DUAL NATURE OF MATTER AND RADIATION

Introduction

The phenomenon such as interference, diffraction and diffraction were successfully explained on the basis of wave nature of light. On the other hand, photoelectric effect {*when a photon strikes a metal surface, it gives up all its energy to a single electron in an atom and the electron is knocked out of the metal.*} can be explained on the basis of quantum nature of radiation.

The various phenomena concerning radiation can be divided into three parts:-

(i) The phenomena such as interference, diffraction, polarisation etc can be explained on the basis of electro-magnetic (wave) nature of radiation only.

(ii) The phenomena such as photoelectric effect can be explained on the basis of quantum (particle) nature of radiation.

(iii) The phenomena such as rectilinear propagation, reflection, refraction etc can be explained on the basis of either of the two natures of the radiation.

It may be pointed out that *in a particular experiment, radiation has a particular nature i.e. either it possesses wave nature or particle nature.*

Photon.

A photon is a packet of energy. It possesses energy given by $E = h\nu$; where h is the Planck's constant = 6.62 x 10^{-34} Js and ν is frequency of photon. If λ is the wavelength of the photon, then $c = \nu\lambda$; where c is velocity of light = 3 x 10^8m/s.

Therefore, $E = h\nu = \frac{hc}{\lambda}$. Energy of a photon is usually expressed in electron volt (eV) . 1 eV = 1.6 x 10^{-19}J.

Electron emission

We know that metals have free electrons that are responsible for their conductivity. The free electrons cannot normally escape out of the metal surface. If an electron attempts to come out of the metal, the metal surface acquires a +ve charge and pulls the electron back to the metal. The free electron is thus held inside the metal surface by the attractive forces of the ions.

Work function.

The electron can come out of the metal surface only if it gets sufficient energy to overcome the attractive pull. A certain minimum amount of energy is required to be given to an atom to pull it out from the metal surface.

This minimum energy required by an electron to escape from the metal surface is called the work function of the metal and is measured in electron volt (eV)

Work function depends on the properties of the metal and the nature of its surface.

Different types of electron emission are:-

1) **Thermionic emission** :- By giving thermal energy, electrons are made to come out of the metal.

2) **Field emission** :- By applying strong electric field, electrons can be pulled out.

3) **Photoelectric emission** :- By using light of suitable frequency, electrons are made to come out of the metal surface.

Photoelectric effect

Hertz observed that when light falls on a metal surface, some electrons absorb energy from the incident radiation. After gaining sufficient energy from the incident light, the electrons escape from the metal surface into the surrounding space.

"The phenomenon of ejection of electrons from a metal surface, when light of sufficiently high frequency falls upon it is known as photoelectric effect".

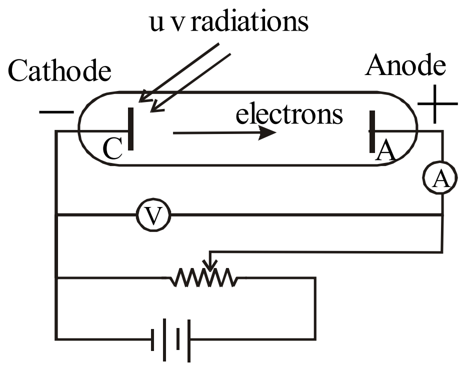
The electrons so emitted were called photoelectrons.

The alkali metals like Lithium, Potassium etc. are photosensitive even to visible light. Metals like Cd, Zn etc. are sensitive only to uv, X rays and gamma rays. So *there should be a minimum frequency (ν_0) for the incident radiations to produce photoelectric effect. This minimum frequency is called the* **threshold frequency**. It depends on the nature of the material (i.e. work function)

Experimental study of photoelectric effect.

The experimental set up consists of an evaquated glass tube or quartz tube fitted with two zinc electrodes C and A

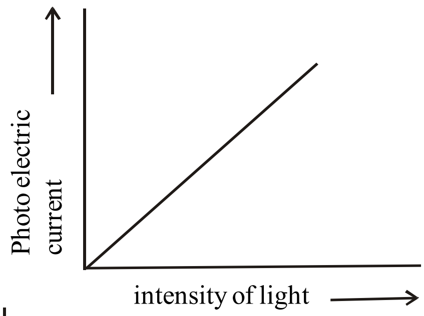
The electrodes are connected to the respective terminals of a battery. A varying pd is applied across the two electrodes (using rheostat). When uv radiations fall on the plate C, electrons are emitted form it and these electrons are collected by A. The photoelectric current flows in the circuit and is measured with a sensitive ammeter.



Factors affecting photoelectric effect.

(i) **Effect of intensity of incident radiation.**

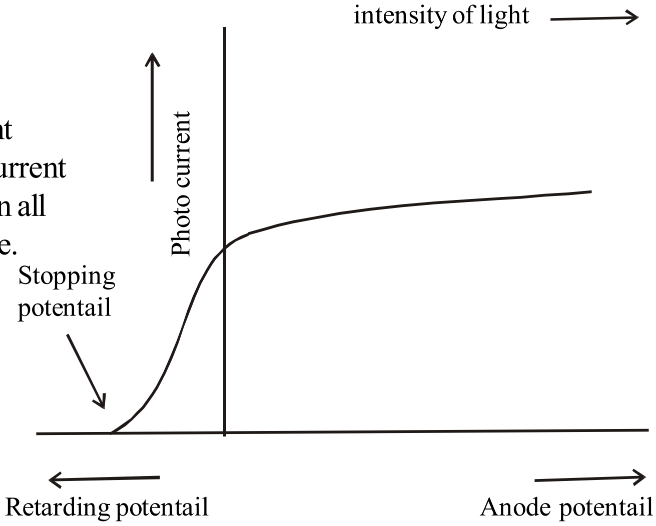
If the accelerating pd across the plates A and C is kept constant, then the photocurrent increases with the intensity of the incident radiation. A graph drawn between intensity of incident radiation and photocurrent is a straight line. So the number of photoelectrons emitted is directly proportional to the intensity of incident radiation.



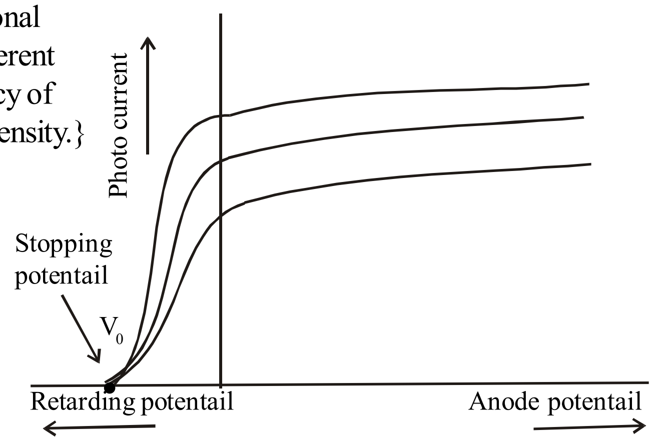
Effect of anode potential.

As accelerating potential increases, photocurrent increases. At a particular anode potential, photocurrent reaches maximum or it saturate. This happens when all the electrons of emitter plate reaches collector plate. Further increase in accelerating potential does not increase photocurrent.

When we apply -ve potential to anode, photo current get retarded and hence photocurrent decrease. At a particular retarding potential, photocurrent becomes zero. This potential is called **cut off or stopping potential**.



The saturation current is found to be large at higher intensity {because photocurrent is directly proportional to intensity.}. But stopping potential is same for different intensity at fixed frequency {i.e. for a given frequency of radiation, stopping potential is independent of its intensity.}



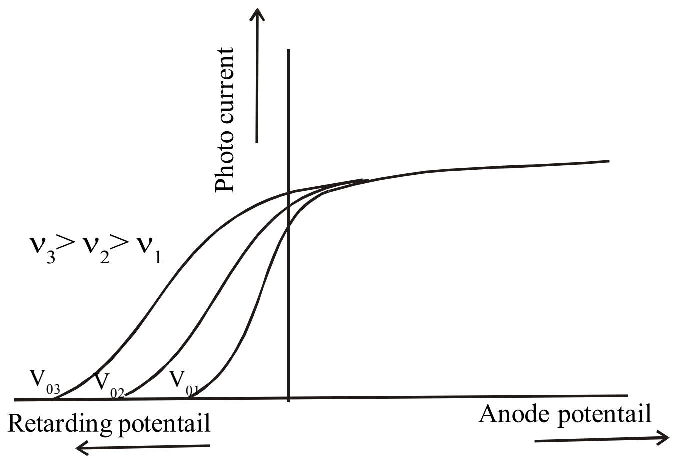
Note:
* The maximum value of photocurrent is called saturation current (I_{sat}). It depends only on intensity.
* The retarding anode potential at which photocurrent reaches zero is called stopping potential (V_0). When retarding potential is applied, only most energetic electrons can reach collector plate. At stopping potential, no electrons reach the plate. i.e., the stopping potential is sufficient to repel the electron with maximum kinetic energy.

$$\frac{1}{2} m v_{max}^2 = e V_0$$

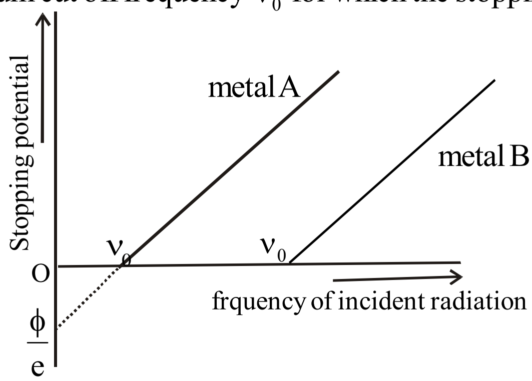
$$e V_0 = \frac{1}{2} m v_{max}^2 = h \nu$$

* At zero potential, photo current is not zero. i.e., photoelectric effect takes place even if anode potential is not applied.

Effect of frequency of incident radiation on stopping potential.
The stopping potential increases with increase in frequency.



The graph of stopping potential with frequency.
* Stopping potential varies linearly with incident frequency for a given photosensitive material.
*There exist a certain minimum cut off frequency ν_0 for which the stopping potential is zero.



Summary of the experimental study of photoelectric effect - LAWS OF PHOTOELECTRIC EFFECT.
1) For a given frequency of radiation, number of photoelectrons emitted is proportional to the intensity of incident radiation.
2) The kinetic energy of photoelectrons depends on the frequency of incident light but it is independent of the light intensity.
3) Photoelectric effect does not occur if the frequency is below a certain value. The minimum frequency ν_0 required to produce photoelectric effect is called the threshold frequency.
4) Photoelectric effect is an instantaneous phenomenon.

Einstein's Photoelectric Equations.
Einstein explained photoelectric effect based on quantum theory. According to quantum theory, light contain photons having energy $h\nu$. When a photon of energy $h\nu$ is incident on a metal surface, electrons are

liberated. A small portion of the photon energy is used for work function (ϕ) and remaining energy is appeared as KE of the electron.

By law of conservation of energy, we can write, photon energy = work function + KE of electrons.

$$h\nu = \phi + \frac{1}{2}mv^2$$

$$\therefore \frac{1}{2}mv^2 = h\nu - \phi \quad ....(1)$$

If threshold frequency ν_0 is incident, then KE = 0.

So $0 = h\nu_0 - \phi$

$$\phi = h\nu_0$$

Substitute in (1) $\quad \frac{1}{2}mv^2 = h\nu - h\nu_0$

$$\frac{1}{2}mv^2 = h(\nu - \nu_0) \quad ....(2)$$

But $\nu = \frac{c}{\lambda}$ & $\nu_0 = \frac{c}{\lambda_0}$

So $\frac{1}{2}mv^2 = h\left(\frac{c}{\lambda} - \frac{c}{\lambda_0}\right)$

$$\therefore \frac{1}{2}mv^2 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \quad ....(3)$$

(1), (2) and (3) are known as **Einstein's photoelectric equations**.

Particle nature of light - The PHOTON.

The photon picture of electromagnetic radiation is as follows: -

(i) In interaction of radiation with matter, radiation behaves as if it is made up of particles called photons.

(ii) Each photon has energy $E = h\nu$ and momentum $p = \frac{h}{\lambda}$ and speed C, the speed of light.

(iii) Photon energy is independent of intensity of radiation.

(iv) Photons are electrically neutral and are not deflected by electric and magnetic fields.

(v) In a photon particle collision (Eg:- photon - electron collision) the total energy and total momentum are conserved. However, the number of photons may not be conserved in a collision. {Photon may be absorbed or a new photon may be created.}

Wave nature of matter.

Louis Victor de Broglie put forward the hypothesis that moving particles of matter should display wave like properties under suitable conditions. *The waves associated with material particles are known as matter waves or de Broglie's waves.* de Broglie wave is seen with microscopic particles like proton, electron, neutron etc.The wavelength of matter wave is called de-Broglie wavelength. de Broglie wavelength,

$\lambda = \frac{h}{mv}$;where h is Planck's constant, m = mass of particle and v, the velocity of particle.

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

Wavelength of matter waves.

The energy of photon $E = h\nu$ ....(1)

If photon is considered as a particle of mass 'm', the energy of photon can be written as

$E = mc^2$ ....(2)

From (1) and (2), $h\nu = mc^2$ OR $m = \frac{h\nu}{c^2}$ ....(3)

Momentum of the electron can be written as P = mass x velocity ....(4)

$$P = m \times c = \frac{h\nu}{c^2}c = \frac{h\nu}{c}$$

i.e. $p = \frac{h}{c/\nu} = \frac{h}{\lambda}$ since $\lambda = \frac{\text{velocity}}{\text{frequency}}$

i.e. $p = \frac{h}{\lambda}$ Or $\lambda = \frac{h}{p}$

The wavelength of electron wave.

If an electron of mass m and charge e is accelerated through a pd of V volt, the de Broglie wavelength can be written as $\lambda = \frac{h}{\sqrt{2meV}}$ ....(1)

We know $KE = \frac{1}{2}mv^2 = \frac{p^2}{2m}$ But eV = KE i.e. $eV = \frac{p^2}{2m}$ $\therefore p = \sqrt{2meV}$

So $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$.

Substituting the vales of h, m and e we get $\lambda = \sqrt{\frac{150}{V}}\ A^0$

Uncertainty principle

According to Heisenberg's uncertainty principle, it is not possible to measure both the position and momentum of an electron {or any other particle} at the same time exactly. There is always some uncertainty (Δx) in the specification of positions and some uncertainty (Δp) in the specification of momentum.

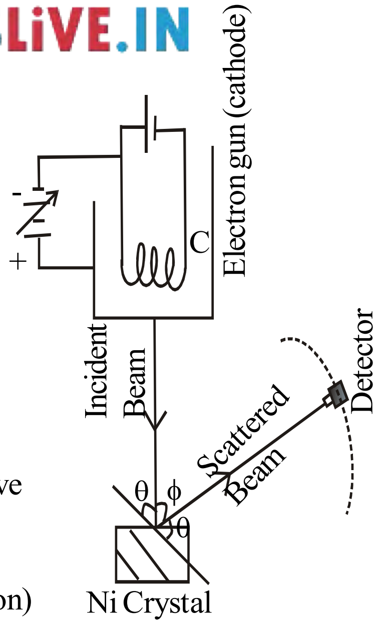
The product of Δx and Δp is of the order of $\Delta x\, \Delta p = \frac{h}{2\pi}$.

The above equation allows the possibility that if Δx is zero, then Δp must be infinite in order that the product is non zero. Similarly if Δp is zero, Δx must be infinite. Ordinary both Δx and Δp are non zero such that their product is of the order of $\frac{h}{2\pi}$ $\left[\because \Delta x\, \Delta p = \frac{h}{2\pi}\right]$

Davison Germer Experiment

It is used to confirm the wave nature of electron. The experimental arrangement used by Davisson and Germer is as shown.

Electrons from hot tungsten cathode (C) are accelerated by a potential difference between the cathode (C) and anode (A). A narrow hole in the anode render the electrons into a fine beam of electrons and allows it ti strike the nickel crystal. The electrons are scattered in all directions by the atoms in the crystal. The intensity of the electron beam scattered in a given direction is found by using a detector. By rotating the detector about an axis through the point O, the intensity of the scattered beam can be measured for different values of ϕ (i.e. the angle between incident and scattered direction of electron beam.). The variation of the intensity of scattered electrons with the angle of scattering θ is obtained for different accelerating voltages from 44V to 68 V. It was noticed that a strong peak appeared in the intensity of the scattered electron for an accelerating voltage of 54 V at a scattering angle $\theta = 50^0$.



Observations

The diffraction peak is observed at 50^0 for an accelerating voltage of 54 V.

So energy of electron, $E = eV = 1.6 \times 10^{-19} \times 54$ J.

momentum $p = \sqrt{2mE} = \sqrt{2meV}$.

Associated de Broglie wavelength, $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}} . = \sqrt{\frac{150}{V}}$

V = 54 V, So $\lambda = 1.67 A^0$

The appearance of the peak in a particular direction is due to the constructive interference of electron beam scattered from different layers of regularly spaced atoms in the crystal. From electron diffraction experiment, the wavelength of this scattered beam (electron waves which produce diffraction) was found to be $1.65 A^0$.

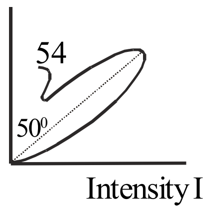
Note: The wavelength of electrons can be found from the formula

$2d\sin\theta = n\lambda$ ....(1)

From fig, $\theta + \phi + \theta = 180^0$.

$2\theta = 180 - \phi = 180 - 50 = 130.$

$\theta = 65^0$



n = 1 , for nickel crystal $d = 0.91 A^0$. Substuting, $\lambda = 1.65 A^0$.

The experimentally measured wavelength is found in agreement with de Broglie wavelength. Thus wave nature of electron is confirmed.

Q1. The threshold wavelength of sodium is 680 nm. Find the workfunction of sodium in eV.
($h = 60625 \times 10^{-34}$ Js, $c = 3 \times 10^8$ m/s, 1 eV = 1.6×10^{-19}J) [1.827 eV]

Q2. A photon of energy 2.5 eV is incident on the metal surface of work function 2 eV. Find the xamimum kinetic energy of electrons emitted? [0.8×10^{-19}J]

Q3. The photoelectrons produced by a frequency of 4×10^{15} Hz is stopped by a potential difference of 10V. Calculate the threshold frequency of the metal. [1.58×10^{15} Hz]

Q4. Calculate the velocity and KE of a neutron having de Broglie wavelength 1 A^0.
mass of electron 1.675×10^{-27}kg. [3.96×10^3m/s; 1.315×10^{-20} J]

Q5. An electron microscope uses electrons accelerated by a voltage of 50 kV. Determine the de Broglie wavelength of the electrons. [0.0549 A^0]