UNIT – 7 (Marks – 4)

DUAL NATURE OF MATTER AND RADIATION.

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Free electrons in metals ↦ Loosely bound electrons of the outer shell of an atom are called free electro[ns]. These free electrons can move freely inside the lattice of +ve ions. However they can[not] leave the surface of the metal at their own. So external energy has to be provided to these free electron to eject them out of the metal surfa[ce].

The minimum amount of energy required by an electron to just escape from the metal surface is called work function of the metal.

The work function of the metal is denoted by w_0 and measured in electron volt. (eV). The work function depends upon the nature of metal. Work function for caesium (Cs) is lowest (2.14 eV) and for platinum (Pt) is highest (5.65 eV).

Electron Volt ↦ Energy gained by an electron when it is accelerated by applying a pot. diff. of 1 Volt is called 1 eV.

ie $1eV = 1e \times 1V$ $(W \text{ or } E = qV)$

$\Rightarrow 1eV = 1.6 \times 10^{-19} C \times 1V$

$= 1.6 \times 10^{-19} CV$

$\Rightarrow \boxed{1eV = 1.6 \times 10^{-19} J}$

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Electron ~~Of~~ Emission ↦ The phenomenon of emission of electron from the metal surface by giving it an energy more than the work function of the metal is called ~~a~~ electron emission.

Electron emission can be of four types ↦

① **Thermionic emission** ↦ The emission of electrons on heating is called thermionic emission. Emitted e^-s are called thermions or thermo-electrons.

2. **Field Emission** ↦ The emission of e^-s from the metal surface by applying strong electric field is called field emission.

3. **Photo-electric emission** ↦ The phenomenon of emission of electrons from the metal surface when light of suitable high frequency falls on it is called photo-electric emission. The emitted electrons are photo-electrons.

4. **Secondary emission** ↦ When a fast moving electrons hit the metal surface, it ~~imports its energy~~ imparts its energy to the free electron of the metal and produces secondary emission. The emitted electron is called secondary electron.

Photo-Electric Effect ↦ The phenomenon of emission of free electrons from the metal surface, when light of suitable high frequency falls on it is called photo electric effect.

The photo electric effect can be explained by considering the particle nature of light.

These particles of light are called photons.
Some basic properties of the photons are as under:-

1. Velocity of photon through free space is equal to velocity of light.
2. The speed of photon changes as it travels through different mediums.
3. The frequency of photon does not change as it travels through different mediums.
4. ~~and~~ As $\lambda = \frac{c}{\nu}$. Thus wave length also changes through different mediums.
5. Energy of the photon,
$$E = h\nu$$
where $h = 6.63 \times 10^{-34}$ J s = Plank's const.

6. Mass of the photon moving with velocity u ~~of light~~ u
$$m = \frac{m_0}{\sqrt{1 - \frac{u^2}{c^2}}}$$
Thus rest mass, $m_0 = m\sqrt{1 - \frac{u^2}{c^2}}$

Since velocity of photon u = velocity of light c
$$\therefore \quad m_0 = 0$$

7. The moving mass of the photon can be determined by using Einstein's mass energy relationship.
ie $E = mc^2 = h\nu$
$$\therefore \quad m = \frac{h\nu}{c^2}$$
8. Thus momentum of the photon
$$p = mc = \frac{h\nu}{c} = \frac{h}{\lambda}$$

9. Photons are electrically neutral. Hence can't be deflected by electric and magnetic field.

10. A photon may collide with material particle. In such collisions, total momentum and total energy remains conserved. However no. of photons may increase or decrease.

11 If intensity of light of given frequency is increased, then no. of photons increases however energy of each photons remains same

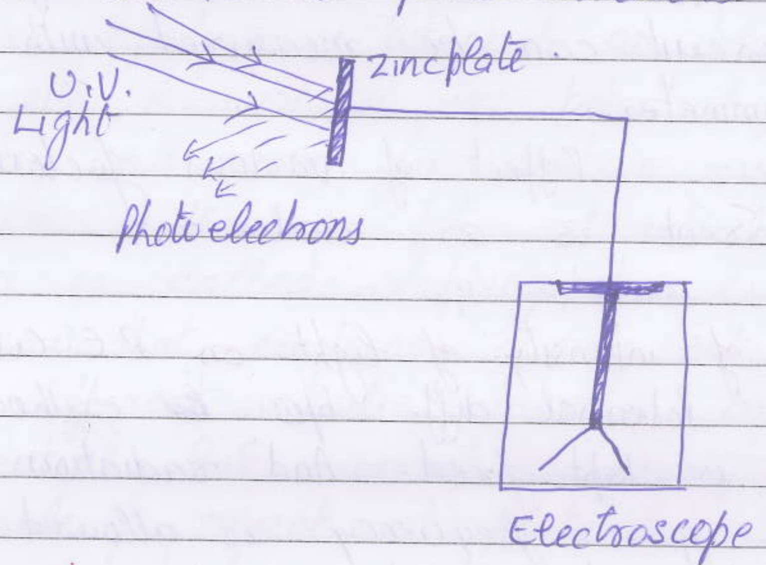
Experimental study of photo-electric effect ↦

Hertz's Observations ↦ While demonstraighting the existance of electromagnetic waves, Hertz found that the sparks across the metallic spheres of detected can be obtained more easily, when the cathode was illuminated by the ultraviolet radiations. This happened because ultraviolet radiations caused the emission of electrons which enhanced the high voltage sparks.

Hallwach's ~~and Lenard's~~ observations ↦ Hallwach connected a zinc plate to an electroscope. He allowed ultraviolet light to fall on zinc plate and observed that

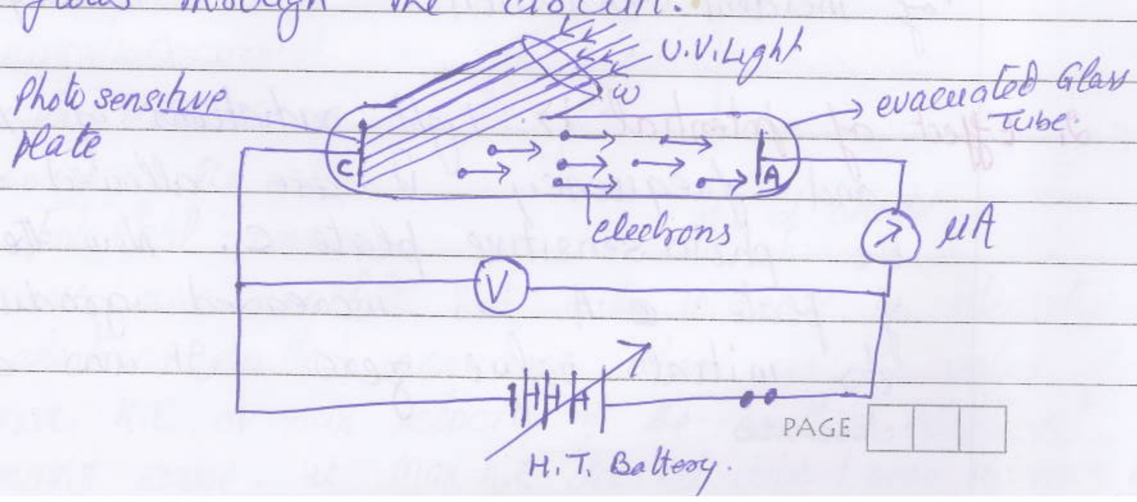
1. Zinc plate get uncharged if initially -vely charged
2. " " " +vely charged if " uncharged.
3. " " " more +vely charged if " +vely charged.

ie some -vely charged particles are being removed ~~by~~ from the zinc plate when exposed to U.V. Light.
Later on these particles are discovered to be electrons and named as photo electrons



Lenards observations ↦

Lenard observed that when U.V. radiation are allowed to fall on the emitter plate of an evacuated glass tube as shown, then current flows in the circuit. The current through the circuit stops as soon as the U.V. radiation are stopped. Lenard explained that as soon as the U.V. Radiations fall on the emitter (Cathode) C, photoelectrons ~~are~~ emit from it and these electrons are attracted by the ~~-vely char~~ +ve collector (Anode). Thus current k/a photoelectric current flows through the circuit.



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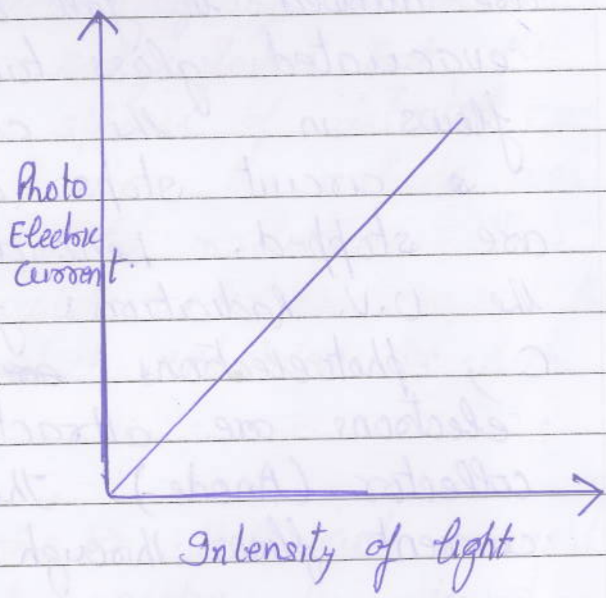
Potential applied across cathode C and anode A can be varied with the help of potential divider arrangement and its value can be noted from voltmeter. Where as current flowing through the circuit can be measured with the help of micro ammeter.

Effect of various factors on photo electric current is as under:-

① Effect of intensity of light on P.E. Current ↦

Potential diff. b/w cathode C and anode A is kept fixed. And radiation of different intensities of given frequency is allowed to fall on the photosensitive plate C and the value of P.E. current flowing through circuit is measured with the help of micro ammeter.

It was observed that P.E current varies linearly with intensity as shown in the graph. Thus it implies that number of photo electrons emitted per second is proportional to the intensity of incident radiation.



2. Effect of potential ↦ Light radiations of intensity I_1 and frequency ν are allowed to fall on the photo sensitive plate C. Now the potential of plate A is increased gradualy from its initial value zero. It was observed that

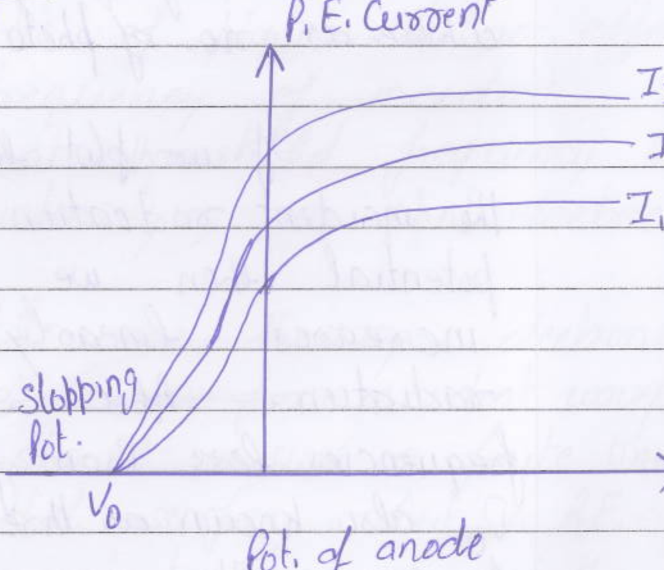
P.E. C increases with increase in +ve pot. of plate A a
soon it attains saturated value. At this stage all the photoelectrons emitted by plate C are collected by anode A.

If we apply −ve potential on plate A, it w observed that with increase in −ve potential, P.E. curr reduces sharply and soon for certain −ve pot. V_0 P.E. current becomes zero. This −ve pot. at which P.E. curr becomes zero is called stopping pot or cut-off poten

We know that electrons coming out from catho C move with different velocities towards anode A. S at stopping potential, P.E. current is zero, i.e no electron is able to reach at plate A. Thus we can say that potential energy due applied pot. V_0 has balanced the max. Kinetic energy of the electron i.e

$$eV_0 = \frac{1}{2} m v_{max}^2$$

$$\text{or} \quad v_{max} = \sqrt{\frac{2eV_0}{m}}$$



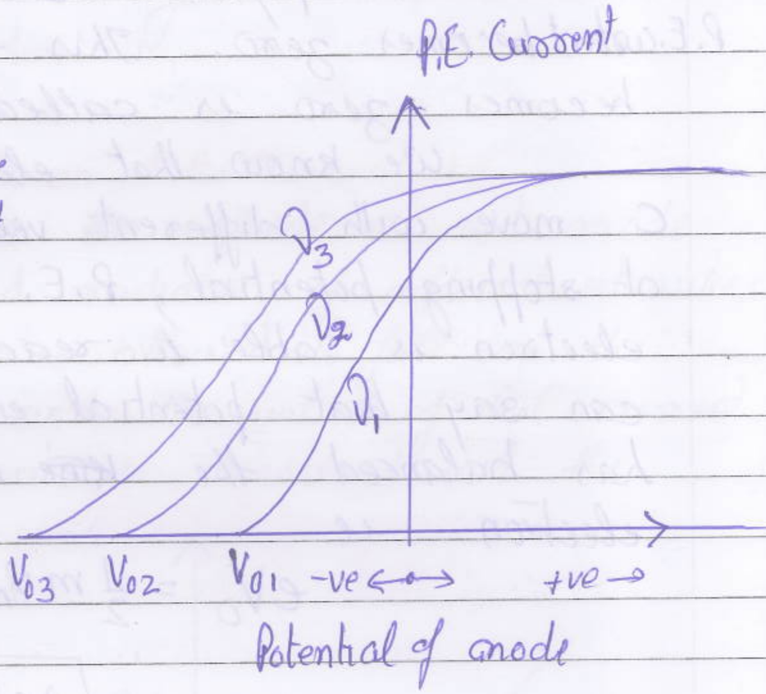
If we repeat the experiment with different intensities I_2 and I_3 so that $I_3 > I_2 > I_1$ then we observe that the value of saturation current increases with increase in intensity, however the value of stopping potential remains same. Thus we can conclude that with increase in intensity no. of photo electrons emitted increases where as the value of max. K.E or max velocity of the emitted electrons remains same. i.e Max K.E does not depend upon intensity of radiation.

③ Effect of freq. of incident radiation on stopping pot.

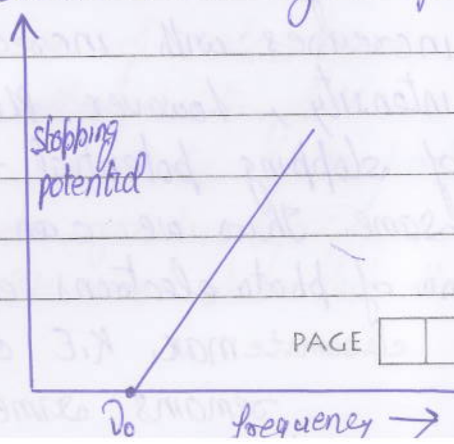
If we repeat the above experiment for three different radiations of same intensity but of different frequencies ν_1, ν_2, ν_3 so that $\nu_3 > \nu_2 > \nu_1$ then the graphs obtained are as shown.

From the graphs it is clear that stopping pot increases with increase in frequency of incident radiation. However the value of saturation current remains same.

Thus we can say that max K.E or max velocity of the emitted photo electrons increases with increase in frequency where as no. of photoelectrons emitted remains same.



If we plot the graph b/w frequency of the incident radiation and corresponding stopping potential then we find that stopping potential increases linearly with frequency of incident radiation. Also stopping potential is zero for frequencies less than frequency ν_0 also known as threshold frequency. Thus we can say no photo electric emission takes place for a frequency less than threshold frequency.
(what so ever be the value of intensity.)



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Laws of photo electric effect ↦

① The P.E emission is an instanteneous process.
② Photoelectric current is directly proportional to the intensity of incident radiation.
3. The K.E of the emitted photoelectrons is independent of the intensity of incident radiations and depends only upon the frequency of incident radiations.
4. The photo electric emission takes place only above certain frequency of incident radiation k/a threshold freq.

Failure of classical wave theory ↦

Ques ↦ Explain why photoelectric effect cannot be explained on the basis of wave nature of light.

Ans ↦ According to wave theory of light, with increase in intensity of incident light wave, the energy density of the wave also increases. Hence waves of higher intensity should be able to escape the photo electro[n]. But the experimental studies of photo-electric effec[t] suggests that if the frequency of incident radiation is less that threshold frequency the[n] what so ever be its intensity, no photoelectric emission will take place.

Further according to wave theory, electrons will absorb energy from the ~~wave fro~~ incident wavefro[nt] slowly and slowly so it should require a finite time to escape from the metal surface. But in P.E. eff[ect] emission of electrons is instanteneous ie as the light falls on the metal surface, photoelectric emissi[on] takes place.

Thus on the basis of above two facts we can say that wave theory fails to explain P.E. effect.

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Einstein's theory of Photo-Electric effect ↦

Einstein explained photo electric effect on the basis of Plank's quantum theory.

The main features of Einstein's theory of P.E. effect are

① Photoelectric emission is the result of interaction b/w the photon of incident radiation and electron of photosensitive plate. More importantly each photon can eject only one photo-electron.

2. Each photon on collision with electron, imparts its entire energy to the electron and electron uses ~~consumes~~ this energy in two parts ie

(a) ~~while~~ Energy equals to the work function (w_0) of the metal is used while coming to the metal surface and.

(b) Remaining energy of the photon is used in gaining the kinetic energy.

3. ~~Very~~ ie $h\nu = w_0 + \frac{1}{2}mu^2_{max}$ —— ①

if the incident photon is threshold frequency ν_0 then electron will just escape from the metal surface and its K.E will be zero.

$\therefore$ if $\nu = \nu_0$

then $\frac{1}{2}mu^2_{max} = 0$

Thus eqn. no. ① becomes

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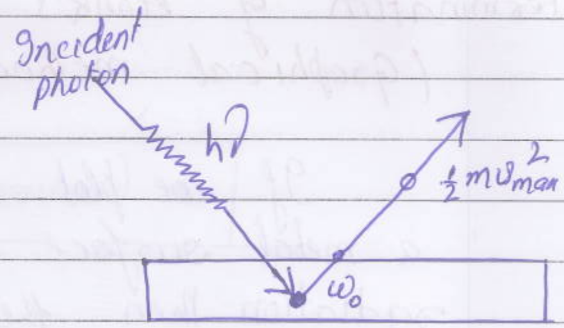
$h\nu_0 = w_0 + 0$

$\Rightarrow w_0 = h\nu_0$



Substitute w_0 in eqn no ①
we get

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

$$\Rightarrow \frac{1}{2}mv_{max}^2 = h\nu - h\nu_0$$

$$\Rightarrow \boxed{\frac{1}{2}mv_{max}^2 = h(\nu - \nu_0)}$$ ⟶ Einsteins eqn of photo elec effect.

Explanation of laws of photo electric effect on the ba of Einsteins theory of P.E. ~~effect~~/emission ↦ .

① Incident photon imparts its entire energy ($h\nu$) in go. (ie energy is not absorbed by the electro from the incident wavefront slowly and slowly Thus photo electric emission takes place instaneneou

(2) Since according ~~of~~ to Einstein's theory, each pho can eject only one electron. Thus ~~no~~. number of photo electrons emitted and hence the photo electric cur depends upon the no. of incident photons ie intens of incident ~~p~~ radiation.

3. According to Einstein's eqn. of Photo electric effec K.E. of the emitted photo electron ($\frac{1}{2}mv_{max}^2$) depen upon the frequency (ν) of incident photon (radiation)

4. If $\nu < \nu_0$ then from Einstein's eqn. K.E. of the emitted electron will be $-ve$. which is not possi Thus photo electric emission will take place only above threshold

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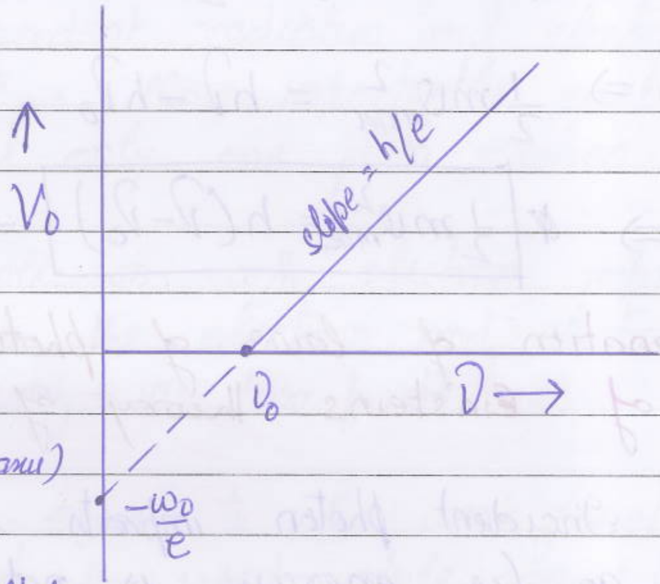
Determination of Plank's constant and work function ↦ (Graphical method)

If we plot the graph b/w stopping pot. for a metal surface with frequency of incident radiation then the graph obtained is a straight inclined line as shown.



from eqn of straight line,

$$y = mx + c \quad —(1)$$

where m is slope of the line and c is y intercept (or intercept on vertical axis)

Also from Einsteins eqn of Photo electric effect.

$$K.E_{max} = h\nu - h\nu_0$$

$$\Rightarrow K.E_{max} = h\nu - w_0 \quad —(2)$$

also $K.E_{max} = eV_0 \quad —(3)$

from (2) and (3)

$$eV_0 = h\nu - w_0$$

$$\therefore V_0 = \frac{h}{e}\nu + \left(\frac{-w_0}{e}\right) \quad —(4)$$

comparing eqn. no. (4) with eqn no (1) we get

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

$$\therefore h = m \times e$$

$$\Rightarrow \boxed{h = (\text{slope of } V_0 - \nu \text{ curve})\, e}$$

also $-\frac{w_0}{e} = c$

$$\Rightarrow -\frac{w_0}{e} = y \text{ intercept}$$

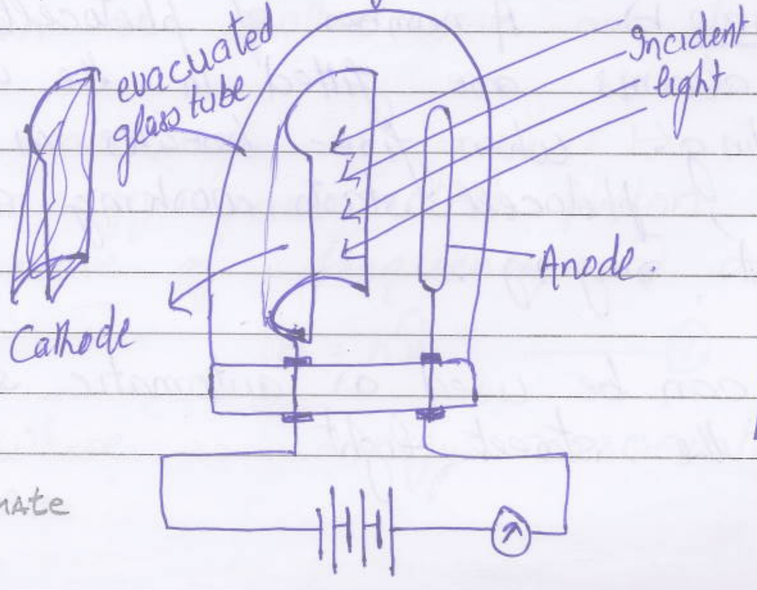
$$\therefore \boxed{w_0 = e\,(\text{magnitude of intercept on vertical a}}$$

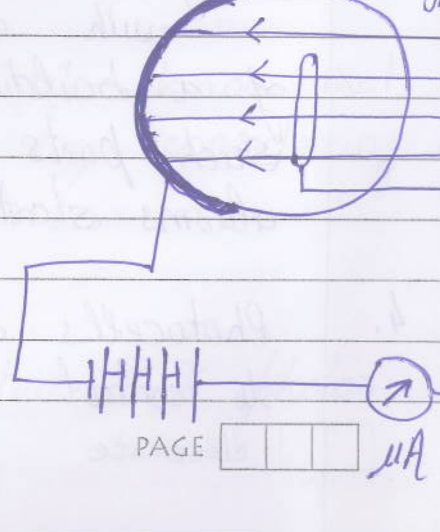
The values of h and w_0 determined graphically fo sodium agreed well with the values known from other experiments.

Photocell ↦ A photo cell or photo-electric cell is a device which converts light energy into electrical energy.

It works on the principle of P.E. effect.

Construction and working ↦ It consist of a semi cyllinder cathode made up of a photo sensitive material and anode made up of thin wire in the form of loo





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when light of frequency greater than threshold frequencies falls on the cathode, photoelectrons are emitted by it and these emitted electrons are attracted by the anode and current starts flowing through the circuit. Since this photo electric current is very feeble thus it is first amplified before using for useful purpose.

Applications of photocells ↦

① A photocell connected to counter can be used as counting device, provided the persons enter one by one. As the person enters the room/hall it intercepts the light and photocell stops working and counter counts the number of times photocell stops working.

2. In bulgar alarms ↦ when a person enters in the prohibbeted area, it intercepts the invisible ultraviolet light falling on the photocell. This photocell is connected to ~~alam~~ alarm which starts ringing as photocell stops working.

3. In fire alams ↦ A number of photocells attached with alarms are fitted in the various parts of a building. when fire breaks in one of such parts, photocell starts working and alarms start ringing.

4. Photocells can be used as automatic switches to control the street light.

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5. To determine the opacity of solids and liquids.
6. In locating the minor flaws or holes in large metal sheets.
7. As a complexion meter.
8. In finding out the amount of day light (during bad light appeals in matches).

Dual Nature of radiation and matter ↦ Some phenomenons of light like diffraction, interference, polarization can only be explained by considering light a wave where as some other phenomenons like photo electric effect, compton effect etc can ~~d~~ only be explained by considering light as particle. This shows that light has dual nature i.e wave nature as well as particle nature.

In 1924, De Broglie argued that nature (universe) is made up of either mass or energy, and since nature loves symmetry therefore as the light radiations (energy) has dual nature hence material particles (mass) must also have dual nature.

He gave the theory that material particles in motion must possess wave and is known as matter wave or de-Broglie wave.

de-Broglie wave length of matter ↦ We know that energy associated photon by considering it as wave of frequency ν is,

$$E = h\nu \quad \text{——— (1)}$$

Where as energy associated with photon

by considering it as a particle of mass m is

$$E = mc^2 \quad \text{——— (2)}$$

from (1) and (2),

$$h\nu = mc^2$$

$$\Rightarrow \frac{hc}{\lambda} = mc^2$$

$$\Rightarrow \lambda = \frac{hc}{mc^2}$$

$$\Rightarrow \boxed{\lambda = \frac{h}{mc}}$$

Where as for some other particles like proton, neutron or electron of mass m and moving with velocity v, the de-Broglie wavelength of particle can be given as

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

or $$\boxed{\lambda = \frac{h}{p}}$$

This is also k/a de-Broglie's wave equation for material particle.

Note If $v = 0$ the $\lambda = \infty$. That is no de-Broglie wave is associated with the particle which is at rest.

Also de-Broglie matter wave can't be considered as em wave. Because em wave are associated only with accelerated charged particles only. Where as for de broglie waves neither charge is required nor acceleration is required (only mo... is requ...

de-Broglie wave length of an electron ↦

Consider an electron of mass m is accelerated by applying a pot. diff of V volts. Let u is the velocity gained by the electron at rest then the K.E of the electron is as a result of workdone on it by the applied potential

ie

$$\frac{1}{2}mu^2 = eV$$

$$\Rightarrow \frac{p^2}{2m} = eV$$

$$\Rightarrow p = \sqrt{2meV}$$

$$\left\{ \because K.E = \frac{1}{2}mu^2 = \frac{m^2u^2}{2m} = \frac{p^2}{2m} \right.$$

Thus wave length associated with the electron

ie.

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

$$\Rightarrow \boxed{\lambda = \frac{h}{\sqrt{2meV}}}$$

on substituting the standard value of h, m, and e. we get,

$$\boxed{\lambda = \frac{12.27}{\sqrt{V}} \mathring{A}}$$

This value is of the same order as is obtained through experiments. de-Broglie was awarded the Nobel Prize in Physics in 1929 for this discovery.

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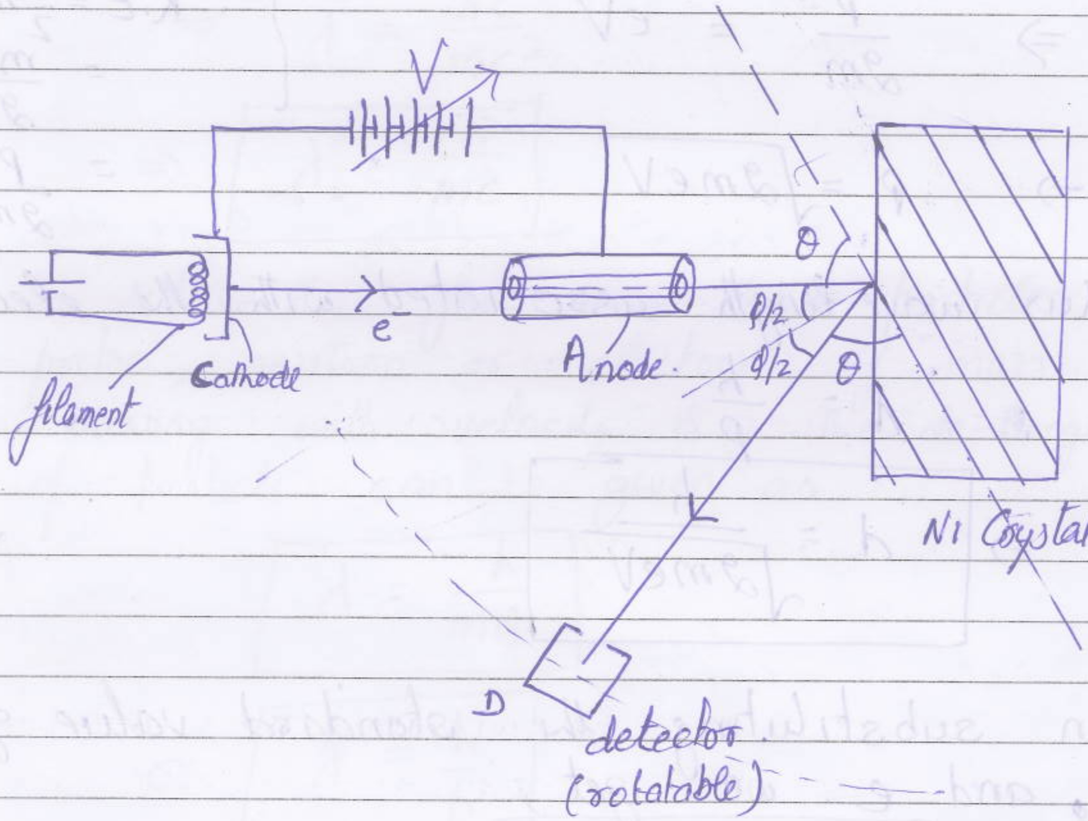
Experimental demonstration of wave nature of electrons or Davison and Germers experiment :-

In Davison and Germers experiment, electrons emitted from the hot cathode are accelerated by applying a suitable potential difference V. This fine beam of electrons is allowed to fall on a nickle crystal cut diagonally.



The electron beam scattered at various scattering angles were received by the rotatable detector D.

This experiment was repeated at various accelerating potential b/w 44V to 68V and it was observed that intensity of scattered beam of electron was maximum for the scattering angle of 50° and for an accelerating potential of 54V.

It was explained that it happened so because of formation of diffraction maxima of first orde[r by] the atoms of Ni crystal.

from the figure it is clear that

$$\theta + \phi + \theta = 180^\circ$$

where θ is glancing angle

$$\Rightarrow 2\theta = 180 - \phi$$

$$\Rightarrow \theta = \frac{180-\phi}{2}$$

for first order diffraction maxima

$$\phi = 50^\circ$$

$$\therefore \theta = \frac{180-50}{2} = \frac{130}{2} = 65^\circ.$$

Also from Bragg's law, for first order diffrac[tion] maxima

$$2d\sin\theta = 1\lambda$$

ie $\lambda = 2d\sin\theta$

where $d = .91 A^\circ$ = interatomic separation in Ni c[rystal]

and $\theta = 65^\circ$ = glancing angle.

on substituting the values.

$$\lambda = 2 \times 0.91 \times \sin 65^\circ$$

$$\Rightarrow \lambda = 1.65 A^0$$

from De-Broglie's hypothesis at 54V pot.

$$\lambda = \frac{12.27}{\sqrt{54}} = 1.67 A^0$$

This value is very close to the experimental value of Davi[sson] and Germer. Thus we can say that Davisons and Germer ha[ve] experimentally established the de-Broglies hypothesis.