# Dual Nature of Radiation and Matter ①

Electron emission: Metals have free electrons that are responsible for their conductivity. However, the free electrons cannot normally escape out of the metal surface.

The minimum energy required by an electron to escape from the metal surface is called the work function of the metal denoted by $\phi_0$ and measured in eV.

The work function of platinum is the highest 5.65 eV while it is the lowest for caesium 2.14 eV.

The minimum energy required for the electron emission from the metal surface can be supplied to the free electrons by any one of the following physical processes

(1) Thermionic emission: Thermal energy can be imparted to the free electrons to enable it to come out of the metal.

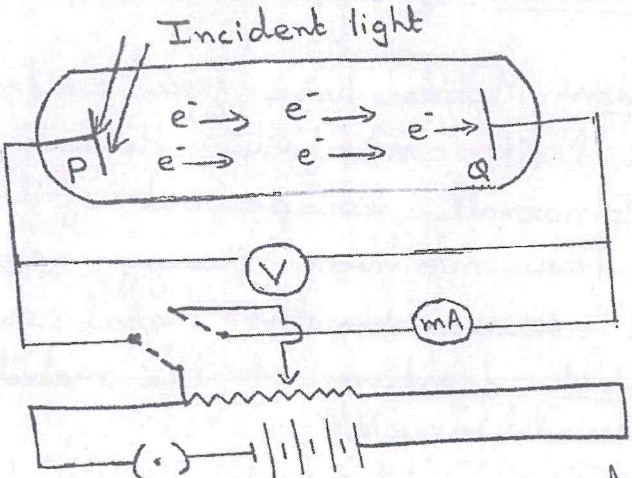
(2) Field emission: By applying a strong electric field electrons are emitted from the metal surface.

(3) Photo electric emission: When light of suitable frequency illuminates a metal surface electron's are emitted from the metal surface called photo electrons.

Photo electric effect: It is the phenomenon of emission of electrons from the surface of metals when radiations of suitable frequency is incident on it.

example: Alkali metals show photoelectric effect with visible light whereas metals like Zn, Mg etc are sensitive only to uv light.

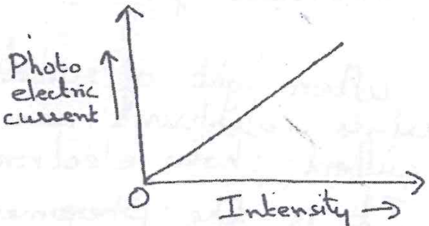
Experimental study of photo electric effect: (Hallwach's & Lenard's expt)




When monochromatic light of suitable frequency falls on a photosensitive plate P (cathode), photo electrons are emitted which get accelerated towards the plate Q (anode) kept at a positive potential. The reading of mA measures the photo electric current.

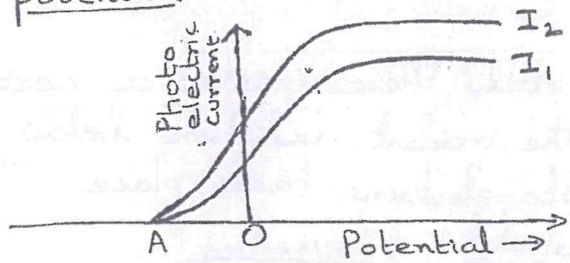
X, Observations on the exptl study of photo electric effect

(1) Effect of intensity of incident radiation: When plate Q is maintained at a definite +ve potential w.r.t. plate P and radiations of definite frequency are incident on the plate P it is found that the photo electric current increases linearly with increase in intensity of incident light.




(2) Effect of potential on photo electric current: The frequency and intensity of incident radiation are kept constant. The photo electric current increases gradually with increase in positive potential of plate Q and then reaches saturation.

However if a –ve potential is applied to the plate Q w.r.t. plate P and thereafter gradually increased it is observed that the photo electric current decreases rapidly until it becomes zero. This minimum negative potential given to the plate Q at which the photo electric current becomes zero is called <u>stopping potential</u> or <u>cut off potential</u>.

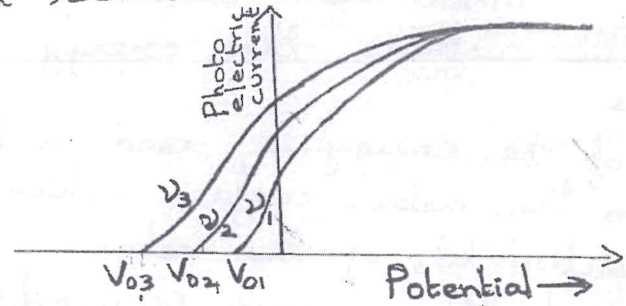



OA represents stopping potential.

Note (a) For a given frequency, the stopping potential is independent of intensity of incident radiation.

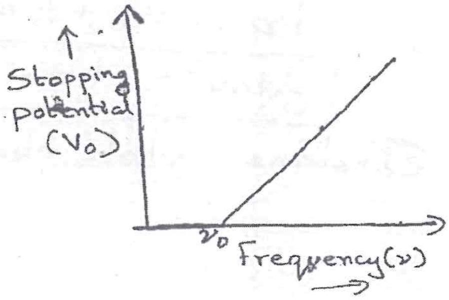
(3) <u>Effect of frequency of incident radiation on stopping potential</u>

When varying frequencies of the incident radiations but of same intensity are studied it is observed that the saturation current is the same but the stopping potential increases with increase in frequency of incident radiation.




$\nu_3 > \nu_2 > \nu_1$

<u>Note</u>: A graph between stopping potential and frequency shows a linear variation.



(4) The time lag between the incidence of radiation and emission of photo electrons is less than $10^{-9}$ sec.

※ Laws of photo electric emission

1. For a given metal and frequency of incident radiation, the number of photo electrons emitted per second is directly proportional to the intensity of the incident light.
2. For a given metal, there exists a certain minimum frequency of the incident radiation below which no emission of photo electrons takes place. This frequency is called threshold frequency.
3. Above the threshold frequency the maximum KE of the emitted photo electrons is independent of intensity of incident light but depends only on the frequency of the incident light.
4. The photoelectric emission is an instantaneous process.

Einstein's photo electric equation

When light radiation $h\nu$ is incident on the metallic surface, the energy is used up in two ways

(a) a part of the energy is used in liberating the electron from the metal surface which is equal to the work function $W_0$ of the metal.

(b) The rest of the energy is used in imparting KE to the emitted photo electron.

$$\therefore h\nu = W_0 + \frac{1}{2}mv^2$$

$$\boxed{\frac{1}{2}mv^2 = h\nu - W_0}$$

This is Einstein's photo electric equation.

Note: If the incident photon is of threshold frequency $\nu_0$, then the incident photon of energy $h\nu_0$ is just sufficient to eject the electrons from the metal surface

$$h\nu_0 = W_0$$

$$\therefore \frac{1}{2}mv^2 = h\nu - h\nu_0$$

$$KE = h[\nu - \nu_0] \quad \text{OR} \quad \boxed{eV_0 = h(\nu - \nu_0)}$$

$V_0 \rightarrow$ stopping potential

Explanation of laws of photo electric emission on the basis of Einstein's photo electric equation

(1) Since one photon ejects one photo electron from the metal surface the number of photo electrons emitted per second depends on the number of photons incident on the metal surface per second which in turn depends on the intensity of incident radiations.

(2) From Einstein's photo electric equation it is clear that if $\nu < \nu_0$, KE is $-ve$. Hence photoelectric emission does not take place below the threshold frequency.

(3) From the photo electric equation it is clear that when $\nu > \nu_0$, $KE \propto \nu$.
$\therefore$ KE of photoelectrons depends only on the frequency of incident radiation but is independent of intensity of incident radiation.

(4) Due to elastic collision between the photon and the electron in the metal it involves transfer of energy at once without any time lag.

Failure of wave theory to explain the photo electric effect

(1) According to wave theory, the energy associated with a beam of light is measured in terms of intensity of the beam. When the waves of light of higher intensity falls on the metal surface it

will impart more energy to the $e^{-s}$ and the KE of the ejected electrons should increase. However this is against exptl facts.

(2) According to wave theory the emission of $e^{-s}$ from a surface is possible at any frequency provided the intensity of incident beam is more. This also contradicts exptl facts.

(3) When a wave of light is incident on the metal surface then the $e^{-s}$ in the metal would take sometime to accumulate the energy required for their emission from the metal surface. This also contradicts exptl observation.

Some important concepts.

(a) Relation between $V_0$; $\nu$ and $\nu_0$.

If m is the mass and $V_{max}$ the max: velocity of photoelectrons emitted then.

Max KE of photoelectrons = $\frac{1}{2} m v_{max}^2$

If e is the charge on electron and $V_0$ the stopping potential, then work done by the stopping potential from stopping the electron = $eV_0$

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

Acc: to Einstein's photoelectric equation.

$$\frac{1}{2} m v^2 = h\nu - h\nu_0.$$

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

$$eV_0 = h\nu - h\nu_0$$

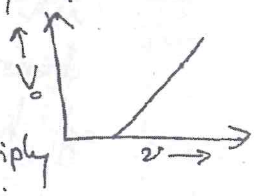
$$eV_0 = h\frac{c}{\lambda} - \frac{hc}{\lambda_0}$$

(b) How can the value of Planck's constant be determined from the graph showing variation of stopping potential with frequency of incident radiation

Einstein's photo electric eqn: $eV_0 = h\nu - h\nu_0$.

Differentiating $e\Delta V_0 = h\Delta\nu$

$\therefore \frac{\Delta V_0}{\Delta \nu} = h/e$, To get Planck's const: multiply slope of the graph by e.



# Particle nature of light: The photon

Photoelectric effect thus gave evidence to the fact that light in interaction with matter behaved as if it was made of quanta, or packets of energy called photon.

## Characteristics of photons

1. In interaction of radiation with matter, radiation behaves as if it is made up of particles called photons.
2. Each photon has energy $E = h\nu$ and momentum $p = h\nu/c$ and speed $c$, the speed of light.
3. All photons of light of a particular frequency $\nu$ or wavelength $\lambda$ have the same energy $E = h\nu = \frac{hc}{\lambda}$ and momentum $p = \frac{h\nu}{c} = h/\lambda$. Photon energy is independent of intensity of radiation.
4. Photons are electrically neutral and are not deflected by electric and magnetic fields.
5. In a photon-particle collision, the total energy and total momentum are conserved. However, the number of photons may not be conserved in a collision.

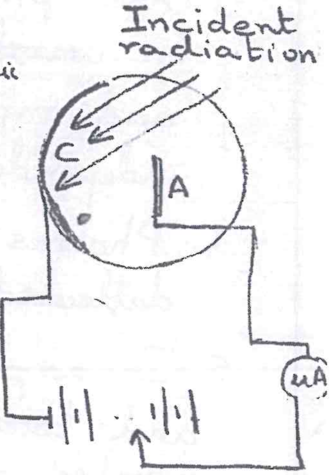
Photo cell : It is a device which converts light energy into electrical energy. It is also known as an electric eye

Construction (a) It consists of a semi-cylindrical photo-sensitive metal plate C (emitter) and a wire loop A (collector) supported in an evacuated glass or quartz bulb.

(b) It is connected to the external circuit having a HT battery and μ ammeter.

Working : When light of suitable wavelength falls on the cathode, photo electrons are emitted. These photo electrons are drawn to the anode by an electric field. The resulting current can be measured by a sensitive microammeter.

Applications : (a) A photo cell converts changes in intensity of illumination to photoelectric current. Therefore it is used in




(a) Light meters in photographic camera.

(b) Photocells are used in street light electric circuit, to switch on and off the lighting system automatically at dusk and dawn.

(c) They are used in the control of counting device which records every interruption of the light beam caused by a person passing across the beam.

(d) In burglar alarm, uv light is made to fall continuously on the photocell installed at the doorway. A person entering the door interrupts the beam falling on the photocell. The abrupt change in photocurrent is used to start an electric bell.

It is also made use of in fire alarm systems, in detecting minor flaws or holes in metal sheets and detection of traffic law defaulters.

## Wave nature of matter



**Dual nature of radiation**: Phenomena such as diffraction, interference and polarisation could be explained by considering radiation to exhibit wave nature. However certain phenomena like photoelectric effect and Compton effect can be explained by considering radiation to have particle nature. Thus radiation is said to possess dual nature.

Since universe is composed of matter and radiation, de Broglie concluded that matter must also exhibit wave nature.

**De Broglie hypothesis**: The wave associated with a moving particle known as de Broglie wave or matter wave has a wavelength given by $\lambda = \frac{h}{mv}$.

**Derivation of De Broglie wavelength**

Acc: to Planck's quantum theory: $E = h\nu$. —(1)

Acc: to Einstein's mass-energy relation $E = mc^2$ —(2).

Combining (1) and (2):

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

$\therefore$ Momentum of the photon is $p = \frac{h\nu}{c} = \frac{h}{\lambda}$.

De Broglie assumed that the wavelength is applicable to photons and other material particles.

The de Broglie wave equation for a material particle moving with velocity $v$ is $\boxed{\lambda = \frac{h}{mv}}$.

**Conclusion of de Broglie hypothesis**: The material particle may be charged or uncharged but when it is in motion the waves are charge independent.

The de Broglie waves are therefore not electromagnetic in nature because em waves are produced due to charges in motion.

## De Broglie wavelength of an electron

Consider an $e^-$ of mass $m$ accelerated from rest due to potential $V$.

Work done on the $e^-$ = $eV$

Gain in KE of $e^-$ = $\frac{1}{2}mv^2$

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

$$v = \sqrt{\frac{2eV}{m}}$$

The de Broglie wavelength $\lambda = \frac{h}{mv}$

$$\lambda = \frac{h}{m\sqrt{\frac{2eV}{m}}}$$

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

Substituting standard values.

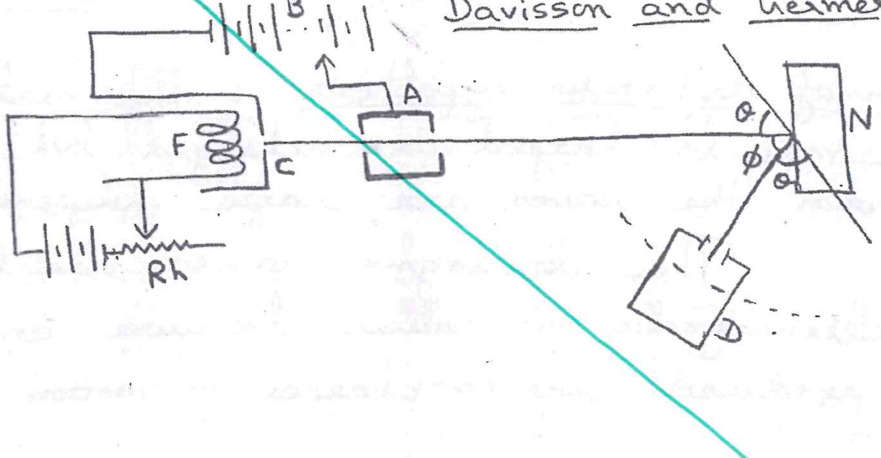
$$\lambda = \frac{6.6\times10^{-34}}{\sqrt{2\times9\times10^{-31}\times1.6\times10^{-19}\times V}}$$

$$= \frac{12.27}{\sqrt{V}}\times10^{-10}\ m$$

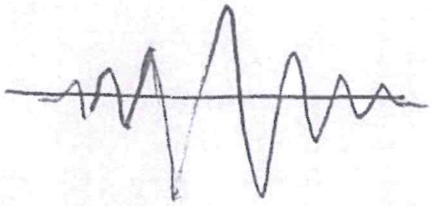
$$= \frac{12.27}{\sqrt{V}}\ A^\circ$$

## Experimental demonstration of wave nature of electron

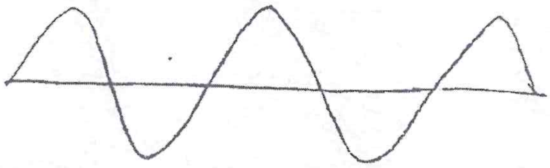
### Davisson and Germer experiment



Note: The matter-wave picture incorporates the Heisenberg's uncertainity principle. "It is not possible to measure both the position and momentum of a particle at the same time exactly".
There is always some uncertainity ($\Delta x$) in the specification of position and some uncertainity ($\Delta p$) in the specification of momentum. The product of
$\Delta x \, \Delta p = h/2\pi$



(a)
The wavepacket description of an electron is that $\Delta x$ is not infinite but has some finite value. ∴ The wave packet is built up of wave lengths spread around some central wavelength. This implies that the electron will have an uncertainity $\Delta p$.



(b)
The matter wave corresponds to definite momentum p (where $\Delta p = 0$) as a result of which the wave has a definite wavelength $\lambda$. A wave of definite wavelength extends all over space ie its position uncertainity is infinite.