SPIRO ACADEMY
(NO.1 COACHING INSTITUTE FOR MEDICAL & ENGINEERING ENTRANCE IN TAMIL NADU)
Address :
#1,C.V.R Complex (Big Bazaar Back side),
Singaravelu St,
T.Nagar, Chennai - 17 .
Mobile no: 733 888 4137 , 733 888 4136
www.spiroacademy.com , info@spiroacademy.com

Dual Nature of Radiation and Matter

Emission of electrons:

We know that metals have free electrons (negatively charged particles) that are responsible for their conductivity.

However, 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 positive 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. Consequently, the electron can come out of the metal surface only if it has got sufficient energy to overcome the attractive pull. 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. It is generally denoted by ϕ_0 and measured in eV (electron volt).

The work function (ϕ_0) depends on the properties of the metal and the nature of its surface. These values are approximate as they are very sensitive to surface impurities.

The work function of platinum is the highest (ϕ_0 = 5.65 eV) while it is the lowest (ϕ_0 = 2.14 eV) for caesium.

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:

(i) Thermionic emission: By suitably heating, sufficient thermal energy can be imparted to the free electrons to enable them to come out of the metal.

(ii) Field emission: By applying a very strong electric field (of the order of 108 V m^{-1}) to a metal, electrons can be pulled out of the metal, as in a spark plug.

(iii) Photo-electric emission: When light of suitable frequency illuminates a metal surface, electrons are emitted from the metal surface. These photo(light)-generated electrons are called photoelectrons.

Photoelectric effect

When an electromagnetic radiation of enough high frequency is incident on a cleaned surface, electrons can be liberated from the metal surface. This phenomenon is known as the photoelectric effect and the electron emitted are known as Photo electrons.

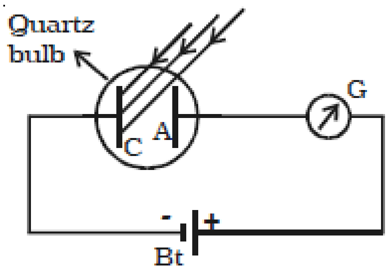
To have photo emission, the frequency of incident light should be more than some minimum frequency. This minimum frequency is called the threshold frequency (f_o).

It depends on the type of the metal.

For most of the metals (e.g. Zn, Cd, Mg) threshold frequency lies in the ultraviolet region of electromagnetic spectrum. But for alkali metals (Li, K, Na, Rb) it lies in the visible region

Hallwachs' and Lenard's observations
Hallwachs, in 1888, undertook the study further and connected a negatively charged zinc plate to an electroscope. He observed that the zinc plate lost its charge when it was illuminated by ultraviolet light. Further, the uncharged zinc plate became positively charged when it was irradiated by ultraviolet light. Positive charge on a positively charged zinc plate was found to be further enhanced when it was illuminated by ultraviolet light. From these observations he concluded that negatively charged particles were emitted from the zinc plate under the action of ultraviolet light

Lenard (1862-1947) observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube enclosing two electrodes (metal plates), current flows in the circuit as shown in figure. As soon as the ultraviolet radiations were stopped, the current flow also stopped. These observations indicate that when ultraviolet radiations fall on the emitter plate C, electrons are ejected from it which are attracted towards the positive, collector plate A by the electric field. The electrons flow through the evacuated glass tube, resulting in the current flow. Thus, light falling on the surface of the emitter causes current in the external circuit. The emission of electrons causes flow of electric current in the circuit. The potential difference between the emitter and collector plates is measured by a voltmeter (V) whereas the resulting photo current flowing in the circuit is measured by a microammeter (μA). The photoelectric current can be increased or decreased by varying the potential of collector plate A with respect to the emitter plate C. The intensity and frequency of the incident light can be varied, as can the potential difference *V* between the emitter C and the collector A.



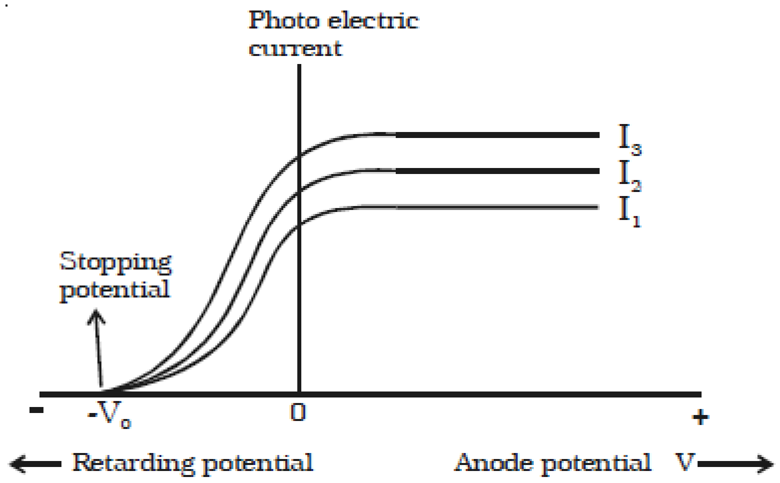
The amount of current passing through the ammeter gives an idea of the number of photoelectrons. At some value of positive potential difference, when all the emitted electrons are collected, increasing the potential difference further has no effect on the current.

Effect of potential on photoelectric current

When the collector (A) is made negative with respect to C, the emitted electrons are repelled and only those electrons which have sufficient kinetic energy to overcome the repulsion may reach to the collector(A) and constitute current.
So the current in ammeter falls. On making Collector (A) more negative , number of photoelectrons reaching the collector further decreases.

For specific negative potential of the collector, even the most energetic electrons are unable to reach collector and photoelectric current becomes zero.
It remains zero even if the potential is made further negative than the specific value of negative potential.
This minimum specific negative potential of the collector with respect to the emitter (photo sensitive surface) at which photo-electric current becomes zero is known as the Stopping Potential (V_O) for the given surface.
It is thus the maximum kinetic energy $\frac{1}{2}mv^2$ of the emitted photoelectrons. If charge and mass of an electron are e and m respectively then

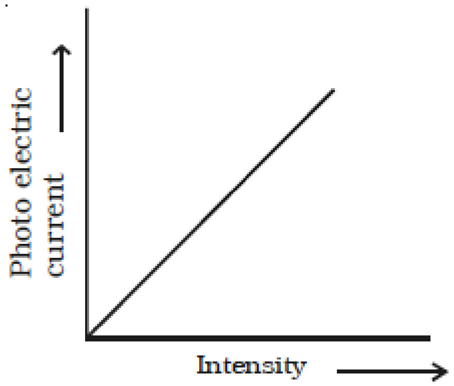
$$\frac{1}{2}mv^2 = eV_o$$



We can now repeat this experiment with incident radiation of the same frequency but of higher intensity I_2 and I_3 ($I_3 > I_2 > I_1$). We note that the saturation currents are now found to be at higher values. This shows that more electrons are being emitted per second, proportional to the intensity of incident radiation. But the stopping potential remains the same as that for the incident radiation of intensity I_1, as shown graphically in Fig.
Thus, for a given frequency of the incident radiation, the stopping potential is independent of its intensity. In other words, the maximum kinetic energy of photoelectrons depends on the light source and the emitter plate material, but is independent of intensity of incident radiation.

Effect of intensity of incident radiation on photo electric current

Keeping the frequency of the incident radiation and the potential difference between the collector(A) and the Surface (C) at constant values, the intensity of incident radiation is varied. The corresponding photoelectric current is measured in the micro-ammeter.
It is found that the photo electric current increases linearly with the intensity of incident radiation (Fig).



Since the photoelectric current is directly proportional to the number of photoelectrons emitted per second, it implies that the number of photoelectrons emitted per second is proportional to the intensity of incident radiation.

Effect of frequency of incident radiation on stopping potential

Keeping the photosensitive plate (C) and intensity of incident radiation a constant, the effect of frequency of the incident radiations on stopping potential is studied.

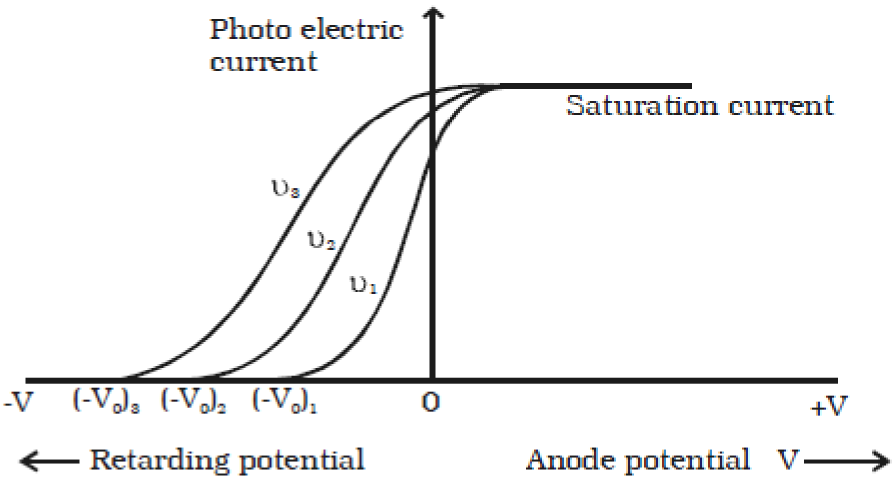
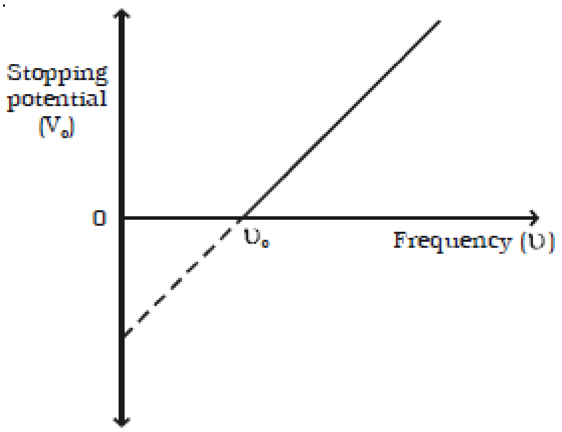


Fig shows the variation of the photo electric current with the applied potential difference *V* for three different frequencies. From the graph, it is found that higher the frequency of the incident radiation, higher is the value of stopping potential *Vo.* For frequencies $\nu_3 > \nu_2 > \nu_1$, the corresponding stopping potentials are in the same order $(V_o)_3 > (V_o)_2 > (V_o)_1$.
It is concluded from the graph that, the maximum kinetic energy of the photoelectrons varies linearly with the frequency of incident radiation but is independent of its intensity.
If the frequency of the incident radiation is plotted against the corresponding Stopping potential, a straight line is obtained as shown in Fig



From this graph, it is found that at a frequency ν_o, the value of the stopping potential is zero. This frequency is known as the threshold frequency for the photo metal used. The photoelectric effect occurs above this frequency and ceases below it.
Therefore, threshold frequency is defined as the minimum frequency of incident radiation, below which the photoelectric emission is not possible completely. The threshold frequency is different for different metals.

Laws of photoelectric emission:

The experimental observations on photoelectric effect may be summarized as follows, which are known as the fundamental laws of photoelectric emission.
(i) For a given photo sensitive material, there is a minimum frequency called the threshold frequency, below which emission of photoelectrons stops completely, however great the intensity may be.
(ii) For a given photosensitive material, the photo electric current is directly proportional to the intensity of the incident radiation, provided the frequency is greater than the threshold frequency.
(iii) The photoelectric emission is an instantaneous process. i.e. there is no time lag between the incidence of radiation and the emission of photo electrons.
(iv)The maximum kinetic energy of the photo electrons is directly proportional to the frequency of incident radiation, but is independent of its intensity.

Wave theory fails to explain the photoelectric effect as:

(1) According to the wave theory of light, energy and intensity of wave depend on its amplitude. Hence intense radiation has higher energy and on increasing intensity, energy of photoelectrons should increase. But experimental results show that photoelectric effect is independent of intensity of light, but depends on the frequency of light. According to wave theory of light, energy of light has nothing to do with frequency. Hence change in energy of photoelectrons with change in frequency cannot be explained

(2) Photons are emitted immediately (within 10^{-9}s) on making light incident on metal surface. Since the free electrons within metal are withheld under the effect of certain forces, and to bring them out, energy must be supplied

Now if the incident energy is showing wave nature, free electrons in metal get energy gradually and when accumulates energy at least equal to work function then they escape from metal.

Thus electrons get emitted only after some time

(3) According to wave theory of light , less intense light is 'weak' in terms of energy. To liberate photoelectron with such light one has to wait long till electron gather sufficient energy. Whereas experimental result shows that phenomenon depends on frequency and for low intensity light of appropriate frequency photoelectrons are emitted instantly

Solved Numerical

Q) Let an electron requires 5×10^{-19} joule energy to just escape from the irradiated metal. If photoelectron is emitted after 10^{-9}s of the incident light, calculate the rate of absorption of energy. If this process is considered classically, the light energy is assumed to be continuously distributed over the wave front. Now, the electron can only absorb the light incident within a small area, say 10^{-19} m^2. Find the intensity of illumination in order to see the photoelectric effect

Solution:

Rate of absorption of energy is power

$$P = \frac{E}{t} = \frac{5\times10^{-19}}{10^{-9}} = 5\times10^{-10}\frac{J}{s}$$

From the definition of intensity of light

$$I = \frac{Power}{Area} = \frac{5\times10^{-10}}{10^{-19}} = 5\times10^{9}\frac{J}{s.m^2}$$

Since, practically it is impossibly high energy, which suggest that explanation of photoelectric effect in classical term is not possible

Q) Work function is 2eV. Light of intensity 10^{-5} W m^{-2} is incident on 2cm^2 area of it. If 10^{17} electrons of these metals absorb the light, in how much time does the photo electric effect start? Consider the waveform of incident light

Solution:

Intensity of incident light is 10^{-5} W m^{-2}

Now intensity

$$I = \frac{E}{A\cdot t}$$

$$E = IAt$$

$$E = 10^{-5}\times2\times10^{-4}\times1 = 2\times10^{-9}J$$

This energy is absorbed by 10^{17} electrons

Average energy absorbed by each electron = $2\times10^{-9}/10^{17} = 2\times10^{-26}$ J

Now, electron may get emitted when it absorbs energy equal to the work function of its metal = 2eV = 3.6×10^{-19} J

Thus time required to absorb energy = 3.6×10^{-19} J / 2×10^{-26} J = 1.6×10^{7} s

Light waves and photons

The electromagnetic theory of light proposed by Maxwell could not explain photoelectric effect. But, Max Planck's quantum theory successfully explains photoelectric effect. According to Planck's quantum theory, light is emitted in the form of discrete packets of energy called 'quanta' or photon. The energy of each photon is $E = h\nu$, where h is Planck's constant. Photon is neither a particle nor a wave. In the phenomena like interference, diffraction, polarization, the photon behaves like a wave. Energy of n photon $E = n h\nu$

In the phenomena like emission, absorption and interaction with matter (photo electric effect) photon behaves as a particle. Hence light photon has a dual nature.

Solved Numerical

Q) If the efficiency of an electric bulb is of 1 watt is 10%, what is the number of photons emitted by it in one second? The wave length of light emitted by it is 500nm,

$h = 6.625\times10^{-34}$

Solution:

As the bulb is of 1W, if its efficiency is 100%, it may emit 1 J radiant energy in 1s. But here the efficiency is 10%, hence it emits 10^{-1} J energy in the form of light in 1 s , and remaining in the form of heat.

∴Radiant energy obtained from bulb in 1s = 10^{-1} J

If it consists of n photons then

$E = n h\nu$

$$E = nh\frac{c}{\lambda}$$

$$n = \frac{E\lambda}{hc}$$

$$n = \frac{10^{-1}\times 500\times 10^{-9}}{6.625\times 10^{-34}\times 3\times 10^{8}}$$

$n = 2.53 \times 10^{17}$ photons

Einstein's photoelectric equation

In 1905, Albert Einstein successfully applied quantum theory of radiation to photoelectric effect.
Plank had assumed that emission of radiant energy takes place in the quantized form, the photon, but once emitted it propagate in the form of wave. Einstein further assumed that not only the emission, even the absorption of light takes place in the form of photons.
According to Einstein, the emission of photo electron is the result of the interaction between a single photon of the incident radiation and an electron in the metal. When a photon of energy *h*ν is incident on a metal surface, its energy is used up in two ways:

(i) A part of the energy of the photon is used in extracting the electron from the surface of metal, since the electrons in the metal are bound to the nucleus. This energy W spent in releasing the photo electron is known as photoelectric work function of the metal. The work function of a photo metal is defined as the minimum amount of energy required to liberate an electron from the metal surface.
(ii) The remaining energy of the photon is used to impart kinetic energy to the liberated electron. If *m* is the mass of an electron and *v*, its velocity then
Energy of the incident photon = Work function + Kinetic energy of the electron

$$h\nu = \phi_0 + \frac{1}{2}mv^2$$

If the electron does not lose energy by internal collisions, as it escapes from the metal, the entire energy $(h\nu - \phi_0)$ will be exhibited as the kinetic energy of the electron.
Thus, $(h\nu - \phi_0)$ represents the maximum kinetic energy of the ejected photo electron. If V_{max} is the maximum velocity with which the photoelectron can be ejected, then

$$h\nu = \phi_0 + \frac{1}{2}mv_{max}^2 - -(1)$$

This equation is known as Einstein's photoelectric equation.
When the frequency (ν) of the incident radiation is equal to the threshold frequency (ν_o) of the metal surface, kinetic energy of the
electron is zero. Then equation (1) becomes,
$h\nu_o = \phi_0$ ...(2)
Substituting the value of *W* in equation (1) we get,

$$h\nu - h\nu_0 = \frac{1}{2}mv_{max}^2 - -(3)$$

Or $K_{max} = h\nu - \phi_0$ or $eV_O = h\nu - \phi_0$ –--(4)
This is another form of Einstein's photoelectric equation.

Solved numerical

Q) A beam of photons of intensity 2.5 W m^{-2} each of energy 10.6eV is incident on 1.0×10^{-4} m^2 area of the surface having work function 5.2eV. If 0.5% of incident photons emits photo-electrons, find the number of photons emitted in 1s. Find the minimum and maximum energy of photo-electrons.

Solution:
Intensity I

$$I = \frac{E}{A \cdot t}$$

But E = nhν, here n is number of photons

$$I = \frac{nh\nu}{At}$$

$$n = \frac{IAt}{h\nu}$$

Energy of each photon = hν =10.6eV =$10.6\times1.6\times10^{-19}$ J

$$n = \frac{2.5 \times 1 \times 10^{-4} \times 1}{10.6 \times 1.6 \times 10^{-19}} = 1.47 \times 10^{14}$$

As 0.5% of these photons emits electrons
Number of photo electrons emitted N = $1.47\times10^{14} \times (0.5/100) = 7.35\times10^{11}$

The minimum energy of photo electron is = 0 J. Such photoelectron spend all its energy gained from the photon against work function
Maximum energy of photo electron:
E = hν – ϕ_0 = 10.6 eV – 5.2eV = 5.4 eV

Q) U.V light of wavelength 200nm is incident on polished surface of Fe. Work function of Fe is 4.5eV Find
1) Stopping potential
2) maximum kinetic energy of photoelectrons
3) Maximum speed of photoelectrons
m = 9.11×10^{-31} kg ,
Solution
Work function = 4.5eV = 4.5e J

$$eV_O = h\nu - \phi_0$$

$$eV_0 = h\frac{c}{\lambda} - \phi_0$$

$$V_0 = \frac{h}{e}\frac{c}{\lambda} - \frac{\phi_0}{e}$$

$$V_0 = \frac{6.625 \times 10^{-34}}{1.6 \times 10^{-19}} \times \frac{3 \times 10^8}{200 \times 10^{-9}} - \frac{e \times 4.5}{e}$$

V_0 = 6.21 – 4.5 = 1.71 V

Maximum kinetic energy = eV_0

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

$$v_{max} = \sqrt{\frac{2eV_0}{m}}$$

$$v_{max} = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 1.71}{9.11 \times 10^{-31}}}$$

V_{max} = 7.75 $\times 10^5$ m/s

Experimental verification of Einstein's photoelectric equation

(1) According to Eq. (4), K_{max} depends linearly on ν, and is independent of intensity of radiation, in agreement with observation.

This has happened because in Einstein's picture, photoelectric effect arises from the absorption of a single quantum of radiation by a single electron. The intensity of radiation (that is proportional to the number of energy quanta per unit area per unit time) is irrelevant to this basic process.

(2) Since K_{max} must be non-negative, Eq. (4) implies that photoelectric emission is possible only if $h\nu > \phi_0$

Or $\nu > \nu_0$

Where $\nu_0 = \phi_0 / h$ –eq(5)

Equation (4) shows that the greater the work function ϕ_0, the higher the minimum or threshold frequency ν_0 needed to emit photoelectrons. Thus, there exists a threshold frequency ν_0 (= ϕ_0/h) for the metal surface, below which no photoelectric emission is possible, no matter how intense the incident radiation may be or how long it falls on the surface

(3) Intensity of radiation as noted above is proportional to the number of energy quanta per unit area per unit time.

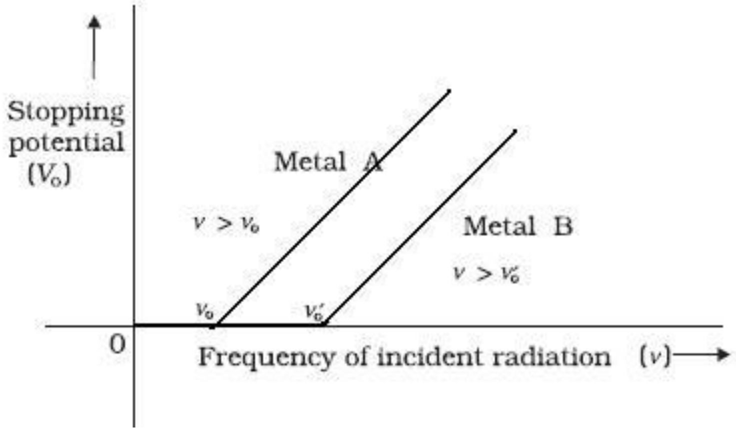
The greater the number of energy quanta available, the greater is the number of electrons absorbing the energy quanta and greater, therefore, is the number of electrons coming out of the metal (for ν > ν0). This explains why, for $\nu > \nu_0$,photoelectric current is proportional to intensity.

(4) The photoelectric equation, Eq. (3), can be written as

$$eV_0 = h\nu - \phi_0$$

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

This is an important result. It predicts that the V_0 versus ν curve is a straight line with slope = (h/e), independent of the nature of the material.
During 1906-1916, Millikan performed a series of experiments on photoelectric effect, aimed at disproving Einstein's photoelectric equation. He measured the slope of the straight line obtained for sodium, similar to that shown in Fig.



Using the known value of *e*, he determined the value of Planck's constant *h*. This value was close to the value of Planck's constant (= 6.626 × 10–34J s) determined in an entirely different context.
In this way, in 1916, Millikan proved the validity of Einstein's photoelectric equation, experimentally and found that it is in harmony with the observed facts.

PARTICLE NATURE OF LIGHT: THE PHOTON

(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*ν) and momentum *p* (= *h* ν/*c*), and speed *c*, the speed of light.
(iii) All photons of light of a particular frequency ν, or wavelength λ, have the same energy *E* (=*h*ν = *hc*/λ) and momentum *p* (= *h*ν/*c* = *h*/λ),
whatever the intensity of radiation may be. 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. Thus, 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 (such as photon-electron 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.
(v) Mass of photon m = E/c^2

WAVE NATURE OF MATTER

The radiant energy has dual aspects of particle and wave, hence a natural question arises, if radiation has a dual nature, why not the matter. In 1924, a French Physicist Louis de Broglie put forward the bold hypothesis that moving particles should possess wave like properties under suitable conditions. He reasoned this idea, from the fact, that nature is symmetrical and hence the basic physical entities– matter and energy should have symmetrical characters. If radiation shows dual aspects, so should matter.

de Broglie's wavelength of matter waves

de Broglie equated the energy equations of Planck (wave) and Einstein (particle).
For a wave of frequency ν, the energy associated with each photon is given by Planck's relation,
$E = h\nu$ ...(1)
where h is Planck's constant.
According to Einstein's mass energy relation, a mass m is equivalent to energy,
$E = mc^2$ ...(2)
where c is the velocity of light.
If, $h\nu = mc^2$

$$\therefore \frac{hc}{\lambda} = mc^2 or\ \lambda = \frac{h}{mc} - -(3)$$

For a particle moving with a velocity v, if $c = v$
from equation (3)

$$\lambda = \frac{h}{mv} = \frac{h}{p} - -(4)$$

where $p = mv$, the momentum of the particle. These hypothetical matter waves will have appreciable wavelength only for very light particles.

de Broglie wavelength of an electron

When an electron of mass m and charge e is accelerated through a potential difference V, then the energy eV is equal to kinetic energy of the electron.

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

$$v = \sqrt{\frac{2eV}{m}} - -(1)$$

The de Broglie wavelength is ,

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

Substituting the value of v,

$$\lambda = \frac{h}{m\sqrt{\frac{2eV}{m}}} = \frac{h}{\sqrt{2meV}} - -(2)$$

Substituting the known values in equation (2),

$$\lambda = \frac{12.27}{\sqrt{V}} \text{Å}$$

If V = 100 volts, then λ = 1.227 Å i.e., the wavelength associated with an electron accelerated by 100 volts is 1.227 Å.

Since E = eV is kinetic energy associated with the electron, the equation (2) becomes,

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

Wave packet:

Classically, particle men as a point like object endowed with a precise position and momentum.

The de Broglie's hypothesis, which also supports wave-like behavior of matter, question about how to measure accurately position and momentum of a material particle.

A pure harmonic wave extended in space obviously cannot represent a point like particle. This suggest that the wave activity of a wave representing a particle must be limited to the space occupied by the particle. For this reason an idea of wave packet, a wave which is confined to small region of space is introduced. Wave packet may be considered as superposition of many harmonic wave of slightly different wavelength

If the concept of wave packet is used to represent particle, position of the particle is more and is proportional to the size of the wave-packet. But as several waves of different wave lengths are used to represent a particle, its momentum is no longer unique and become uncertain.

In general, the matter wave associated with the electron is not extended all over space. It is a wave packet extending over some finite region of space. In that case Δx is not infinite but has some finite value depending on the extension of the wave packet. Wave packet of finite extension does not have a single wavelength. It is built up of wavelengths spread around some central wavelength.

Heisenberg's uncertainty Principle:

According to Heisenberg's uncertainty principle, if the uncertainty in the x-coordinate of the position of a particle is Δx and uncertainty in the x-component of momentum is Δp (i.e. in one dimension) them

$$\Delta x \cdot \Delta p \geq \frac{h}{2\pi}$$

Similarly

$$\Delta E \cdot \Delta t \geq \frac{h}{2\pi}$$

Solved numerical

Q) Find the certainty with which one can locate the position of

1) A bullet of mass 25g 2) An electron moving with speed 500 m/s accurate to 0.01%. .

Mass of electron is 9.1×10^{-31}kg

Solution

1) Uncertainty in measurement of momentum of bullet is 0.01% of its exact value i.e.
Δp = 0.01% of mv

$$\Delta p = \left(\frac{0.01}{100}\right) \times (25 \times 10^{-3})(500)$$
$$\Delta p = 1.25 \times 10^{-3} kgms^{-1}$$

Therefore, corresponding uncertainty in position

$$\Delta x = \frac{h}{2\pi p}$$
$$\Delta x = \frac{6.625 \times 10^{-34}}{2 \times 3.14 \times 1.25 \times 10^{-3}}$$
$$\Delta x = 8.44 \times 10^{-32} m$$

(2) Uncertainty in measurement o momentum of an electron is

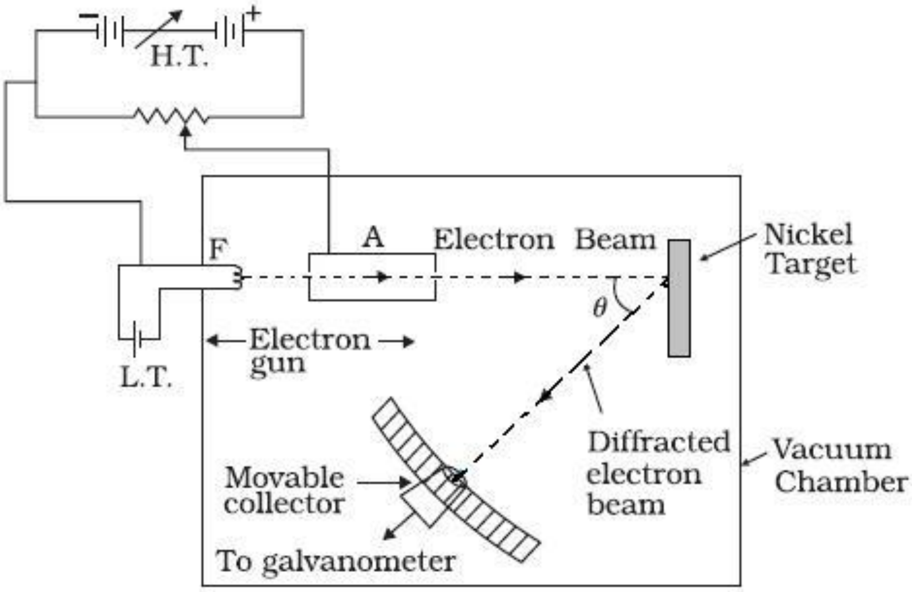
$$\Delta p = \frac{0.01}{100} \times (9.1 \times 10^{-31})(500) = 4.55 \times 10^{-32} kgms^{-1}$$
$$\Delta x = \frac{6.625 \times 10^{-34}}{2 \times 3.14 \times 4.55 \times 10^{-32}} = 0.23\, mm$$

Conclusion: The value of Δx is too small compared to the dimension of the bullet, and can be neglected. That is, position of the bullet is determined accurately

DAVISSON AND GERMER EXPERIMENT

The wave nature of electrons was first experimentally verified by C.J. Davisson and L.H. Germer in 1927 and independently by G.P. Thomson, in 1928, who observed diffraction effects with beams of electrons scattered by crystals.

The experimental arrangement used by Davisson and Germer is schematically shown in Fig.



It consists of an electron gun which comprises of a tungsten filament F, coated with barium oxide and heated by a low voltage power supply (L.T. or battery).
Electrons emitted by the filament are accelerated to a desired velocity by applying suitable potential/voltage from a high voltage power supply (H.T. or battery).
They are made to pass through a cylinder with fine holes along its axis, producing a fine collimated beam.
The beam is made to fall on the surface of a nickel crystal. The electrons are scattered in all directions by the atoms of the crystal.
The intensity of the electron beam, scattered in a given direction, is measured by the electron detector (collector). The detector can be moved on a circular scale and is connected to a sensitive galvanometer, which records the current.
The deflection of the galvanometer is proportional to the intensity of the electron beam entering the collector. The apparatus is enclosed in an evacuated chamber.
By moving the detector on the circular scale at different positions, the intensity of the scattered electron beam is measured for different values of angle of scattering θ which is the angle between the incident and the scattered electron beams.
The variation of the intensity (*I*) of the scattered electrons with the angle of scattering θ is obtained for different accelerating voltages.
The experiment was performed by varying the accelerating voltage from 44 V to 68 V.
It was noticed that a strong peak appeared in the intensity (*I*) of the scattered electron for an accelerating voltage of 54V at a scattering angle $\theta = 50^o$
The appearance of the peak in a particular direction is due to the constructive interference of electrons scattered from different layers of the regularly spaced atoms of the crystals.
From the electron diffraction measurements, the wavelength of matter waves was found to be 0.165 nm.
The de Broglie wavelength λ associated with electrons, using

$$\lambda = \frac{12.27}{\sqrt{V}} \text{Å}$$

$$\lambda = \frac{12.27}{\sqrt{54}} \text{Å}$$

λ=1.67Å

Thus, there is an excellent agreement between the theoretical value and the experimentally obtained value of de Broglie wavelength.
The de Broglie hypothesis has been basic to the development of modern quantum mechanics. It has also led to the field of electron optics. The wave properties of electrons have been utilized in the design of electron microscope which is a great improvement, with higher resolution, over the optical microscope.

Solved numerical

Q) An electron is at a distance of 10m from a charge of 10C. Its total energy is 15.6×10^{-10} J. Find its de Broglie wavelength at this point

$m_e = 9.1\times10^{-31}$ kg

Solution:

Potential energy of an electron

$$U = k\frac{qe}{r}$$

$$U = -\frac{9\times10^{9}\times10\times1.6\times10^{-19}}{10}$$

$$U = -14.4\times10^{-10}J$$

Total energy = Kinetic energy (K) + Potential energy

K = E – U

$K = 15.6\times10^{-10} + 14.4\times10^{-10} = 30\times10^{-10}$

But

$$K = \frac{p^2}{2m_e}$$

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

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2Km_e}}$$

$$\lambda = \frac{6.625\times10^{-34}}{\sqrt{2\times30\times10^{-10}\times9.1\times10^{-31}}}$$

$\lambda = 8.97\times10^{-15}$ m

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