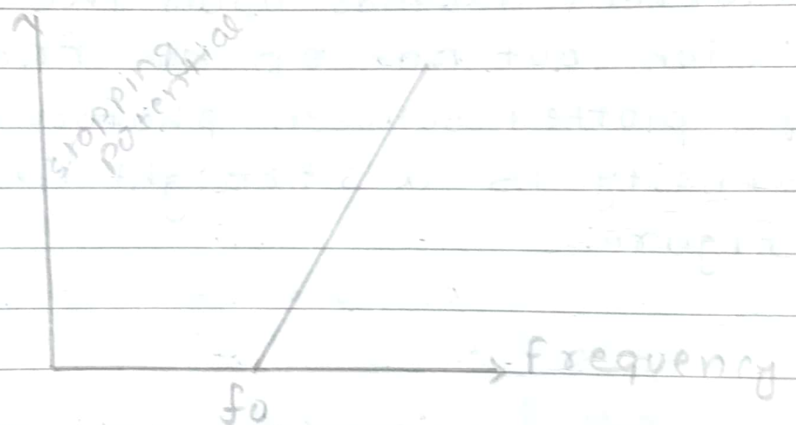
(ii) The number of photoelectrons and hence the photocurrent depends upon the intensity of radiation but not on the frequency. A graph plotted between photocurrent and Intensity is a straight line as shown in figure.



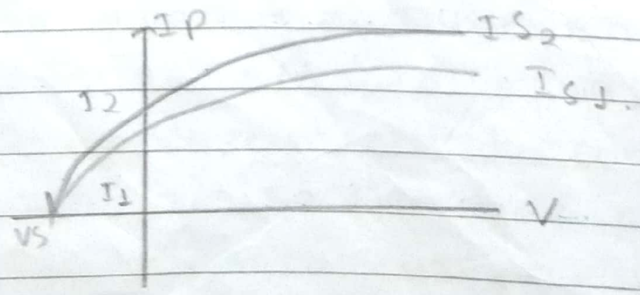
(iii) The kinetic energy of emitted photo electrons depends upon the frequency of radiation



(iv) The stopping potential is independent of the intensity but depends upon the frequency of radiation.



V) A graph of photo current with the stopping potential at various intensities as shown in figure:-



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Einstein's photoelectric Equation:-

According to Einstein, a photon carries energy proportional to the frequency of radiation. If 'f' is the frequency of radiation and 'h' is the plank's constant. Then the energy of photon is given by

$$E = hf.$$

When a photon interacts with an electron, a parts of its energy is used up to eject the electron from metal surface and remaining energy is used up to impart kinetic energy to the ejected photoelectrons. The energy equivalent to work function is used up to eject electrons. So, we can write,

$$hf = \phi + k.E \quad \text{---(i)}$$

If v_{max} is the maximum velocity of ejected electrons and 'fo' is the frequency of radiation corresponding to work function then, equ(i) can be written as:

$$hf = hf_o + \frac{1}{2} m v_{max}^2 \quad \text{---(ii)}$$

This is known as Einstein's photoelectric Equation. Further, If Vs is stopping potential which has to do work to stop the most energetic electrons then, from energy consideration

$$eV_s = \frac{1}{2} m v_{max}^2 \quad \text{---(iii)}$$

Using equ (iii) in equ (ii), we get
$$hf = hf_0 + eV_s \quad -(iv)$$

This is another form of Einstein's photo electric Equation.

In terms of wavelength, If 'λ' and 'λ₀' are the wavelengths corresponding to 'f' and 'f₀', we can write equ (iv) as
$$eV_s = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

(4) * Experimental verification of Einstein's photoelectric Equation:

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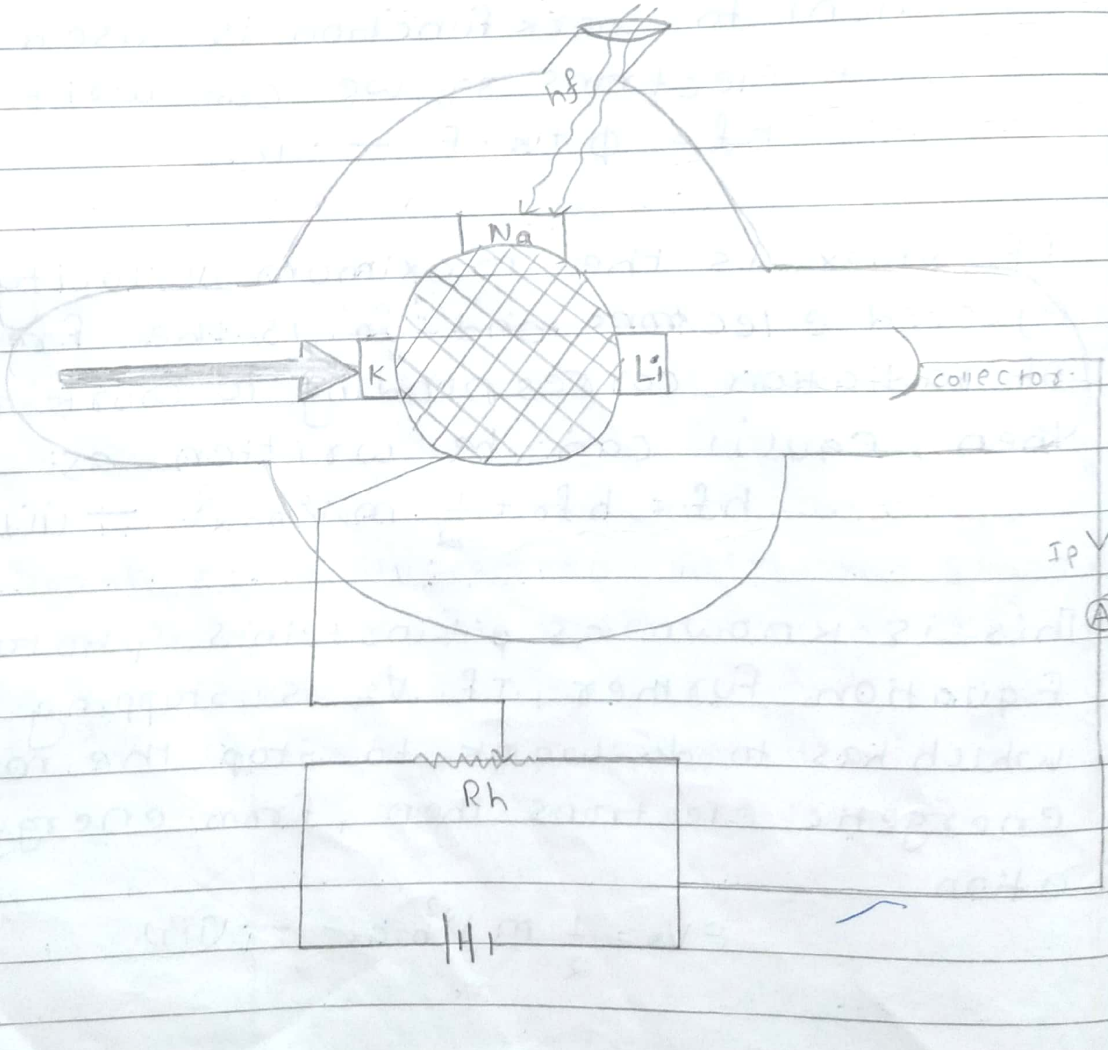

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Page

According to Einstein, the maximum K.E of the emitted photoelectrons depend upon the frequency of photon.

$$\text{i.e } \frac{1}{2} m v_{max}^2 \propto f \quad -(i)$$

Whenever the polarity of emitter and collector is reversed such that the collector is at negative potential, then the negative potential does work to stop the photoelectrons from reaching towards it. At certain negative potential (V_s) applied to the collector, the photo current becomes zero and in this condition

$$eV_s = \frac{1}{2} m v_{max}^2 \quad -(ii)$$

from equation (i) and (ii), we can write

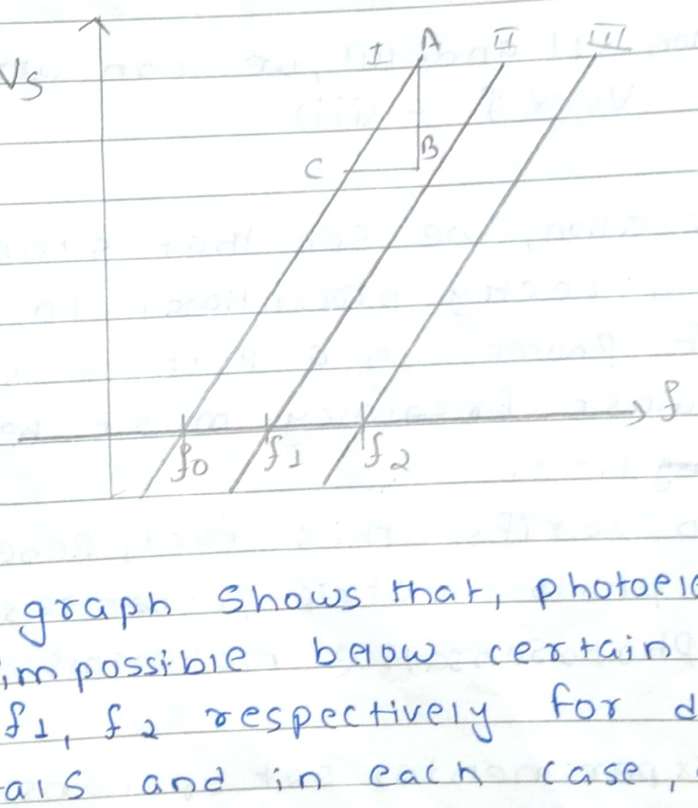
$$V_s \propto f \quad -(iii)$$

From this relation, we see that stopping potential is directly proportional to the frequency of photon. so, a plot of stopping potential against frequency must be a straight ~~lin~~ line.

In order to verify this fact, Robert milikan studied the photo-electric properties of different photosensative materials experimentally.

Milikan's experimental set up consists of three different photosensative metal. such as Na, li and K mounted over a cylindrical wheel which can be rotated with the help of electromagnet. A knife is provided to wipe off the rust or any dust particles on the surface of metal. This arrangement is made inside a discharge tube which has a collector connected to negative potential.

The frequency of radiation falling on anyone of the metal is varied and the corresponding Stopping potential is noted. It is found that, the value of stopping potential increases with frequency. The same was observed for other metals too. A plot of stopping potential against frequency for different metals is as shown below:-



The graph shows that, photoelectric effect is impossible below certain frequency f_0, f_1, f_2 respectively for different metals and in each case, above threshold frequency, the V_s increases with f. This experimentally observed fact is in accordance with Einstein's photoelectric equation given by

$$eV_s = hf - hf_0 \quad \text{—(iv)}$$

Further,

$$V_s = \frac{h}{e} f - \frac{h}{e} f_0 \quad \text{—(V)}$$

Comparing equ(V) with equation of straight line $y = mx + c$

we get

$y = V_s$, $x = f$ $m = \frac{h}{e}$ and $c = -\frac{h}{e} f_0$

i.e Einstein's photo-electric equation is a Straight line with negative intercept. This verifies Einstein's photoelectric equation.

Further, Referring to graph the slope of line (i) is $m = -\frac{AB}{CB} = \frac{\Delta V_s}{\Delta f}$

But $m = \frac{h}{e}$

$$\therefore h = \frac{\Delta V_s}{\Delta f} \cdot e$$

This equation defines the value of h to be 6.62×10^{-24} JS.