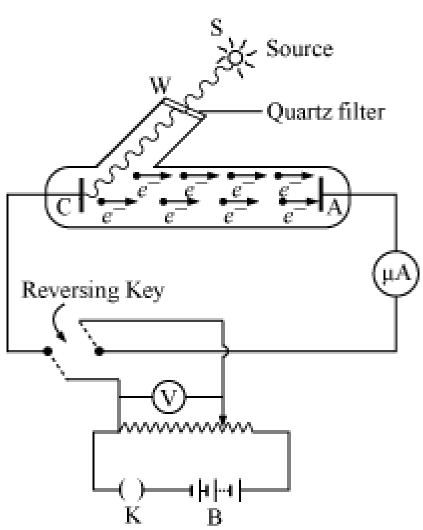
Dual Nature Of Radiation And Matter

Electron Emission and Photoelectric Effect

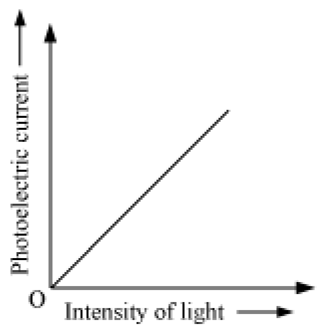
- The phenomenon of emission of electrons from the surface of a metal is called electron emission.
- **Work function –** A certain minimum amount of energy is required to be given to an electron to pull it out from the surface of the metal. This minimum energy required by an electron to escape from the metal surface is called the work function of the metal.
- 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:
- **Thermionic emission** – By suitable heating, sufficient thermal energy can be imparted to the free electrons to enable them to come out of the metal.
- **Field emission** – By applying a very strong electric field to a metal, electrons can be pulled out of the metal.
- **Photoelectric emission** – When light of suitable frequency illuminates a metal surface, electrons are emitted from the metal surface.

Photoelectric Effect



- The apparatus consists of an evacuated glass or quartz tube, which encloses a photosensitive plate C and a metal plate A.
- The window W will allow the light of a particular wavelength to pass through it.

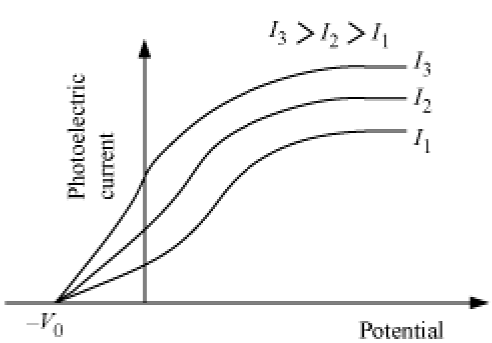
- When a monochromatic radiation of suitable frequency obtained from source *S* falls on the photosensitive plate *C*, the photoelectrons are emitted from *C*, which get accelerated towards the plate *A* (kept at positive potential).
- These electrons flow in the outer circuit, resulting in the photoelectric current. Due to this, the microammeter shows a deflection.
- Factors affecting photoelectric current:
- Effect of intensity of light on photocurrent – The number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation.



- Effect of potential on photoelectric current

  Keep plate *A* at some positive accelerating potential with respect to plate *C* and illuminate plate *C* with light of fixed frequency ν and fixed intensity I_1.

  It is found that photoelectric current increases with increase in accelerating potential. At some stage, for a certain positive potential of plate *A*, all the emitted electrons are collected by plate *A* and the photoelectric current becomes maximum or saturates. This maximum value of photoelectric current is called saturation current.



  The minimum negative potential V_0 given to plate *A* with respect to plate *C* at which the photoelectric current becomes zero is called stopping potential or cut off potential. If *e* is the charge on the photoelectron, then

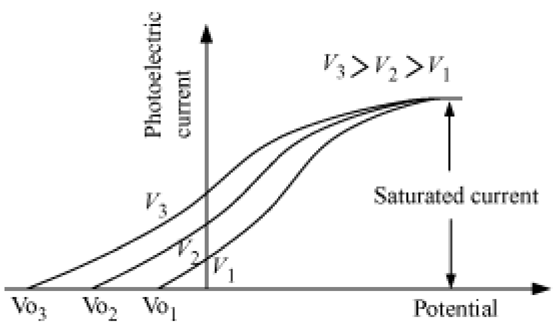
$$k_{max} = eV_0 = \frac{1}{2}mv_{max}^2$$

Where,

m = Mass of photoelectron

v_{max} = Maximum velocity of emitted photoelectron

- Effect of frequency of the incident radiation − Taking radiations of different frequencies but of same intensity, the variation between photoelectric current and potential of plate *A* is obtained and shown in graph given below.



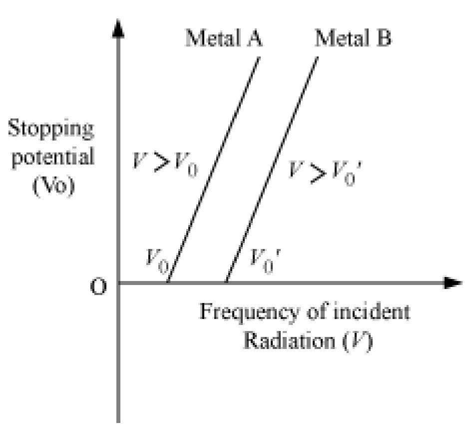
From the graph, we note:

(i) The value of stopping potential is different for radiation of different frequency.

(ii) The value of stopping potential is more negative for radiation of higher incident frequency.

(iii) The value of saturation current depends on the intensity of incident radiation, but is independent of the frequency of the incident radiation.

- Graph between stopping potential and the frequency of the incident radiation:



From the graph, we note:

(i) For a given photosensitive material, the stopping potential varies linearly with the frequency of the incident radiation.

(ii) For a given photosensitive material, there is a certain minimum cut-off frequency ν_0 (called threshold frequency), for which the stopping potential is zero.

- Laws of photo-electric emission:
- For a given metal and frequency of incident radiation, the number of photoelectrons ejected per second is directly proportional to the intensity of the incident light.
- For a given metal, there exists a certain minimum frequency of the incident radiation below which no emission of photoelectrons takes place. This frequency is called threshold frequency.
- Above the threshold frequency, the maximum kinetic energy of the emitted photoelectron is independent of the intensity of the incident light, but depends only upon the frequency (or wavelength) of the incident light.
- The photoelectric emission is an instantaneous process.

Wave Theory of Light & Energy Quantum of Radiation

Einstein's Photoelectric Equation

- Einstein explained the various laws of photoelectric emission on the basis of Planck's quantum theory. According to Planck's quantum theory, light radiation consists of small packets of energy called quanta. One quantum of light radiation is called a photon, which travels at the speed of light. The energy of a photon,

$E = h\nu$

Here,

h – Planck's constant

ν – Frequency of light

- Consider a photon of light frequency ν incident on a photosensitive metal surface. The energy of the photon (= $h\nu$) can be used in two ways:

(i) Some of the energy is used to liberate the electron from the metal surface (= work function).

(ii) The rest of the energy of the photon is used in imparting the maximum kinetic energy k_{max} to the emitted photoelectrons.

$$\therefore h\nu = \phi_0 + \frac{1}{2}mv_{max}^2$$

Here,

Φ_0 – Work function of the metal

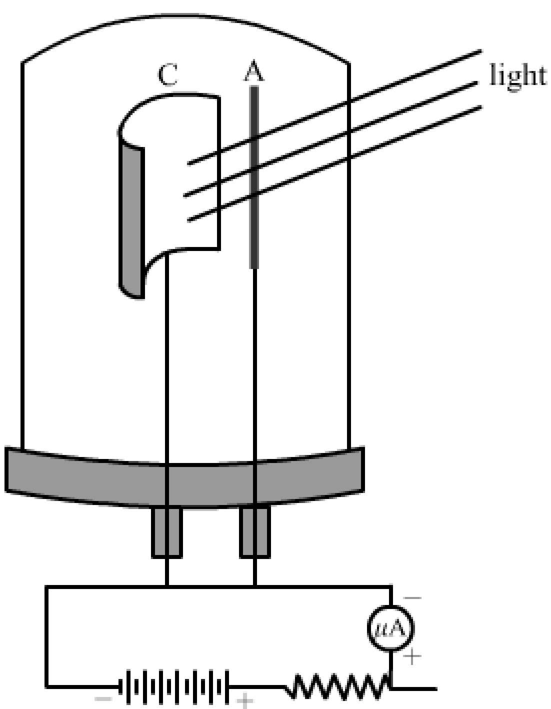
v_{max} – Maximum velocity of the emitted photoelectron

$$\boxed{k_{max} = \frac{1}{2}mv_{max}^2 = h\nu - \phi_0}$$

Here,

k_{max} – Maximum kinetic energy of the photoelectrons

Photoelectric Cell and Its Applications:



- It is a device that converts light energy into electrical energy.

- It works on the principle of photoelectric effect.
- It consists of an evacuated glass tube inside which there is a semi-cylindrical photosensitive metal plate C and a wire loop A.
- Plate C functions as an emitter and a wire loop A serves as a collector.
- A high tension battery and a microammeter are connected to it in the external circuit.

Working:
When a light of suitable wavelength is allowed to fall on the emitter C, photoelectrons are emitted. These photoelectrons are attracted by collector A. A small photoelectric current starts flowing in the circuit that is recorded by the microammeter. If the intensity of incident radiation is increased, the rate of photoelectric emission increases, causing an increase in the current.

Applications of Photoelectric Cell:
(i) Exposure meter:

- It is a device that is used to determine the correct time of exposure to take a photograph.
- It consists of a photoelectric cell, a battery and a microammeter connected in series.
- Light enters the photoelectric cell when the exposure meter is directed towards the object to be photographed and sets up a current in the circuit.
- The extent of deflection of the pointer in the microammeter is proportional to the intensity of light.

(ii) Burglar alarm:

- It makes use of a photoelectric cell to activate a relay mechanism.
- Light from an infrared lamp falls on the photosensitive surface of the photoelectric cell.
- The infrared beam is invisible and when someone crosses the beam, the light is cut off and the photoelectric current stops. This operates the relay circuit and the bell starts ringing.

(iii) Sound reproduction from motion pictures:

- In this, light from a powerful lamp passes through the soundtrack at the edge of the film and falls on the photosensitive surface of the photoelectric cell.
- The photoelectric current varies according to the intensity of light transmitted by the recorded soundtrack.
- The varying current is amplified and fed to the loudspeaker, which reproduces the sound recorded on the soundtrack.

Particle Nature of Light: The Photon

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

- Each photon has energy E (= $h\nu$), momentum p (= $h\nu/c$), and speed c, which is the speed of light.

- All photons of light of a particular frequency ν, or wavelength λ, have the same energy E (=$h\nu$ = hc/λ) and momentum p (= $h\nu/c$), independent of the intensity of radiation. By increasing the intensity of light of given wavelength, there is only an increase in the number of photons per second crossing a given area, with each photon having the same energy.

- Photons are electrically neutral and are not deflected by electric and magnetic fields.

- 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. The photon may be absorbed or a new photon may be created.

Wave Nature of Matter

- **Dual nature of matter:** Radiation has dual nature. Radiation shows both wave-like as well as particle-like properties. The universe is composed of both radiation and matter. Therefore, de Broglie concluded that moving material particles must also possess dual nature since nature loves symmetry.

- **de Broglie's hypothesis** – According to de Broglie, a moving material particle sometimes acts as a wave and sometimes as a particle; or a wave is associated with moving material particle, which controls the particle in every respect. The wave associated with moving particle is called matter wave or de Broglie wave.

  de Broglie wave, $\lambda = \frac{h}{mv}$

  Here, m and v are the respective mass and velocity of the particle and h is Planck's constant.

- **Derivation of the de Broglie wavelength**

  According to Planck's quantum theory, the energy of a photon of a radiation of frequency ν and wavelength λ is

  $E = h\nu$ ...(i)

  According to Einstein's mass-energy relation, we have:

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

  From (i) and (ii), we *get:*
  $h\nu = mc^2$

  $\therefore m = \frac{h\nu}{c^2}$ ...(iii)

Since each photon moves with the same velocity c, momentum of photon, p = mass × velocity

$$p = \frac{h\nu}{c^2} \times c = \frac{h\nu}{c} = \frac{h}{\frac{c}{\nu}} = \frac{h}{\lambda}$$

i.e.,

$$\Rightarrow \boxed{\lambda = \frac{h}{p}} \qquad \ldots(\text{iv})$$

Equation (iv) is equally applicable to both photons of radiation and other material particles.

Matter waves:

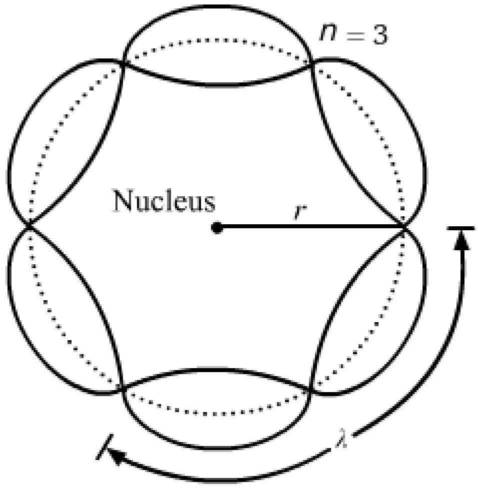
- According to de Broglie, every moving particle is associated with a wave of wavelength given by

  $\lambda = h/p = h/mv$
  These waves are called matter waves.

- They are associated with moving material particles only.
- The greater the momentum of the particle, the shorter is the wavelength.
- Matter waves travel with the speed equal to or less than the speed of the light.
- The de-broglie wavelength is independent of the charge of the particle.
- Matter waves are not electromagnetic in nature.
- They are proposed to locate the position of moving particle, i.e., the higher the intensity of wave at a point, the greater is the probability of the associated particle being there.

Explanation of Bohr's 2nd postulate by de Broglie's hypothesis:

- Bohr's second postulate states that the angular momentum of an electron has only those values that are integral multiples of h2πh2π. He thought that the motion of electrons within an atom is associated with the standing wave along the orbit as shown.



- About standing waves in stretched strings, we know that only those waves survive for which the distances travelled in the round trip between the ends are integral multiples of the wavelength. Similarly, for an electron moving in the n^{th} orbit of radius r_n,, the distance travelled in one trip is $2\pi r_n$, which should be an integral multiple of the wavelength.

i.e., $2\pi r_n = n\lambda$, where n = 1, 2, 3, 4, ...

- By de Broglie hypothesis, we have:
- $\lambda = \frac{h}{p} = \frac{h}{mv_n}$
- Substituting the value of λ in the above expression, we get:

$$2\pi r_n = n\frac{h}{mv_n}$$

$$\Rightarrow mv_n r_n = n\frac{h}{2\pi}$$

- Angular momentum = $n\frac{h}{2\pi}$

Wavelength of an electron:

- Also, $E = \frac{1}{2}mv^2$ ven

  $\Rightarrow E = \frac{1}{2}\frac{m^2v^2}{m}$

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

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

  - Substituting the value of p in the above expression of wavelength, we get:

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

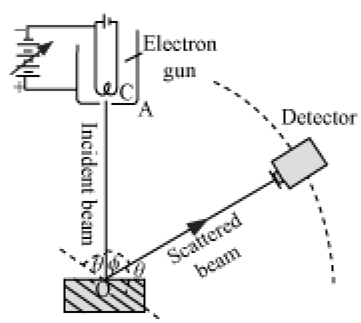
  $\Rightarrow \lambda = \frac{12.27}{\sqrt{V}}\ \mathring{A}$

  This formula is useful to determine the wavelength at low voltage.

Davisson and Germer Experiment

- The wave nature of the material particles as predicted by de Broglie was confirmed by Davisson and Germer (1927).
- **Experiment –** Experimental arrangement used by Davisson and Germer: Electrons from hot tungsten cathode are accelerated by a potential difference *V* between the cathode (C) and anode (A).

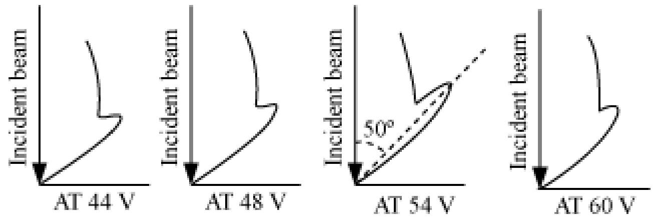
  A narrow hole in the anode renders the electrons into a fine beam of electrons and allows them to strike the nickel crystal.



  The electrons are scattered in all directions by the atoms in the crystal and its intensity in a given direction is found by the use of a detector.

  The graph is plotted between angle *Φ* (angle between incident and the scattered direction of electron beam) and intensity of scattered beam.

  The experimental curves obtained by Davisson and Germer are as shown in the figure below.



Incident beam
AT 44 V
Incident beam
AT 48 V
Incident beam
50°
AT 54 V
Incident beam
AT 60 V