Chapter:

Dual Nature of Radiation and Matter

Electron Emission

The process by which e⁻s are emitted (free e⁻s) from a metal surface is known as electron emission. Electron emission are of three types:

- Thermionic Emission:

  If e⁻ emission takes place by the application of sufficient heat energy is called thermionic emission

- Field Emission:

  If the emission of e⁻ is due to application of strong electric field (10^8 V/m) then it is called feild emission

- Photoelectric Emission:

  The Electron emission takes place by the application of light of suffient energy is called the photo electric emission

Work Function (ϕ_0)

The minimum energy required to eject an e⁻ from a metal surface is known as the work function.

Photoelectric Effect

The phenomenon by which e⁻s are ejected from a metal surface when light with sufficient energy is falling on it is called the photoelectric effect. It was first observed by Heinrich Hertz.

Experimental observations of Photoelectric Effect

(Hallwach's and Lenerd's observation)

The experimental setup used to study photoelectric effect is shown in figure.

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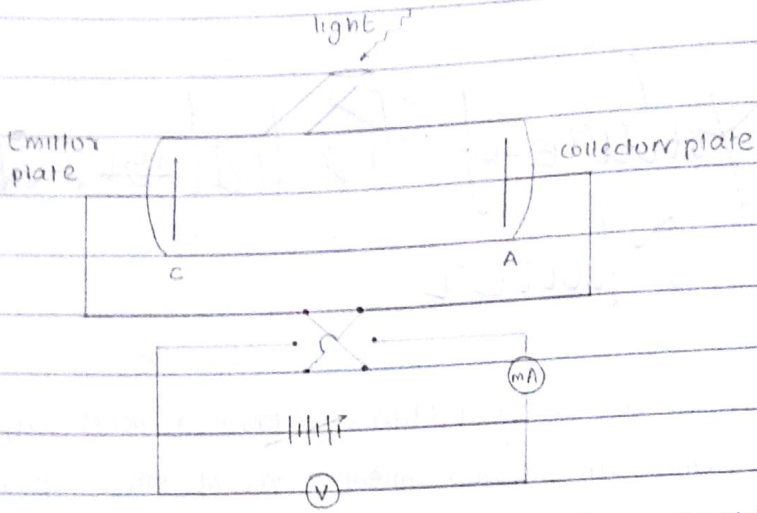
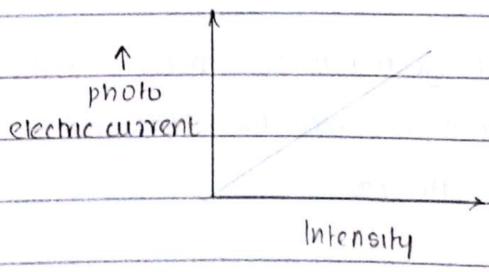


It consists of two metallic plates C and A, arranged in a invacuated chamber. The plates are connected to a source of voltage through a commutator so that the potentials can be adjusted. There is an opening at the top of the tube. Light is allowed to fall on the plate C through a transparent window arranged at the top of the tube. Then photoelectric emission takes place and current begins to flow through the circuit and this current is known as photoelectric current.

Observation

- Effect on intensity of incidence light on photoelectric current

Initially the plate A is given a +ve positive potential with respect to plate C when intensity of incident light increases the no of ejected e^- increases and as result the photoelectric current increases. ie, photoelectric current is directly proportional to the intensity of incident radiation.

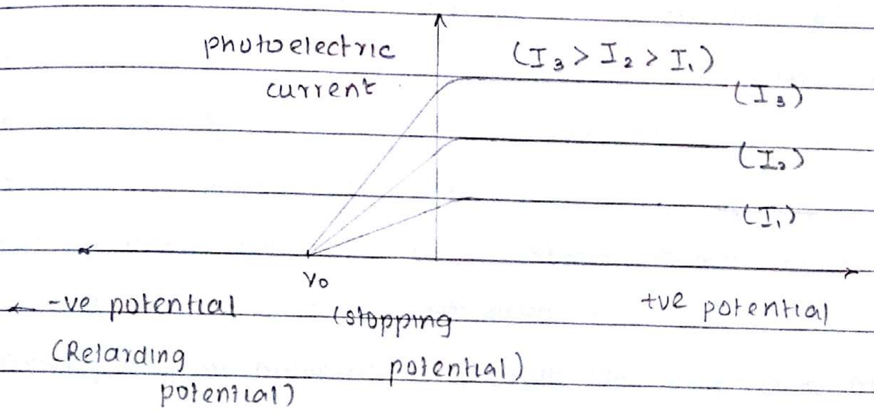


- Effect of Potential in photoelectric current

let the plate A is given +ve potential. When this +ve potential increases the photoelectric current also increases and then become a steady value called the saturated current. This happens when all the electrodes ejected from the plate C reaches the plate A.

When the plate A is given a -ve potential wrt Plate C, one can observe that the photoelectric current decreases with the increase in -ve potential and finally becomes zero. The -ve potential (retarding potential) at which the photoelectric current becomes zero is called the stopping potential (V_0).

When the experiment is repeated with lights of different intensity, it is found that the saturated current is directly proportional to the intensity and the stopping potential is independent of intensity.



At stopping potential V_0 all the ejected e⁻s get stopped that is even the e⁻ with maximum kinetic energy will come to rest due to the repulsive force by the plate A. If Kmax is the maximum kinetic energy of the ejected e⁻s then

$$\boxed{K_{max} = eV_0}$$

energy acquired by a charge

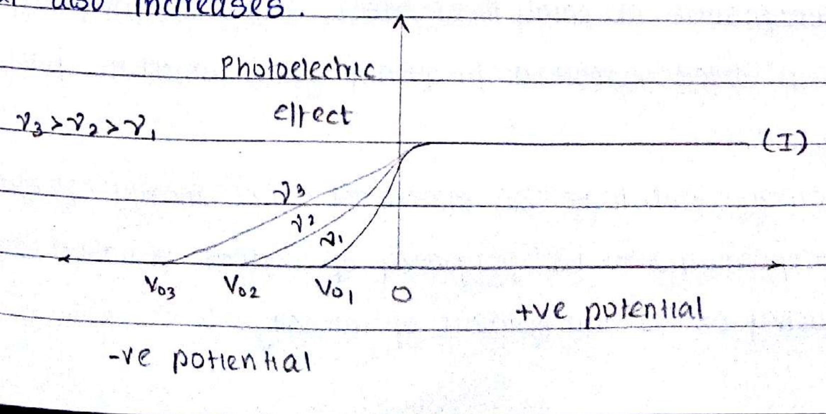
$U = qV$

Here $q = e$ and $V = V_0$

$\therefore U = eV_0$

- **Effect of frequency on stopping potential.**

For a light of given intensity, the stopping potential is found to be proportional to frequency of incident light i.e, when frequency increases stopping potential also increases.



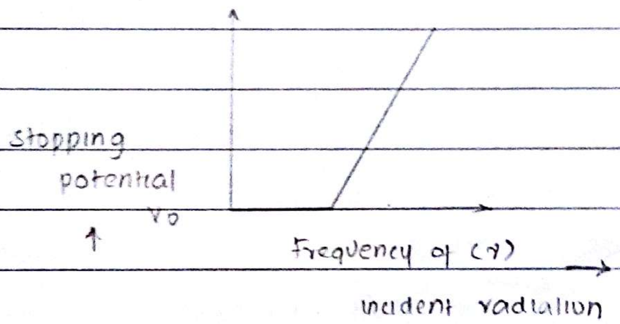
From the above graph it is clear that $V_0 \propto \nu$

But we have $K_{max} = eV_0$

$\therefore K_{max} \propto \nu$

ie, Maximum kinetic energy of ejected electron is directly proportional to frequency of incident light.

- The variation of stopping potential with a frequency of incident radiation is graphically shown in the figure.



From the graph it is clear that there is a minimum frequency below which the stopping potential is 0. ie, No photoelectric current takes place. This minimum frequency of incident radiation below which is no photoelectric current is possible is known as the threshold frequency. (cut of frequency)

The above experimental observation can be concluded as follows:

- For a given photosensitive material, the photoelectric current.
  The photoelectric current is directly proportional to the intensity of incident radiation. provided the frequency is greater than threshold frequency
- For a given photosensitive material, the saturation current is found to be proportional to the intensity and the stopping potential is independent of incident radiation.
- For a given photosensitive material, there exist a minimum frequency for incident radiation called threshold frequency below which no photoelectric emission is possible
- The stopping potential and hence the maximum kinetic energy of ejected e's is found to be proportional to the frequency of incident radiation above threshold frequency and is independent of intensity.

- Photoelectric emission is an instantaneous process i.e, there is no time delay (less than 10^{-8} s) between falling of light and ejection of e's.

Drawbacks of wave theory of light:

- According to wave theory, when intensity increases, the energy also increases i.e, when intensity increases, photoelectric current also increases and is independent of frequency. This is against the experimental observation. (I, II, III). i.e, wave theory doesnot tell anything about threshold frequency
- According to wave theory, when intensity increases, the energy also increases as a result the kinetic energy of ejected e^- should also increase. But it is against the observation that K is independent of intensity. (iv).
- According to wave theory, energy is distributed continously on the entire surface of the metal i.e, the total energy is distributed among all the electrons. it shows may take hours for an e^- to get the sufficient energy to come out of the metal. It is against the observation that photoelectric emission is an instantaneous process.

Photon - Particle nature of light:

The discrete packet of light energy is called a photon. ie, light is travelling in the form of discrete packet of energy called photons. It is also known as quanta.

Characteristics of Photon.

- Each photon carries energy and momentum and they are given by

$$E = h\nu$$

$$p = \frac{h\nu}{c} \qquad h = 6.626 \times 10^{-34}\ Js$$

The rest mass (mass when velocity is 0) of photon is assumed as zero.

- For a given frequency of light, all the photons are having the same energy and momentum.
- Intensity of light increases, the no of photons emitted also increases.
- When photons are interacting with particles, momentum and KE are conserved but no of photons maynot be conserved.

- A photon travels with a speed of 3×10^8 m/s.

Einstein's Photoelectric Equations.

$$\boxed{KE_{max} = h\nu - \phi_0} \quad \text{———(1)}$$

where KE_{max} is the maximum kinetic energy of the ejected electron

$h\nu$ is the energy of incident photon

ϕ_0 is the work fn.

- Let $\phi_0 = h\nu_0$

then $KE_{max} = h\nu - h\nu_0$.

If $\nu < \nu_0$, $KE_{max} = -ve$. It is impossible. This implies there is an minimum frequency for the incident photo below which no photoelectric is possible called the threshold frequency (ν_0)

- When intensity of incident light increases, the no of photons emitted also increases. As a result the no of ejected e^- increases and therefore the photoelectric current increases, ie, the photo electric current is directly proportional to the intensity of incident radiation.
- We have $KE_{max} = eV_0$ where V_0 is the stopping potential.

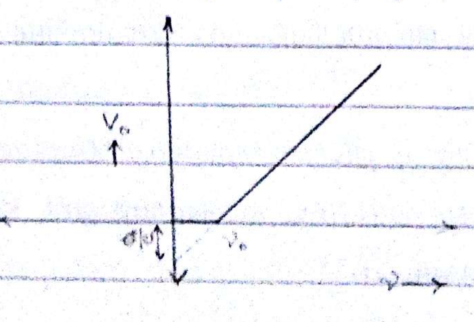
∴ (1) ⟶

$$eV_0 = h\nu - \phi_0 \quad \text{———(2)}.$$

From (1) and (2), it is clear that the stopping potential and hence the KE of ejected e^- is directly proportional to the frequency and is independent of intensity.

- From (2) ⟹ $V_0 = \frac{h}{e}\nu - \frac{\phi_0}{e}$

The above eqn represents a straight line with a slope $\frac{h}{e}$ i.e, Stopping potential V_0 g/frequency graph is a straight line with a slope $\frac{h}{e}$



$y = mx + c$

$V_0 = \frac{h}{e}\nu - \frac{\phi_0}{e}$

• An e^- is ejected when a photon of sufficient energy is falling on it. i.e, there is no time lag between falling of light and ejection of e^-s. It shows photoelectric effect is an instantaneous process.

Matter wave

Louis de Broglie

Louis de Broglie propose that every moving particle is associated with wave directly proportional its wavelength is given by

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

$p = mv$, linear momentum

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

This wavelength is also known as the de broglie wavelength

we have the KE, $KE = \frac{p^2}{2m}$

$$p^2 = 2m \times KE$$

$$p = \sqrt{2mKE}$$

But $KE = eV$ where V is the potential.

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

Then the de broglie wavelength,

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

$\because$ h, m and e are constants, we get

$$\boxed{\lambda = \frac{1.227}{\sqrt{V}} \text{ nm}}$$

Heisenberg's uncertainity principle and wave theory.

The principle states that it is impossible to determine the position and momentum of a moving particle simultaenously and exactly. i.e

$$\Delta x \cdot \Delta p \geq \frac{h}{4\pi}$$

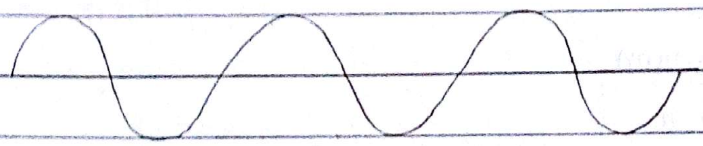
where Δx is the uncertainity is position and Δp is the uncertainity in momentum.

i Let $\Delta P = 0$, i.e there is no uncertainity in the momentum and it shows the momentum has definite value.

We have the de broglie wavelength

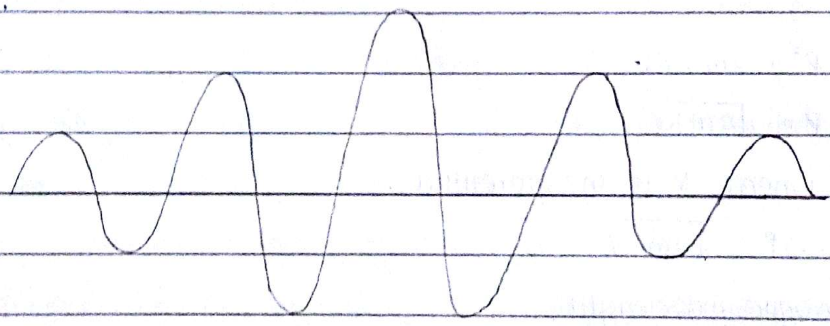
$$\lambda = \frac{h}{p}$$

Since p has a definite value, λ also have a definite value ie, the wave spreads all over the region



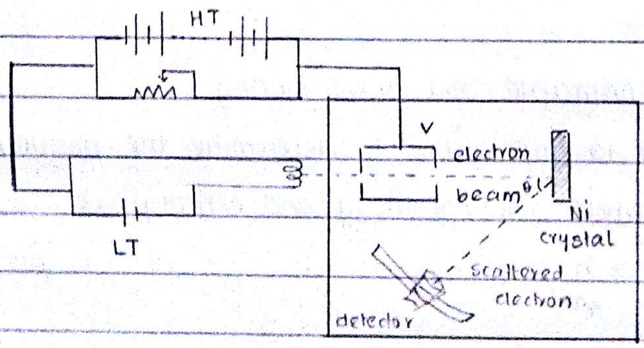
In such a way one cannot determine the position of the body i.e the uncertainity in position (Δx) is maximum.

ii Let Δx is very small then the wavelength doesnot have a ~~do~~ definite value.



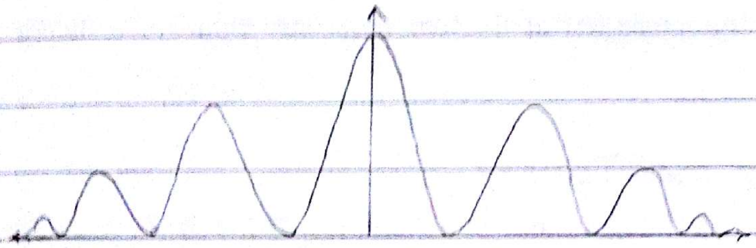
Since the wavelength is not definite there is uncertainity in momentum according to the relation $\lambda = \frac{h}{p}$

Davison - Germer Experiment.



The experimental setup consists of an electron gun connected to a low tension source. The gun emits and e⁻ beam and is allowed to fall on Ni crystal through a cylinder which is connected to a high tension source the voltage across the cylinder is adjustable.

The e⁻s falling on the Ni crystal gets scattered and the intensity of scattered e⁻s were determined by a movable detector. The experiment is repeated for different values of voltage across the cylinder (44V - 68V) It is observed that the maximum intensity is obtained for a voltage of 54V.



This maximas and minimas are obtained due to interference of scattered e⁻s. and it confirmed the wave nature of electrons. The wavelength is determined experimentally as $\lambda = 0.165 nm$

We have the de broglie wavelength, $\lambda = \frac{1.227}{\sqrt{V}} nm$

If $V = 54V$ then $\lambda = \frac{1.227}{\sqrt{54}} nm = 0.167 nm$. It is in accordance with the experimental result.