ATOMIC PHYSICS AND SPECTRO SCOPY

UNIT 4-PHOTOELECTRIC EFFECT

Introduction

Whenever light or electromagnetic radiations (such as X-rays, Ultraviolet rays) fall on a metal surface, it emits electrons.

This process of emission of electrons from a metal plate, when illuminated by light of suitable wavelength, is called the photoelectric effect.

The electrons emitted are known as the photoelectrons. In the case of alkali metals, photoelectric emission occurs even under the action of visible light.

Zinc, cadmium etc., are sensitive to only ultraviolet light.

The Nature of Photo-particles

The arrangement used by Hallwachs is shown in Fig.

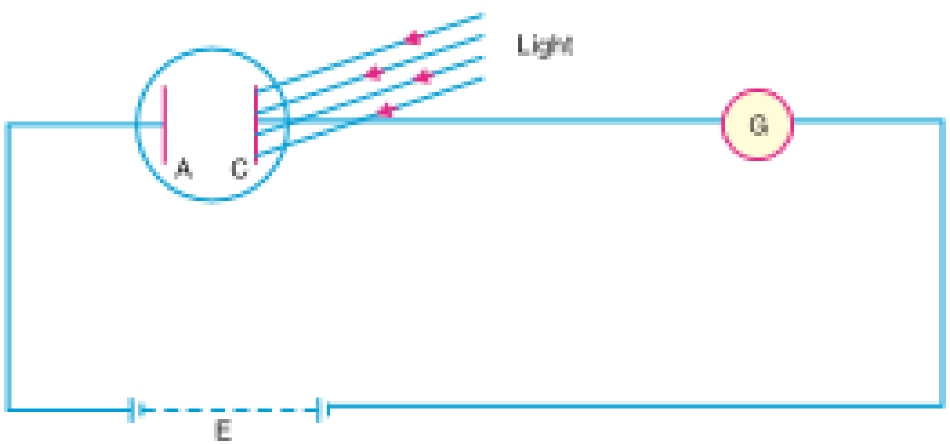
The apparatus consists of two plates A and C placed in an evacuated quartz bulb.

The galvanometer (G) and battery (E) are connected as shown.

When ultraviolet light is incident on the negative plate C, a current flows in the circuit as indicated by the galvanometer.

But when light falls on the positive plate A, there is no current in the circuit.

These observations show that photo- particle must be negatively charged.



Lenard’s method to determine e/m for Photoelectrons

It consists of a glass tube G which can be evacuated through the side tube T.

Ultraviolet light passes through a quartz window W and falls on an aluminium cathode C enclosed in G.

An earthed metal screen A with a small central hole forms the anode. The cathode (C) can be maintained at a desired potential, positive or negative relative to the anode A.

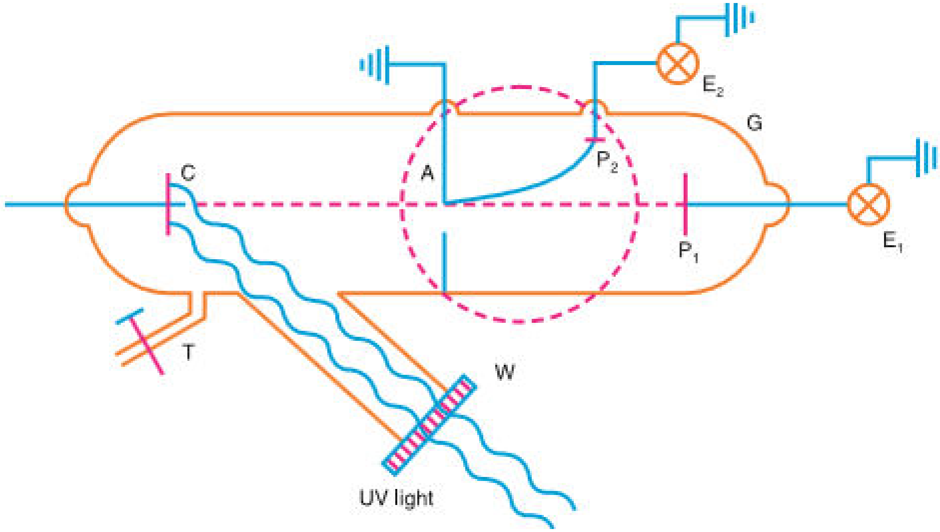
P1 and P2 are small metal electrodes connected to electrometers E1 and E2.

When C is raised to a negative potential and illuminated, negatively charged particles are produced and accelerated towards the anode.

A few particles pass through the hole in A and proceed with uniform velocity to P1. Their arrival at P1 is indicated by E1.

By applying a uniform magnetic field B (represented by the dotted circle) perpendicular to the plane of the figure and directed towards the reader, the photoelectrons can be deflected towards P2.

Their arrival at P2 is indicated by the deflection they produce in E2.



Lenard first studied the relation between current and the potential applied to C.

When the cathode potential was several volts positive, the current was zero.

When V was +2 volts, there was a feeble current showing that a few particles possessed enough velocity to overcome the retarding potential of 2 volts.

When the potential was further decreased, the current increased and reached a saturation value for –20 volts.

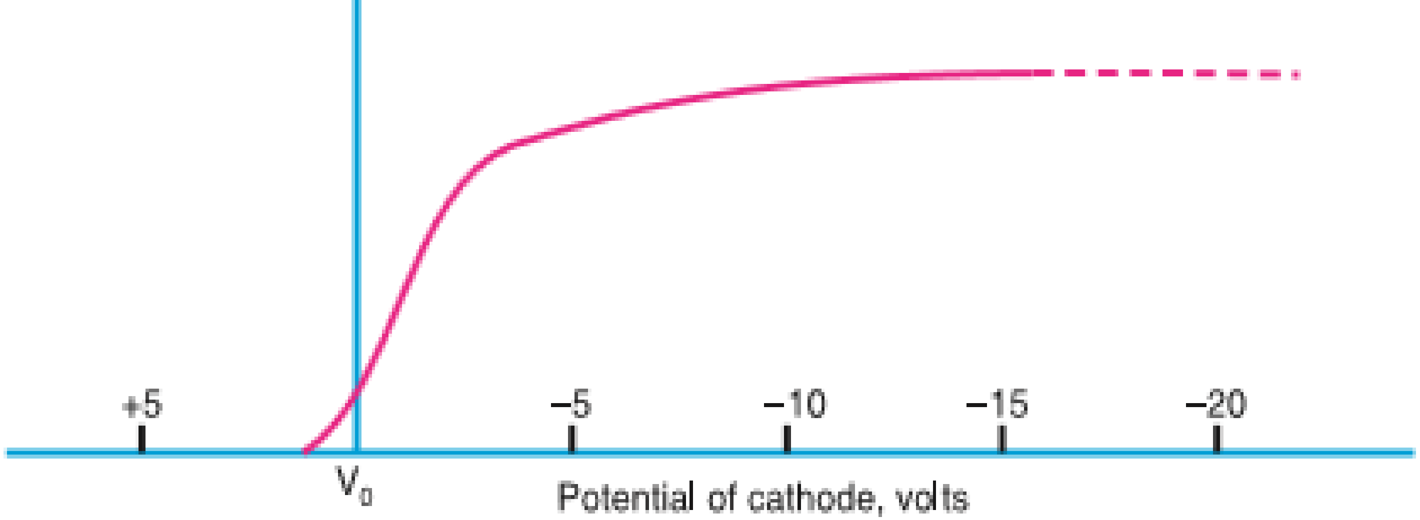


Figure shows the variation of photoelectric current with cathode potential.

After this preliminary investigation, Lenard applied to C a negative potential V, very large compared to the potential of 2 volts.

The velocity imparted by the accelerating potential is so large that the velocity of the particles in the act of emission is negligible in comparison to it.

Let V be the accelerating potential and v the velocity acquired by the photoelectrons. Then, $1/2mv^2 = eV$ ...(1)

where e is the charge and m the mass of the photoelectron.

Let R be the radius of the circular path described by the photoelectrons in the region of uniform magnetic field of strength B.

Then $mv^2/R = Bev$

$\therefore \; v = BeR/m \quad ....(2)$

Substituting this value of v in eqn. (1),

$1/2 \, m(BeR/m)^2 = eV$

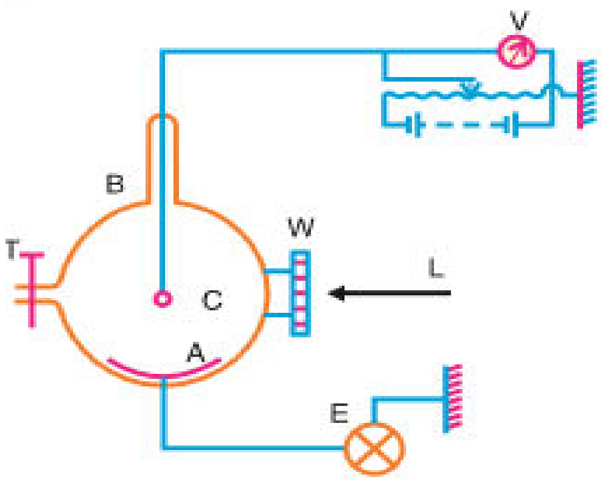
$\therefore e/m = 2V/B^2 R^2 \; ...(3)$

Knowing V, B and R, e/m is calculated.

Lenard found the value of e/m to be the same as that for electrons.

This clearly shows that the photoparticles are nothing but electrons

Richardson and Compton Experiment



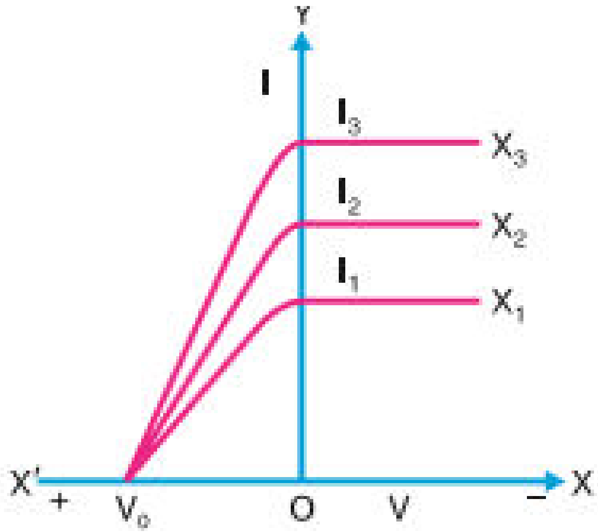
The emitter of photoelectrons (C) is a small strip of the metal under study and is kept at the centre of a spherical glass bulb B.

B is silvered on the inner side and can be evacuated through the tube T.

The silver coating on the inside of the bulb serves as the anode A and is connected to an electrometer E which measures the photoelectric current.

Monochromatic light L is made to pass through a quartz window W and fall on C.

C can be maintained at any desired potential V relative to A and this potential can be read with a voltmeter.



(i) Relation between photoelectric current and retarding potential.

They first studied the ralation between the photoelectric current I and the retarding potential V.

Irradiating the cathode C with monochromatic light of a given intensity, the cathode potential (V) was varied from a few volts positive upto zero and negative values.

The photoelectric current I was measured for different values of V. The observations were repeated with the intensity of illumination (X) doubled, tripled, etc. The relation between I and V is shown in Figure.

For a given intensity of illumination (X1), there is no photoelectric current when the positive potential on the cathode is greater than a critical value + V0.

At potentials just less than + V0, a small current is produced. As the potential decreases to zero, the current rapidly increases and reaches a maximum value when V = 0.

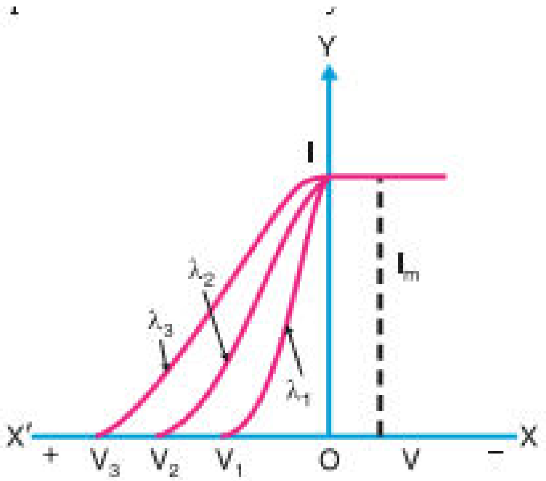
No further increases in current are observed when V becomes negative.

Hence I1 is the maximum current due to illumination of intensity X1.

When the intensity is doubled (X2) as in (2), the maximum current I2 is double I1: But the critical potential V0 is the same as before.

When the intensity of illumination is increased three fold (X3), the corresponding maximum current increases proportionately, but the critical potential remains unchanged.

Thus, the maximum current Im is proportional to the intensity of illumination X, i.e., lm $\propto$ X. The critical potential V0 is independent of the intensity



(ii) Relation between velocity of photoelectrons and the frequency of light.

Several monochromatic radiations of wavelengths λ1, λ2, λ3, etc., are allowed to fall on the emitter.

The intensity of illumination for each wavelength is adjusted to give the same value of Im in each case.

In each case, the photoelectric current I for different values of V is determined.

It is seen from the curves that if λ1 > λ2 > λ3 the critical potentials are V1<V2< V3.

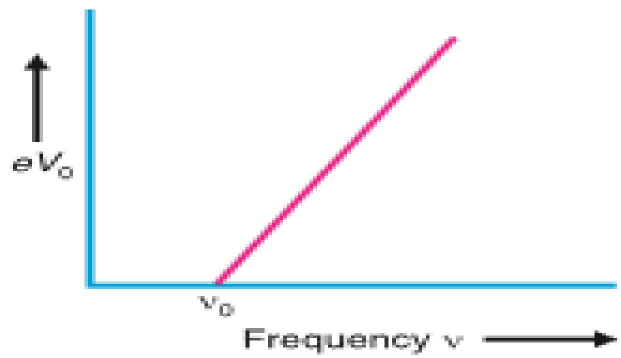
Hence, as the wavelength of light increases, the critical retarding potential decreases.

This means that the maximum K.E. of the photoelectrons (given by $1/2mv^2 = eV0$) increases with increasing frequency of light.

Since V0 is independent of the intensity of illumination, we conclude that the velocity and K.E. of photoelectrons are independent of the intensity of illumination, but dependent on the frequency of the incident light.

A linear relation is found to exist between the maximum energy of emission (eV_0) and the frequency (ν) of the light.

If eV0 is plotted against ν, we get, for any emitting surface a straight line (Fig. 8.7), whose intercept on the frequency axis gives the threshold frequency $\nu_0 = c/\lambda_0$ for this surface.



The slope of the straight line is the same for all emitting surfaces and is found to be equal to h.

The value of ν_0 however, depends on the emiting surface. ν_0 is called the threshold frequency, as it represents the beginning of the photoelectric activity of the emitter.

Threshold frequency is defined as the minimum value of frequency of incident light below which the photo-electric emission stops completely, howsoever high the intensity of light may be.

At threshold frequency, the kinetic energy of emitted photo-electrons is just zero.

Laws of photoelectric emission

(i) For every metal, there is a particular minimum frequency of the incident light, below which there is no photoelectric emission, whatever be the intensity of the radiation. This minimum frequency, which can cause photoelectric emission, is called the threshold frequency.

(ii) The strength of the photoelectric current is directly proportional to the intensity of the incident light, provided the frequency is greater than the threshold frequency.

(iii) The velocity and hence the energy of the emitted photoelectrons is independent of the intensity of light and depends only on the frequency of the incident light and the nature of the metal.

(iv) Photoelectric emission is an instantaneous process. The time lag, if any, between incidence of radiation and emission of the electrons, is never more than 3×10^{-9} sec

Failure of the electromagnetic theory

The above experimental facts could not be explained on the basis of the electromagnetic theory of light.

(1) Calculations showed that it would require about 500 days to dislodge a photoelectron from sodium by exposure to violet light of wavelength 4000 Å. Experimentally, however, we observe that electron ejection commences without delay.

(2) According to the classical theory, light of greater intensity should impart greater K.E. to the liberated electrons. But, this does not happen. Also, the velocity of the emitted electron should not depend on the frequency of the incident light. But it does.

The phenomenon was adequately explained by Einstein on the basis of Planck's Quantum theory of radiation.

Quantum theory

According to Planck, the energy of a monochromatic wave with frequency ν can only assume those values which are integral multiples of energy hν

$E_n = nh\nu$, where n is an integer referring to the number of "Photons".

Thus the energy of a single PHOTON of frequency ν is $E = h\nu$.

Einstein's Photoelectric Equation

According to Einstein, light of frequency ν consists of a shower of corpuscles or photons each of energy hν. When a photon of light of frequency ν is incident on a metal, the energy is completely transferred to a free electron in the metal.

A part of the energy acquired by the electron is used to pull out the electron from the surface of the metal and the rest of it is utilised in imparting K.E. to the emitted electron.

Let φ be the energy spent in extracting the electron from the emitter to which it is bound (photoelectric work function) photoelectron and $1/2mv^2$ = K.E. of the photoelectron

Then $$h\nu = \varphi + \frac{1}{2} mv^2 \qquad ...(1)$$

This relation is known as the *Einstein's Photoelectric equation*. If ν_o is the threshold frequency which just ejects an electron from the metal without any velocity then, $\phi = h\nu_o$.

$$\therefore \quad h\nu = h\nu_o + \frac{1}{2} mv_{max}^2 \qquad ...(2)$$

where v_{max} is the maximum velocity acquired by the electron.

or $$\frac{1}{2} mv^2{}_{max} = h(\nu - \nu_0) \qquad ...(3)$$

(i) The work function of a metal may be defined as the energy which is just sufficient to liberate electrons from the metal surface with zero velocity.

(ii) Equation (3) suggests that the energy of the emitted photoelectrons is independent of the intensity of the incident radiation but increases with the frequency.

Experimental verification of Einstein's Photoelectric Equation—Millikan's Experiment.

Theory

Millikan's experiment is based on what is known as the "stopping potential".

The stopping potential is the necessary retarding potential difference required in order to just halt the most energetic photoelectron emitted.

The K.E. of a photoelectron leaving the surface of a metal irradiated with . light of frequency υ is $1/2\ mv^2 = h\nu - \varphi$

Let V be the P.D. which is applied between the emitter and a collecting electrode in order to prevent the photoelectron from just leaving the emitter, the emitter being maintained at a positive potential with respect to the collector.

$eV = 1/2 mv_{max}{}^2$

$eV = h\nu - \varphi$

$V = (h/e)\nu - \varphi/e$

Φ is constant for a given metal; h and e are also constants.

Hence, Equation (1) represents a straight line.

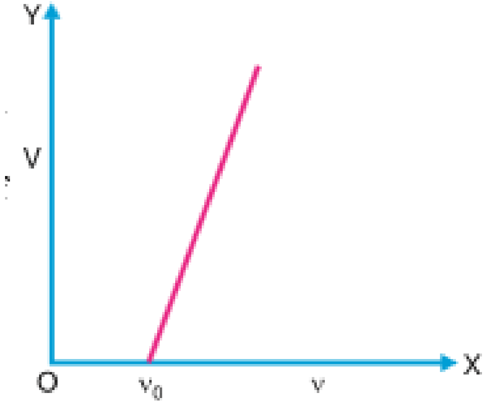
V is measured for different values of ν.

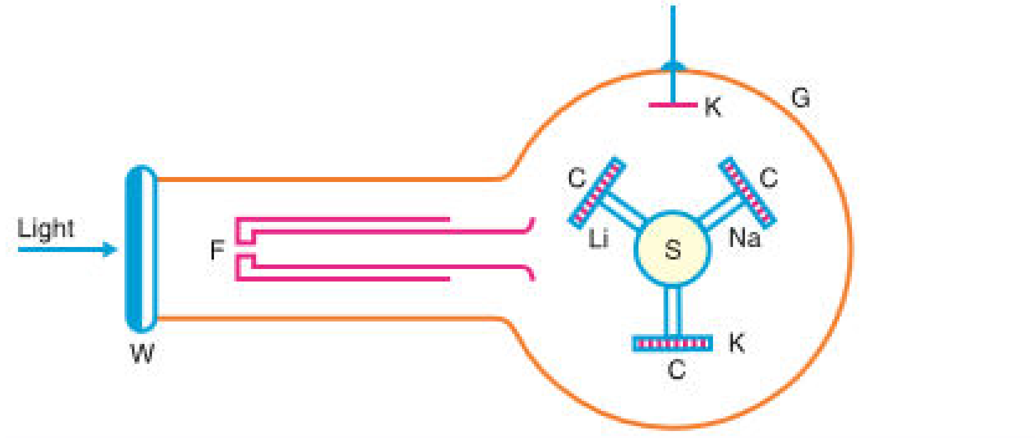
A graph is then plotted between the stopping potential (V) taken along the Y-axis and the frequency of light (ν) taken along the X-axis and it is a straight line

The slope of the straight line $\tan\theta = h / e$; $\therefore h = e \tan\theta$

Hence the value of h (Planck's constant) can be calculated.
The intercept on the X-axis gives the threshold frequency ν_o for the given emitter.

From this, photoelectric work function = $\varphi = h\nu_o$ canbe calculated.





Experiment

Alkali metals are employed as emitters, since they readily exhibit photoelectric emission even with visible light.

Cylindrical blocks (C) of sodium, potassium or lithium are mounted on a spindle S at the centre of the glass flask G.

The flask is evacuated to a very high vacuum to free the metals from all absorbed gases and to prevent their oxidation.

The spindle can be rotated from outside by an electromagnet.

As each metal block passes by the adjustable sharp edge K, a thin layer of it is removed

A fresh surface of the metal is exposed to the irradiating light entering the flask through a quartz window W.

Monochromatic light provided by a spectroscope is used to illuminate the fresh metal surfaces.

The photoelectrons are collected by a Faraday cylinder F.

The Faraday cylinder is made of copper oxide which is not photosensitive.

The photocurrent is measured by an electrometer connected to the Faraday cylinder.

The stopping potential of the liberated photoelectrons is measured by raising the emitter surface to a positive potential, just sufficient to prevent any of the electrons from reaching the collector (F).

The stopping potential is the positive potential applied to the emitter, which corresponds to zero current in the electrometer.

The stopping potential (V) is determined for different wavelengths of the incident light.

The value of V should be corrected for any contact potential between the metal (C) and Faraday cylinder (F).

On plotting V against ν, we get a straight line. Measuring the slope of the straight line, the value of h/e is obtained.

Then substituting the known value of e, h is calculated.

The value of h calculated in this way agrees fairly well with the value obtained by other methods. Thus the Einstein's equation can be verified experimentally.

Photoelectric Cells

Photoelectric cell is an arrangement to convert light energy into electrical energy.

There are three types of photocells, photoemissive, photovoltaic and photoconductive.

Photoelectric Cells

(i) Photo-emissive Cell

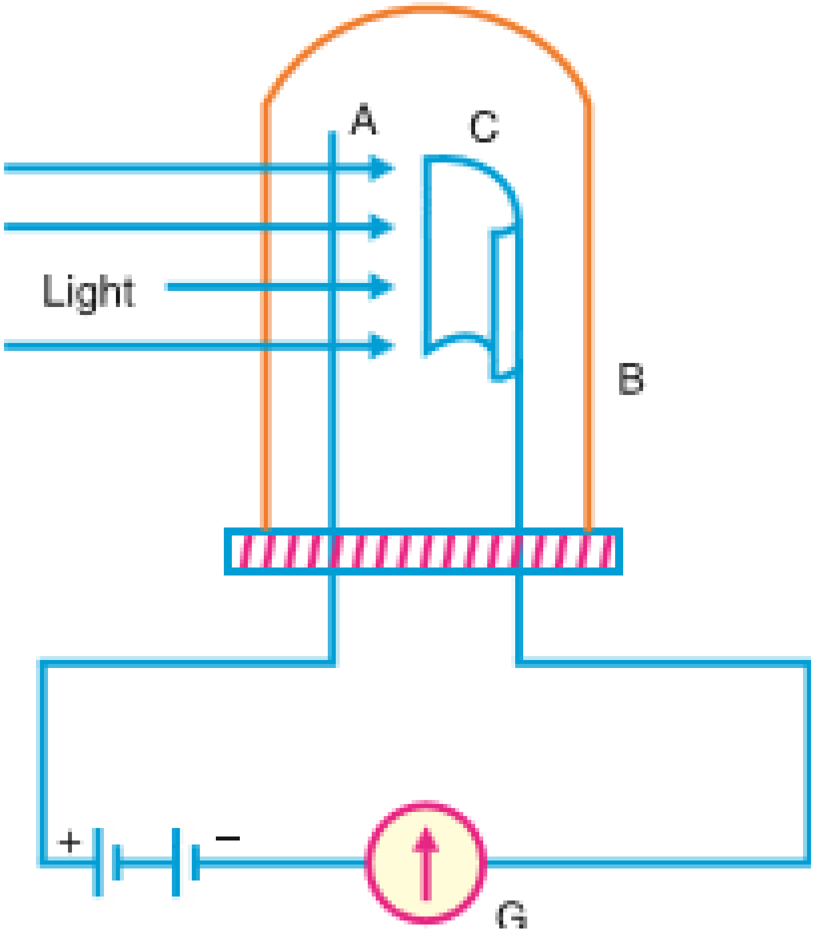
This consists of a glass or quartz bulb (B) according as it is to be used with visible or ultraviolet light (Fig. 8.11). C is the silver cathode in the form of a semi-cylindrical plate.

The anode (A) is a rod mounted vertically at the centre of the bulb and parallel to its axis.

A positive potential of about 100 volts is applied to the anode, the negative being connected to the cathode through a galvanometer G.

When light falls on the cathode C, electrons are ejected from the cathode. A small current flows through the cell and can be measured by the galvanometer.

The photoemissive cell is used for reproduction of sound from photo-films.


A
C
Light
B
+
−
G

(ii) Photo-voltaic cell

It consists of a layer of semiconductor material spread over a metallic surface by heat treatment.

In one type of the photovoltaic cell, the metal plate is made of copper and the semiconductor is cuprous oxide (Cu_2O).

On the other side of the semiconductor, there is a very thin layer of a translucent deposit which allows the semiconductor to be illuminated by radiations

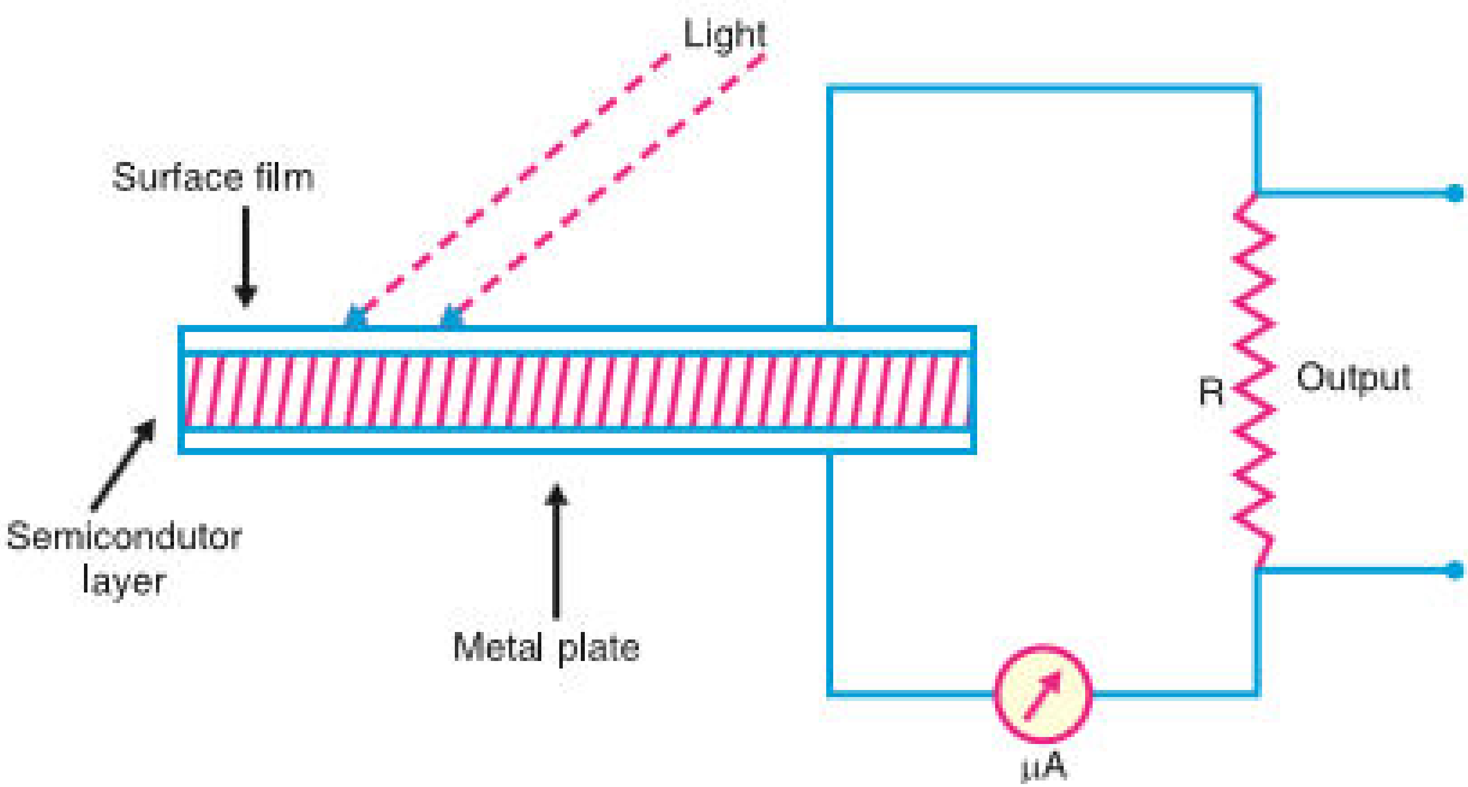
Light falling on the surface film (of gold or silver) penetrates into it and ejects photoelectrons from the semiconductor layer.

These electrons travel in a direction opposite to the direction of the incident light.

The conventional current, therefore, flows in the direction of the incident light.

For small values of the resistance of the galvanometer, the current is directly proportional to the intensity of light.

No external battery is required to operate a photovoltaic cell as the cell itself generates an e.m.f.



(iii) Photoconductive Cell

These cells are based on the principle that the electrical resistance of a semiconductor material, like selenium, decreases with the increase of intensity of radiation incident upon it and conductivity is increased.

A film of selenium is deposited on one side of an iron plate and a P.D. of 100 volts is applied between iron and selenium from an external battery.

A galvanometer is included in the electric circuit. When a beam of light falls on the selenium film, a deflection will be observed in the galvanometer.

As the intensity of the incident light is varied, the resistance of selenium also varies accordingly and the current in the circuit undergoes corresponding variations.

The solar battery consists of several thousand photoconductive cells, which produce several kilowatt power.

Applications of Photoelectric cells

(i) Exposure meters in photography. An exposure meter is a device to calculate the correct time of exposure. The photoelectric cell in the instrument produces a current proportional to the light falling on it. The current operates a galvanometer, the scale of which is calibrated to read the time of exposure.

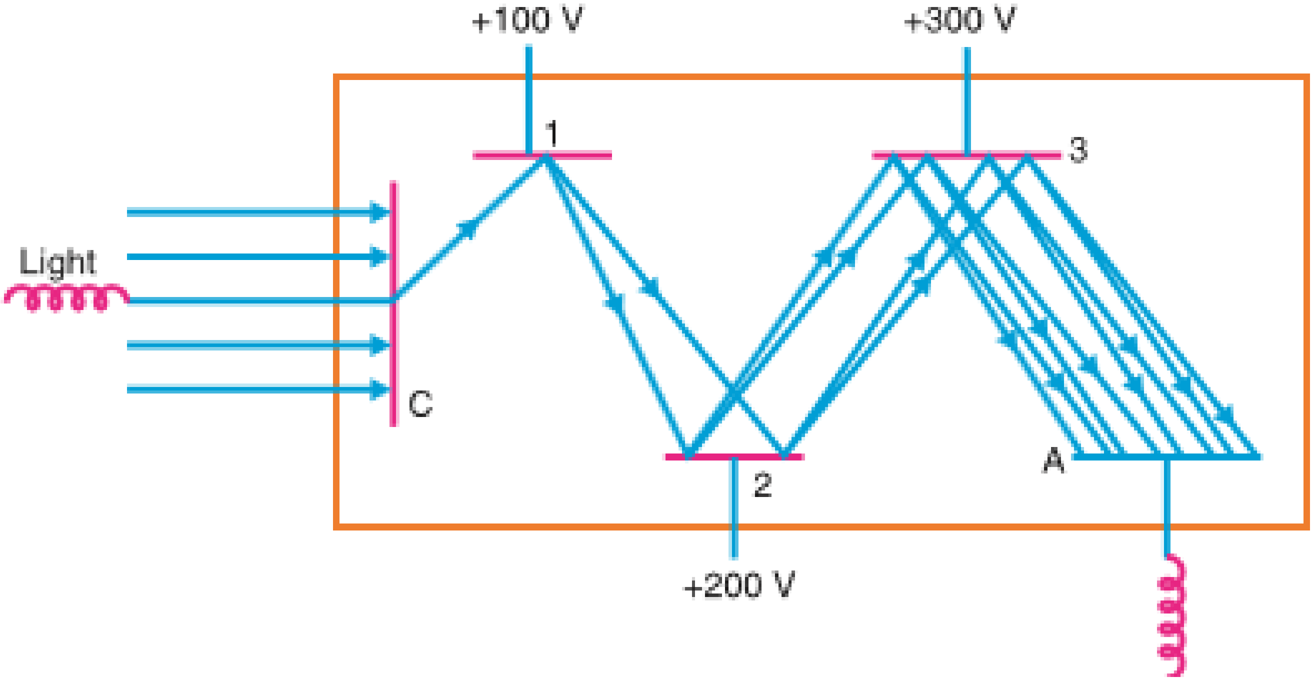
(ii) Photo-multiplier

It is based on the principle of secondary emission.

When light strikes the surface of photosensitive metal plate C, it causes the ejection of photoelectrons from it.

These electrons are then attracted to a metal surface called a dynode, by setting a P.D. between the cathode C and the dynode 1.

High energy electrons striking a metal surface can cause the ejection of one or more secondary electrons from the surface.


+100 V
+300 V
1
3
Light
C
2
A
+200 V

Suppose that a photoelectron striking dynode 1 produces x electrons by secondary emission

These electrons are then directed towards dynode 2 by making its potential higher than that of dynode 1.

Suppose x electrons are again ejected by secondary emission for each incident electron.

Then, for each electron emitted by the photosensitive plate, there are now x2 electrons and so on.

If there are several dynodes, each at a potential higher than the preceding one, an avalanche of electrons reaches the collector plate A.

A strong current then flows in the outer circuit. This device is used to amplify very weak light signals.

(iii) Photoelectric cells are used to compare the illuminating powers of two light sources.

They are also used in the measurement of the intensity of illumination of a light source.

(iv) Sound reproduction in films. The film is provided with a sound track at one edge.
Light passing through the sound track of the film falls on a photocell.

Current is produced, which fluctuates correspondingly with the intensity of sound recorded in the sound track.

The current impulses are converted to sound by speakers.

(v) Automatic operation of street lights. A photoelectric cell, located in a street light circuit, switches off the street light when sunlight is incident on the cell.

When sunlight fades and it becomes dark, the photoelectric cell switches on the street lights.