DUAL NATURE OF RADIATION AND MATTER

CHAPTER – 11

DUAL NATURE OF RADIATION AND MATTER

Dual Nature of Radiations

It is well known that the phenomena of interference, diffraction and polarization indicate that light has wave nature. But some phenomena like photoelectric effect, Compton effect, emission and absorption of radiation could not be explained by wave nature. These were explained by particle (quantum) nature of light. Thus, light (radiation) has dual nature.

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 ($\phi0 = 5.65$ eV) while it is the lowest ($\phi_0 = 2.14$ eV) for cesium. 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. 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.

Lenard's Observations

Phillip Lenard observed that when ultraviolet radiations were made incident on the emitter plate of an evacuated glass tube enclosing two metal plates (called electrodes), current flows in the circuit, but as soon as ultraviolet radiation falling on the emitter plate was stopped, the current flow stopped. These observations indicate that when ultraviolet radiations fall on the emitter (cathode) plate C, the electrons are ejected from it, which are attracted towards anode plate A. The electrons flow through the evacuated glass tube, complete the circuit and current begins to flow in the circuit.

Hallwachs Exp:

Hallwachs studied further by taking a zinc plate and an electroscope. The zinc plate was connected to an electroscope. He observed that:

(i) When an uncharged zinc plate was irradiated by ultraviolet light, the zinc plate acquired positive charge.

(ii) When a positively charged zinc plate is illuminated by ultraviolet light, the positive charge of the plate was increased.

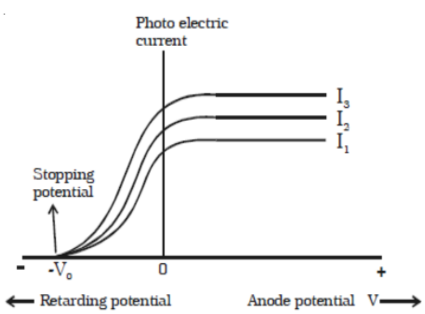
(iii) When a negatively charged zinc plate was irradiated by ultraviolet light, the zinc plate lost its charge. All these observations show that when ultraviolet light falls on zinc plate, the negatively charged particles (electrons) are emitted. Further study done by Hallwach's experiment shows that different metals emit electrons by different electromagnetic radiations.

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 (VO) 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

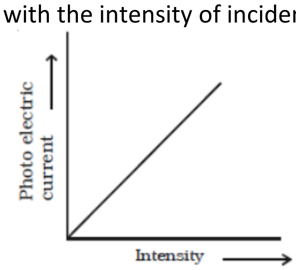
$$\frac{1}{2}mv^2 = eV_0$$



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.

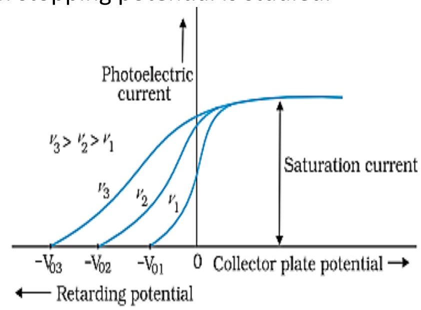
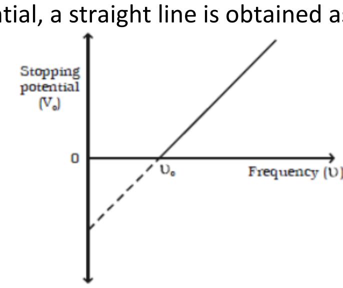


Fig shows the variation of the photo electric current with the applied potential difference V for three different frequencies. From the graph, it is found that higher the frequency of the incident radiation, higher is the value of stopping potential Vo. For frequencies $\nu_3 > \nu_2 > \nu_1$, the corresponding 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, 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

(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

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 = hν, 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 hν 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.

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 $10^{-19}\ \mathrm{m}^2$. Find the intensity of illumination in order to see the photoelectric effect

Sol. Rate of absorption of energy is power $P = \frac{E}{t} = \frac{5\times10^{-19}}{10^{-9}} = 5 \times 10^{-10} \frac{J}{s}$

From the definition of intensity of light $I = \frac{\text{Power}}{\text{Area}} = \frac{5\times10^{-10}}{10^{-19}} = 5 \times 10^{9} \frac{\mathrm{J}}{\mathrm{s}.m^2}$

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 $10^{-5}\ \mathrm{W\ m^{-2}}$ is incident on $2\ \mathrm{cm}^2$ 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

Sol. Intensity of incident light is $10^{-5}\ \mathrm{W\ m^{-2}}$

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

$E = 10^{-5} \times 2 \times 10^{-4} \times 1 = 2 \times 10^{-9}\ \mathrm{J}$

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

Q. Light of frequency 1.5 times the threshold frequency is incident on a photosensitive material. What will be the photoelectric current if the frequency is halved and intensity is doubled?

Sol. Initially, υ = 1.5 υ_0

If the frequency is halved, υ' = $\frac{\upsilon}{2} = \frac{1.5\,\upsilon_0}{2} < \upsilon_0$

Hence, no photoelectric emission will take place

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 hv 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

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

If the electron does not lose energy by internal collisions, as it escapes from the metal, the entire energy $(hv - \phi_0)$ will be exhibited as the kinetic energy of the electron.

Thus, $(hv - \phi_0)$ 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

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

This equation is known as Einstein's photoelectric equation.

When the frequency (v) of the incident radiation is equal to the threshold frequency (v_0) of the metal surface, kinetic energy of the

electron is zero. Then equation (1) becomes,

$hv_o = \phi_0 \ldots (2)$

Substituting the value of W in equation (1) we get,

$hv - hv_0 = \frac{1}{2}mv_{\max}^2 - -(3)$

Or $\mathrm{K_{max}} = \mathrm{hv} - \phi_0$ or $\mathrm{eV_o} = \mathrm{hv} - \phi_0 - -(4)$

This is another form of Einstein's photoelectric equation.

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

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

Particle Nature of Light: The Photon

In interaction of radiation with matter, radiation behaves as if it is made up of particles called photons. (ii) Each photon has energy E (=hv) and momentum p (= hv/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 (=hν = hc/λ) and momentum p (= hν/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

De Broglie's Wavelength of Matter Waves

de Broglie equated the energy equations of Planck (wave) and Einstein (particle). For a wave of frequency v, the energy associated with each photon is given by Planck's relation, $E = h$ ν

where h is Planck's constant.

According to Einstein's mass energy relation, a mass m is equivalent to energy,

$E = mc^2$

where c is the velocity of light.

If, $hv = mc^2$

$\therefore \frac{hc}{\lambda} = mc^2$ or $\lambda = \frac{h}{mc}$

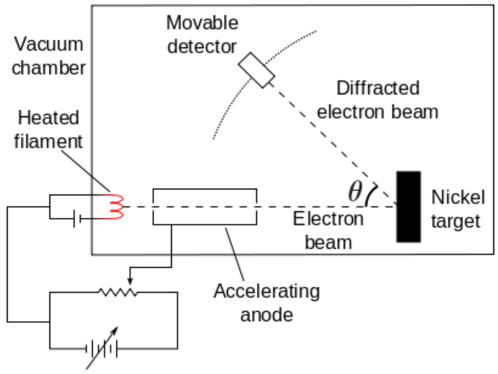
For a particle moving with a velocity v, if $c = v$

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

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

Davisson And Germer Experiment

This experiment gave the first experimental evidence for the wave nature of slow electrons. Later on, it was shown that all material particles in motion behave as waves.



Q. An electron is at a distance of $10\ \mathrm{m}$ from a charge of $10\mathrm{C}$. Its total energy is $15.6 \times 10^{-10}\ \mathrm{J}$. Find its de Broglie wavelength at this point $\mathrm{m_e} = 9.1 \times 10^{-31}\ \mathrm{kg}$

Sol. Potential energy of an electron

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

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

$U = -14.4 \times 10^{-10}\ \mathrm{J}$

Total energy = Kinetic energy (K) + Potential energy

$\mathrm{K = E - U}$

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

But,

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

$p = \sqrt{2Km_e}$

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

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

$\lambda = 8.97 \times 10^{-15}\ \mathrm{m}.$

SUMMARY

- **Electric Discharge:**
The passage of an electric current through a gas is called electric discharge.
- **Discharge Tube:**
A hard glass tube along with the necessary arrangement, which is used to study the passage of electric discharge through gases at low pressure, is called a discharge tube.
- **Cathode Rays:**
Cathode rays are the stream of negatively charged particles, electrons which are shot out at a high speed from the cathode of a discharge tube at pressure below 0.01 mm of Hg.
- **Work Function:**
The minimum amount of energy required by an electron to just escape from the metal surface is known as work function of the metal.
$W_0 = \Phi_0 = hv_0$
- **Electron Emission:**
The minimum amount of energy required by an electron to just escape from the metal surface is known as work function of the metal.
- **Thermionic Emission:**
Here electrons are emitted from the metal surface with the help of thermal energy.
- **Field or Cold Cathode Emission:**
Electrons are emitted from a metal surface by subjecting it to a very high electric field.
- **Photoelectric Emission:**
Electrons emitted from a metal surface with the help of suitable electromagnetic
radiations.
- **Secondary Emission:**
Electrons are ejected from a metal surface by striking over its fast-moving electrons.
- **Forces Experienced by an Electron in Electric and Magnetic Fields:**
  (a) **Electric field:** The force FE experienced by an electron e in an electric field of strength (intensity) E is given by, FE = eE
  (b) **Magnetic field:** The force experienced by an electron e in a magnetic field of strength B weber/m^2 is given by FB=Bev

  where v is the velocity with which the electron moves in the electric field and the magnetic field, perpendicular to the direction of motion.
  (c) If the magnetic field is parallel to the direction of motion of electron, then, FB = 0.
- **Photoelectric Effect:**
The phenomenon of emission of electrons from the surface of substances (mainly metals), when exposed to electromagnetic radiations of suitable frequency, is called photoelectric effect and the emitted electrons are called photoelectrons.
- **Maximum K. E of the Photoelectrons Emitted from the Metal Surface:**
$K_{max} = eV_0\ hv - \Phi$ (Einstein's Photoelectric equation)
- **Cut Off or Stopping Potential:**
The value of the retarding potential at which the photoelectric current becomes zero is called cut off or stopping potential for the given frequency of the incident radiation.
- **Threshold Frequency:**
The minimum value of the frequency of incident radiation below which the photoelectric emission stops altogether is called threshold frequency.
- **Laws of Photoelectric Effect:**
  (a) For a given metal and a radiation of fixed frequency, the number of photoelectrons emitted is proportional to the intensity of incident radiation.
  (b) For every metal, there is a certain minimum frequency below which no photoelectrons are emitted, howsoever high is the intensity of incident radiation. This frequency is called threshold frequency.
  (c) For the radiation of frequency higher than the threshold frequency, the maximum kinetic energy of the photoelectrons is directly proportional to the frequency of incident radiation and is independent of the intensity of incident radiation.
  (d) The photoelectric emission is an instantaneous process.
- **Einstein's Theory of Photoelectric Effect:**
  (a) Einstein explained photoelectric effect with the help of Planck's quantum theory.
  (b) When a radiation of frequency v is incident on a metal surface, it is absorbed in the form of discrete packets of energy called quanta or photons.
  (c) A part of energy hv of the photon is used in removing the electrons from the metal surface and remaining energy is used in giving kinetic energy to the photoelectron.
  (d) Einstein's photoelectric equation is,
  $KE = \frac{1}{2}mv^2 = hv - w_0$
  Where w_0 is the work function of the metal.
  (e) If v_0 is the threshold frequency, then $w_0 = hv_0$
  $KE = \frac{1}{2}mv^2 = h(v - v_0)$
  (f) All the experimental observations can be explained on the basis Einstein's photoelectric equation.
- **Compton Shift:**

It is the phenomenon of increase in the wavelength of X-ray photons which occurs when these radiations are scattered on striking an electron. The difference in the wavelength of scattered and incident photons is called Compton shift, which is given by

$$\Delta\lambda = \frac{h}{m_0 C}(1-\cos\phi)$$

Where Φ is the angle of scattering of the X-ray photon and m_0 is the rest mass of the electron.

- **Charge and Mass of an Electron by Thompson's Method:**
  (a) J. J. Thomson devised an experiment to determine the velocity (v) and the ratio of the charge (e) to the mass (m) i.e., $\frac{e}{m}$ of cathode rays.
  (b) In this method, electric field $\vec{E}$ and magnetic field $\vec{B}$ are applied on the cathode rays.
  (c) In the region where they are applied perpendicular to each other and to the direction of motion of cathode rays, Force due to electric field, FE = Force due to magnetic field FB,

$$eE = Bev \Rightarrow V = \frac{E}{B}$$

Also,

$$\frac{e}{m} = \frac{E}{B^2 R} = \frac{V/d}{B^2 R} = \frac{Vx}{B^2 lLd}$$

Where V = Potential difference between the two electrodes (i.e., P and Q), d = distance between the two electrodes, R = radius of circular arc in the presence of magnetic field B, x = shift of the electron beam on the screen, *l* = length of the field and L = distance between the centre of the field and the screen.

- **Milliken's Oil Drop Method:**
  (a) This method helps to determine the charge on the electron.
  (b) Let ρ be the density of oil, σ is the density of the medium in which oil drop moves and η the coefficient of viscosity of the medium, then the radius r of the drop is

$$r = \sqrt{\frac{9}{2}\frac{\eta V_0}{(\rho-\sigma)g}}$$

Where v_0 is the terminal velocity of the drop under the effect of gravity alone.

  (c) At the terminal velocity v0, the force due to viscosity becomes equal to the electric weight of the body.
  (d) The charge on oil drop is

$$q = \frac{18\pi\eta(V_1+V_0}{E}\sqrt{\frac{\eta V_0}{2(\rho-\sigma)g}}$$

Where v_1 is the terminal velocity of the drop under the influence of electric field and gravity and E is the applied electric field.

- **Photocell:**
  (a) It is an arrangement which converts light energy into electric energy.
  (b) It works on the principle of photoelectric effect.
  (c) It is used in cinematography for the reproduction of sound.
- **Dual Nature of Radiation:**
  Light has dual nature. It manifests itself as a wave in diffraction, interference, polarization, etc., while it shows particle nature in photoelectric effect, Compton scattering, etc.
- **Dual Nature of Matter:**
  (a) As there is complete equivalence between matter (mass) and radiation (energy) and the principle of symmetry is always obeyed, de Broglie suggested that moving particles like protons, neutrons, electrons, etc., should be associated with waves known as de Broglie waves and their wavelength is called de Broglie wavelength.
  (b) The de Broglie wavelength of a particle of mass m moving with velocity v is given by,

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

Where h is Planck's constant.

- **Davison and Germer Experiment:**
  This experiment help to confirm the existence of de Broglie waves associated with electrons.
- **De Broglie Wavelength of an Electron:**
  The wavelength associated with an electron bean accelerated through a potential.

$$\lambda = \frac{h}{\sqrt{2meV}} = \frac{12.3}{\sqrt{V}} \overset{0}{A}$$

- de Broglie wavelength associated with the particle of momentum p is,

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

$$\lambda = \frac{1.22}{\sqrt{V}} nm$$

Where V is the magnitude of accelerating potential.

- **Heisenberg Uncertainty Principle:**
  $\Delta x.\Delta p \approx h / 2\pi$
  Where Δx is uncertainty in position & Δp is uncertainty in momentum
- **Electron Microscope:**
  (a) It is a device which makes use of accelerated electron beams to study very minute objects like viruses, microbes and the crystal structure of solids.
  (b) It has a magnification of ~10^5

MIND MAP

Dual Nature of Radiation & Matter

Dual Nature of Radiation

- Light has both wave character as well as particle
- Interference explained by wave nature
- When light of sufficiently low wavelength, it behaves as a particle
- Light particle having definite energy and definite linear momentum called "photon" or Energy packets.

Energy of each photon = $h\nu = hc/\lambda$

Momentum of each photon = $h/\lambda = E/c$

Contribution

Einstein, after an average academic career put forward quantum theory of light in 1905 while working as a grade III technical officer in a patent office

Matter waves

All matter can exhibit wave–like behaviour e.g. beam of electrons can be diffracted like water wave

de - Broglie relation

$\lambda = h/p$

λ = wavelength associated with particle or de-Broglie wavelength

p = momentum

$$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2\,m\,K_{max}}}$$

Davisson–Germer Experiment

A beam of electrons emitted by electron gun is made to fall on nickel crystal cut along cubical axis at a particular angle .Scattered beam of electrons is received by detector.

Results : λ = de Broglie's wavelength

$= h/p$

$= 1227/\sqrt{v}$ nm

$= 1227/\sqrt{54}$ nm

$= 0.167$ nm $= 1.67$ A°

This experiment verifies the wave nature of electrons & relation with de-Broglie wavelength.

Photoelectric Effect

- When light of sufficiently small wavelength is incident on metal surface, electrons are ejected from the metal, the phenomenon is called photoelectric effect.
- Ejected electrons are called photoelectrons
- Minimum energy equal to work function (ϕ) must be given to an electron so as to bring it out of the metal

Einstein's Photoelectric equation

- $K_{max} = E - \phi = eV_0$

  $= \frac{hc}{\lambda} - \phi$, V_0 = stopping potential

  K_{max} = maximum kinetic energy of elected electrons

Hore, $\lambda_0 = hc/\phi$

λ_0 = Threshold Wavelength

$\lambda_0 = c/\lambda_0 = \phi/h$

λ_0 = Threshold frequency

$K_{max} = \lambda(\nu - \nu_0)$

- If $\lambda = \lambda_0 = hc/\phi$

  $K_{max} = 0$, *i.e.*

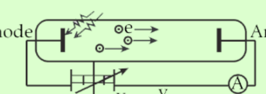
  Electron may just come out.
- If $\lambda > \lambda_0$

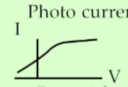
  i.e. $E < \phi$

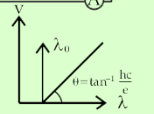
  no electron will come out
- If $\lambda \le \lambda_0$.

  Photoelectric effect takes place this λ_0
- λ_0 = depends on metal used

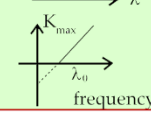
Hertz and Lenard's Observation







$eV_0 = K_{max} = \frac{he}{\lambda} - 4$



PRACTICE EXERCISE

MCQ

Q1. A beam of cathode rays is subjected to crossed electric (E) and magnetic fields (B). The fields are adjusted such that the beam is not deflected. The specific charge of the cathode rays is given by

(a) $\frac{B^2}{2VE^2}$ (b) $\frac{2VB^2}{E^2}$

(c) $\frac{2VE^2}{B^2}$ (d) $\frac{E^2}{2VB^2}$

Q2. A particle of mass 1 mg has the same wavelength as an electron moving with a velocity of 3 $\times$ 10^6 ms^{-1}. The velocity of the particle is:

(a) 2.7 $\times$ 10^{-18} ms^{-1} (b) 9 $\times$ 10^{-2} ms^{-1}

(c) 3 $\times$ 10^{-31} ms^{-1} (d) 2.7 $\times$ 10^{-21} ms^{-1}

Q3. J.J. Thomson's cathode-ray tube experiment demonstrated that

(a)cathode rays are streams of negatively charged ions

(b)all the mass of an atom is essentially in the nucleus

(c)the e/m of electrons is much greater than the e/m of protons

(d)the e/m ratio of the cathode-ray particles changes when a different gas is placed in the discharge tube

Q4. An electron of mass m and a photon have same energy E. The ratio of de-Broglie wavelengths associated with them is:

(a) $\frac{1}{c}\left(\frac{E}{2m}\right)^{\frac{1}{2}}$ (b) $\left(\frac{E}{2m}\right)^{\frac{1}{2}}$

(c) $\left(\frac{E}{2m}\right)^{\frac{1}{2}}$ (d) $\frac{1}{c}\left(\frac{2m}{E}\right)^{\frac{1}{2}}$

Q5. The maximum kinetic energy of the electrons hitting a target so as to produce X-ray of wavelength 1 Å is

(a) 1.24 keV (b) 12.4 keV

(c) 124 keV (d) None of these

Q6. A and B are two metals with threshold frequencies 1.8 $\times$ 10^{-14} Hz and 2.2 $\times$ 10^{14} Hz. Two identical photons of energy 0.825 eV each are incident on them. Then photoelectrons are emitted in (Take h = 6.6 $\times$ 10^{-34} Js)

(a) B alone (b) A alone

(c) neither A or B (d) both A and B.

Q7. Which of the following when falls on a metal will emit photoelectrons?

(a) UV radiations (b) Infrared radiation

(c) Radio waves (d) Microwaves

Q8. A material particle with a rest mass m_0 is moving with speed of light c. The de-Broglie wavelength associated is given by

(a) $\frac{h}{m_0 c}$ (b) $\frac{m_0 c}{h}$

(c) zero (d) ∞

Q9. A 200 W sodium street lamp emits yellow light of wavelength 0.6 μm. Assuming it to be 25% efficient in converting electrical energy to light, the number of photons of yellow light it emits per second is

(a) 1.5 $\times$ 10^{20} (b) 6 $\times$ 10^{18}

(c) 62 $\times$ 10^{20} (d) 3 $\times$ 10^{19}

Q10. Which metal will be suitable for photoelectric cell using light of wavelength 4000Å. The work functions of sodium and copper are respectively 2.0 eV and 4.0 eV.

(a) Sodium (b) Copper

(c) Both (d) None of these

Q11. The maximum velocity of an electron emitted by light of wavelength λ incident on the surface of a metal of work-function Φ is

(a) $\sqrt{\frac{2(hc+\lambda\phi)}{m\lambda}}$ (b) $\frac{2(hc+\lambda\phi}{m\lambda}$

(c) $\sqrt{\frac{2(hc+\lambda\phi)}{m\lambda}}$ (d) $\sqrt{\frac{2(2\lambda-\phi)}{m}}$

Q12. Monochromatic radiation emitted when electron on hydrogen atom jumps from first exited to the ground state irradiates a photosensitive material. The stopping potential is measured to be 3.57 V. The threshold frequency of the materials is:

(a) 4 $\times$ 10^{15} Hz

(b) 5 $\times$ 10^{15} Hz

(c) 1.6 $\times$ 10^{15} Hz

(d) 2.5 $\times$ 10^{15} Hz

Q13. A source of light is placed at a distance of 50 cm from a photo cell and the stopping potential is found to be V_0. If the distance between the light source and photo cell is made 25 cm, the new stopping potential will be :

(a) $V_0/2$ (b) V_0

(c) $4V_0$ (d) $2V_0$

Q14. A photoelectric cell is illuminated by a point source of light 1 m away. When the source is shifted to 2 m then

(a) each emitted electron carries one quarter of the initial energy

(b) number of electrons emitted is half the initial number

(c) each emitted electron carries half the initial energy

(d) number of electrons emitted is a quarter of the initial number.

Q15. If the kinetic energy of the particle is increased to 16 times its previous value, the percentage change in the de Broglie wavelength of the particle is

(a) 25 (b) 75

(c) 60 (d) 50

Q16. If particles are moving with same velocity, then which has maximum de Broglie wavelength?

(a) proton

(b) α-particle

(c) neutron

(d) β-particle

Q17. In the Davisson and Germer experiment, the velocity of electrons emitted from the electron gun can be increased by

(a) increasing the potential difference between the anode and filament
(b) increasing the filament current
(c) decreasing the filament current
(d) decreasing the potential difference between the anode and filament

Q18. An electron of mass m, when accelerated through a potential difference V, has de Broglie wavelength λ. The de Broglie wavelength associated with a proton of mass M accelerated through the same potential difference, will be

(a) $\lambda \frac{M}{m}$ (b) $\lambda \frac{m}{M}$
(c) $\lambda \sqrt{\frac{M}{m}}$ (d) $\lambda \sqrt{\frac{m}{M}}$

Q19. Light of wavelength 500 nm is incident on a metal with work function 2.28 eV. The de Broglie wavelength of the emitted electron is

(a) $\geq 2.8 \times 10^{-9}$ m (b) $\leq 2.8 \times 10^{-12}$ m
(c) $< 2.8 \times 10^{-10}$ m (d) $< 2.8 \times 10^{-9}$ m

Q20. If a photon has velocity c and frequency υ, then which of the following represents its wavelength?

(a) $\frac{h\upsilon}{c^2}$ (b) $h\upsilon$
(c) $\frac{hc}{E}$ (d) $\frac{h\upsilon}{c}$

Q21. When a metallic surface is illuminated with radiation of wavelength λ, the stopping potential is V. If the same surface is illuminated with radiation of wavelength 2λ, the stopping potential is $\frac{V}{4}$. The threshold wavelength for the metallic surface is

(a) $\frac{5}{2}\lambda$ (b) 3λ
(c) 4λ (d) 5λ

ASSERTION AND REASONING

Directions : Each of these questions contain two statements, Assertion and Reason. Each of these questions also has four alternative choices, only one of which is the correct answer. You have to select one of the codes (a), (b), (c) and (d) given below.

(a) Assertion is correct, reason is correct; reason is a correct explanation for assertion.
(b) Assertion is correct, reason is correct; reason is not a correct explanation for assertion
(c) Assertion is correct, reason is incorrect
(d) Assertion is incorrect, reason is correct

Q1. Assertion : Mass of moving photon varies directly as the wavelength.
Reason: Energy of the particle = Mass × $(\text{Speed of light})^2$

Q2. Assertion**:** Photosensitivity of a metal is large if its work function is small.
Reason**:** Work function = hf_0 where f_0 is the threshold frequency.

Q3. Assertion : In process of photoelectric emission, all emitted electrons do not have same kinetic energy.
Reason : If radiation falling on photosensitive surface of a metal consists of different wavelength then energy acquired by electrons absorbing photons of different wavelengths shall be different

Q4. Assertion**:** The de-Broglie wavelength of a molecule varies inversely as the square root of temperature.
Reason**:** The root mean square velocity of the molecule is proportional to square root of absolute temperature

Q5. Assertion: Though light of a single frequency (monochromatic) is incident on a metal, the energies of emitted photoelectrons are different.
Reason : The energy of electrons emitted from inside the metal surface, is lost in collision with the other atoms in the metal.

SHORT ANSWER QUESTIONS

Q1. Do all the electrons that absorb a photon come out as photoelectrons?

Q2. There are materials which absorb photons of shorter wavelength and emit photons of longer wavelength. Can there be stable substances which absorb photons of larger wavelength and emit light of shorter wavelength?

Q3. In photoelectric effect, why should the photoelectric current increase as the intensity of monochromatic radiation incident on a photosensitive surface is increased? Explain.

Q4. Define the term 'threshold frequency' in relations to photoelectric effects.

NUMERICAL TYPE QUESTIONS

Q1. The momentum of a photon of an electromagnetic radiation is 3.3×10^{-29} kg m s^{-1}. What is the frequency of the associated waves? [h = 6.6×10^{-34} J s ; c = 3×10^{8} m s^{-1}]

Q2. When light of wavelength 300 nm (nanometer) falls on a photoelectric emitter, photoelectrons are liberated. For another emitter, however, light of 600 nm wavelength is sufficient for creating photoemission. What is the ratio of the work functions of the two emitters?

Q3. The wavelength of a 1 keV photon is 1.24×10^{-9} m. What is the frequency of 1 MeV photon?

Q4. The photoelectric threshold wavelength of silver is 3250 $\times 10^{-10}$ m. Then find the velocity of the electron ejected from a silver surface by ultraviolet light of wavelength 2536×10^{-10} m . [Given h = 4.14×10^{-15} eV s and c = 3 $\times 10^{8}$ m s^{-1}]

Q5. A particle of mass 1 mg has the same wavelength as an electron moving with a velocity of 3 × 10^6 m s^{-1}. Then determine the velocity of the particle.

Q6. An electron beam has a kinetic energy equal to 100 eV. Find its wavelength associated with a beam, if mass of electron = 9.1 × 10^{-31} kg and 1 eV = 1.6 × 10^{-19} J. (Planck's constant = 6.6 × 10^{-34} Js)

Q7. Two radiations of photons energies 1 eV and 2.5 eV, successively illuminate a photosensitive metallic surface of work function 0.5 eV. Then what will be the ratio of the maximum speeds of the emitted electrons.

Q8. The specific charge of a proton is 9.6 $\times 10^7$ C kg^{-1}. Then determine the specific charge of an α-particle.

Q9. The work function of platinum is 6.35 eV. Then find threshold frequency of platinum.

Q10. The work function of a photosensitive material is 4.0 eV. Find this longest wavelength of light which can cause photon emission from the substance.

HOMEWORK EXERCISE

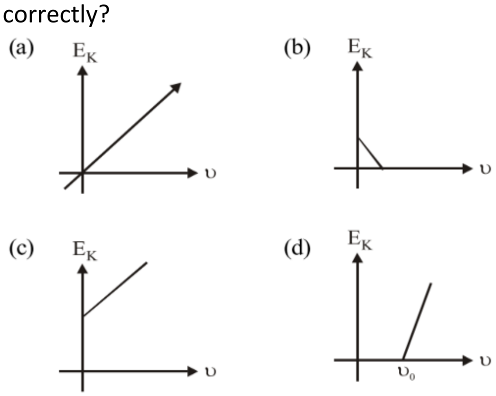
MCQ

Q1. Which of the following is not the property of cathode rays ?
(a) It produces heating effect.
(b) It does not deflect in electric field.
(c) It casts shadow.
(d) It produces fluorescence.

Q2. When the energy of the incident radiation is increased by 20%, the kinetic energy of the photoelectrons emitted from a metal surface increased from 0.5 eV to 0.8 eV. The work function of the metal is:
(a) 0.65 eV (b) 1.0 eV
(c) 1.3 eV (d) 1.5 eV

Q3. In photoelectric effect, stopping potential for a light of frequency n_1 is V_1. If light is replaced by another having a frequency n_2 then its stopping potential will be
(a) $V_1 - \frac{h}{e}(n_2 - n_1)$ (b) $V_1 + \frac{h}{e}(n_2 + n_1)$
(c) $V_1 + \frac{h}{e}(n_2 - n_1)$ (d) $V_1 + \frac{h}{e}(n_2 - 2n_1)$

Q4. Which one of the following graphs represents the variation of maximum kinetic energy (E_K) of the emitted electrons with frequency υ in photoelectric effect correctly?

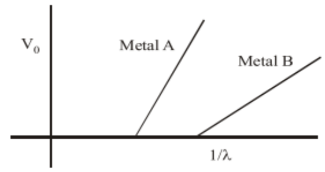


Q5. Electrons used in an electron microscope accelerated by a voltage of 25 kV. If the voltage is increased to 100kV then the de-Broglie wavelength associated with the electrons would
(a) increase by 2 times (b) decrease by 2 times
(c) decrease by 4 times (d) increase by 4 times

Q6. Which of the following is/are false regarding cathode rays?
(a) They produce heating effect
(b) They don't deflect in electric field
(c) They cast shadow
(d) They produce fluorescence

Q7. The ratio of the respective de Broglie wavelength associated with electrons accelerated from rest with the voltages 100 V, 200 V and 300 V is
(a) 1:2:3 (b) 1:4:9
(c) $1:\frac{1}{\sqrt{2}}:\frac{1}{\sqrt{3}}$ (d) $1:\frac{1}{2}:\frac{1}{3}$

Q8. In an experiment on photoelectric effect, a student plots stopping potential V_0 against reciprocal of the wavelength ʎ of the incident light for two different metals A and B. These are shown in the figure.



Looking at the graphs, you can most appropriately says that:
(a) Work function of metal B is greater than that of metal A
(b) For light of certain wavelength falling on both metal, maximum kinetic energy of electrons emitted from A will be greater than those emitted from B.
(c) Work function of metal A is greater than that of metal B
(d) Student data is not correct

Q9. White X-rays are called white due to the fact that
(a) they are electromagnetic radiations having nature same as that of white light.
(b) they are produced most abundantly in X ray rubes.
(c) they have a continuous wavelength range.
(d) they can be converted to visible light using coated screens and photographic plates are affected by them just like light.

Q10. The wavelength associated with an electron, accelerated through a potential difference of 100 V, is of the order of
(a) 1000 Å (b) 100 Å
(c) 10.5 Å (d) 1.2 Å

Q11. Monochromatic light of frequency 6.0×10^{14} Hz is produced by a laser. The power emitted is 2×10^{-3} w. The number of photons emitted, on the average, by the sources per second is
(a) 5×10^{16} (b) 5×10^{17}
(c) 5×10^{14} (d) 5×10^{15}

ASSERTION AND REASONING

Directions : Each of these questions contain two statements, Assertion and Reason. Each of these questions also has four alternative choices, only one of which is the correct answer. You have to select one of the codes (a), (b), (c) and (d) given below.
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(b) Assertion is correct, reason is correct; reason is not a correct explanation for assertion
(c) Assertion is correct, reason is incorrect

(d) Assertion is incorrect, reason is correct

Q1. Assertion : Two photons of equal wavelength must have equal linear momentum.
Reason : Two photons of equal linear momentum will have equal wavelength

Q2. Assertion : Two sources of equal intensity always emit equal number of photons in any time interval.
Reason : Two sources of equal intensity may emit equal number of photons in any time interval.

Q3. Assertion : Photosensitivity of a metal is high if its work function is small.
Reason : Work function = hf_0 where f_0 is the threshold frequency.

Q4. Assertion : Photoelectric saturation current increases with the increase in frequency of incident light.
Reason : Energy of incident photons increases with increase in frequency and as a result photoelectric current increases.

Q5. Assertion : The photoelectrons produced by a monochromatic light beam incident on a metal surface have a spread in their kinetic energies.
Reason : The work function of the metal is its characteristics property.

SHORT ANSWER QUESTIONS

Q1. What is meant by work function of a metal? How does the value of work function influence the kinetic energy of electrons liberated during photoelectron emission?

Q2. Write three characteristic features in photoelectric effect which cannot be explained on the basis of wave theory of light, but can be explained only using Einstein's equation.

Q3. Work function of aluminum is 4.2 eV. If two photons, each of energy 2.5 eV, are incident on its surface, will the emission of electrons take place? Justify your answer.

NUMERICAL TYPE QUESTIONS

Q1. If velocity of a proton is c/20 then find the associated de-Broglie wavelength. (Take $h = 6.626 \times 10^{-34}$ J-s)

Q2. The work function for the surface of aluminum is 4.2 eV. What will be the wavelength of that incident light for which the stopping potential will be zero.
$(h \approx 6.6 \times 10^{-34}\ \mathrm{J-s}\ e \approx 1.6 \times 10^{-19}\ \mathrm{C})$

Q3. The separation between Bragg's planes in a crystal is 10 Å. Then find the wavelength of those X-rays which can be diffracted by this crystal.

Q4. An electromagnetic radiation of frequency 3 × 10^{15} cycles per second falls on a photo electric surface whose work function is 4.0 eV. Find out the maximum velocity of the photo electrons emitted by the surface.

Q5. Light of wavelength 3320 Å is incident on metal surface (work function = 1.07 eV). To stop emission of photo electron, find required retarding potential.
(Take $hc \approx 12420\ \mathrm{eV - Å}$)

Q6. When the light of frequency $2\upsilon_0$ (where υ_0 is threshold frequency), is incident on a metal plate, the maximum velocity of electrons emitted is υ_1. When the frequency of the incident radiation is increased to $5\upsilon_0$, the maximum velocity of electrons emitted from the same plate is υ_2. Then find the ratio of υ_1 to υ_2.

Q7. Find the
(a) maximum frequency and
(b) minimum wavelength of X-rays produced by 30 kV electrons.

Q8. There are two sources of light, each emitting with a power 100W. One emits X-rays of wavelength $1\ \mathrm{nm}$ and the other visible light at $500\ \mathrm{nm}$. Find the ratio of number of photons of X-rays the photons of visible light of the given wavelength.

Q9. A 200 W sodium street lamp emits yellow light of wavelength 0.6 µm. Assuming it to be 25% efficient in converting electrical energy to light, then find the number of photons of yellow light it emits per second.

Q10. Monochromatic radiation emitted when electron on hydrogen atom jumps from first excited to the ground state irradiates a photosensitive material. The stopping potential is measured to be 3.57 V. Then determine the threshold frequency of the materials

PRACTICE EXERCISE SOLUTIONS

MCQ

S1. (d) When a beam of cathode rays (or electrons) is subjected to crossed electric (E) and magnetic (B) fields, the beam is not deflected, if

Force on electron due to magnetic field = Force on electron due to electric field

$Bev = eV$ or $v = \frac{E}{B}$ ...(i)

If V is the potential difference between the anode and the cathode, then

$\frac{1}{2}mv^2 = eV$ or $\frac{e}{m} = \frac{v^2}{2V}$ ...(ii)

Substituting the value of v from equation (i) in equation (ii), we get

$\frac{e}{m} = \frac{E^2}{2VB^2}$

Specific charge of the cathode rays $\frac{e}{m} = \frac{E^2}{2VB^2}$

S2. (d) Wavelength of particle $(\lambda_1) = \frac{h}{mv} = \frac{h}{(1\times10^{-3})\times v}$ where *v* is the velocity of the particle. Wavelength of electron

$(\lambda_1) = \frac{h}{(9.1\times10^{-31})\times(3\times10^6)}$

But $\lambda_1 = \lambda_2$

$\therefore \frac{h}{(1\times10^{-3})\times v} = \frac{4}{(9.1\times10^{-31})\times(3\times10^6)}$

$\Rightarrow v = \frac{9.1\times10^{-31}\times3\times10^6}{10^{-13}}$

= 2.73 $\times$ 10^{-21} ms^{-1}

S3. (c) J.J. Thomson performed cathode ray experiment and concluded that some particles move from cathode plate to anode plate. Since the cathode is negatively charged, so cathode-ray must contain a negatively charged particle called electron.

S4. (a) For electron De-Broglie wavelength,

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

For photon E = pc

$\Longrightarrow$ De-Broglie wavelength, $\lambda_{Ph} = \frac{hc}{E}$

$$\therefore \frac{\lambda_e}{\lambda_{Ph}} = \frac{h}{\sqrt{2mE}} \times \frac{E}{hc} = \left(\frac{E}{2m}\right)^{1/2} \frac{1}{c}$$

S5. (b)

$\lambda_{\min} = 1$Å (given)

$\because \lambda \frac{1240}{E}(eV)(nm)_{min}$

Thus, E $\frac{1240(eV)(nm)}{0.01(nm)} = 12400eV$

E = 12.4 KeV

S6. (b) Photoelectrons are emitted in A alone. Energy of electron needed if emitted from $A = \frac{hv}{e}eV$

$\therefore E_A = \frac{(6.6\times10^{-34})\times(1.8\times10^{14})}{1.6\times10^{-19}} = 0.74eV$

$E_B = \frac{(6.6\times10^{-34})\times(2.2\times10^{14})}{1.6\times10^{-19}} = 0.91eV$

Incident energy 0.825 eV is greater than E_A (0.74 eV) but less than E_B (0.91 eV).

S7. (a) Emission of electron from a substance under the action of light is photoelectric effect. Light must be at a sufficiently high frequency. It may be visible light, U.V., X-rays. So U.V. cause electron emission.

S8. (c) $\lambda = \frac{h}{mv}, v = \frac{m_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} v \to c, m \to \infty$

Hence, $\lambda \to 0$

S9. (a) Given that, only 25% of 200W converter electrical energy into light of yellow color

$$\left(\frac{hc}{\lambda}\right)\times N = 200\times\frac{25}{100}$$

Where *N* is the No. photons emitted per second, *h* is Planck's constant and *c* is speed of light.

$$N = \frac{200\times25}{100}\times\frac{\lambda}{hc}$$

$$= \frac{200\times25\times0.6\times10^{-6}}{100\times6.2\times10^{-34}\times3\times10^{8}} = 1.5\times10^{20}$$

S10. (a)

$$\because \lambda_0 = \frac{hc}{\phi}$$

$$\Rightarrow n = \frac{p}{hv} = \frac{2\times10^{-3}}{6.6\times10^{-34}\times6\times10^{14}} = 5\times10^{15}$$

$$\because \lambda_0 \propto \frac{1}{\phi} \Rightarrow \frac{(\lambda_0)sodium}{(\lambda_0)copper} = \frac{(\phi)copper}{(\phi)sodium}$$

$$\Rightarrow (\lambda_0)_{copper} = \frac{2}{4}\times6188 = 3094 \text{ Å}$$

The eject photo-electrons from sodium the longest wavelength is 6188 Å and that for copper is 3094 Å, sodium is suitable.

S11.(c) $\frac{1}{2}mv^2 = \frac{hc}{\lambda} - \phi \Rightarrow v = \sqrt{\frac{2(hc-\lambda\phi)}{\lambda m}}$

S12.(c) $n \to 2-1$

$E = 10.2eV$

$kE = E - \phi$

$Q = 10.20 - 3.57$

$hv_0 = 6.63eV$

$v_0 = \frac{6.63\times1.6\times10^{-19}}{6.67\times10^{-34}} = 1.6\times10^{15}Hz$

S13. (b) By changing the position of source of light from photo cell, there will be a change in the intensity of light falling on photo cell.
As stopping potential is independent of the intensity of the incident light, hence stopping potential remains same *i.e.*, V_0.

S14. (d) Photoelectric current $I \propto$ intensity of light and intensity $\propto \frac{1}{(\text{distance})^2}$

$\therefore I \propto \frac{1}{(\text{distance})^2}$

S15. (b) de Broglie wavelength,

$\lambda = \frac{h}{\sqrt{2mK}}$ ...(i)

where m is the mass and K is the kinetic energy of the particle.
When kinetic energy of the particle is increased to 16 times, then its de Broglie wavelength becomes,

$\lambda' = \frac{h}{\sqrt{2m(16K)}} = \frac{1}{4}\frac{h}{\sqrt{2mK}} = \frac{\lambda}{4}$ (Using (i))

% change in the de Broglie wavelength

$= \frac{\lambda - \lambda'}{\lambda} \times 100 = \left(1 - \frac{\lambda'}{\lambda}\right) \times 100 = \left(1 - \frac{1}{4}\right) \times 100 =$ 75%

S16. (d) de Broglie wavelength for a particle is given by $\lambda = \frac{h}{p} = \frac{h}{mv}$, where m, v and p are the mass, velocity and momentum respectively. h is Planck's constant. Now, since all the particles are moving with same velocity, the particle with least mass will have maximum de-Broglie wavelength. Out of the given four particles (proton, neutron, α-particles, *i.e.*, He nucleus and β-particles, *i.e.*, electrons) β-particle has the lowest mass and therefore it has maximum wavelength.

S17. (a) The velocity of electrons emitted from the electron gun can be increased by increasing the potential difference between the anode and filament.

S18. (d) Momentum of electrons,

$(p_e) = \sqrt{2meV}$

Momentum for proton $(p_p) = \sqrt{2MeV}$

Therefore, $\frac{\lambda_p}{\lambda_e} = \frac{h/p_p}{h/p_e} = \frac{p_e}{p_p} = \frac{\sqrt{2meV}}{\sqrt{2MeV}} = \sqrt{\left(\frac{m}{M}\right)}$

Therefore, $\lambda_p = \lambda\sqrt{\left(\frac{m}{M}\right)}$

S19. According to Einstein's photoelectric equation, the maximum kinetic energy of the emitted electron is

$K_{\max} = \frac{hc}{\lambda} - \phi_0$

where λ is the wavelength of incident light and ϕ_0 is the work function.

Here, λ = 500 nm, hc = 1240 eV nm and ϕ_0 = 2.28 eV

$\therefore\ K_{\max} = \frac{1240 \text{ eV nm}}{500 \text{ nm}} - 2.28 \text{ eV}$

$= 2.48 \text{ eV} - 2.28 \text{ eV} = 0.2 \text{ eV}$

The de Broglie wavelength of the emitted electron is

$\lambda_{\min} = \frac{h}{\sqrt{2mK_{\max}}}$

where h is the Planck's constant and m is the mass of the electron.

As $h = 6.6 \times 10^{-34}$ J s, $m = 9 \times 10^{-31}$ kg

and $K_{\max} = 0.2 \text{ eV} = 0.2 \times 1.6 \times 10^{-19}$ J

$\therefore \lambda_{\min} = \frac{6.6\times10^{-34} \text{ J s}}{\sqrt{2(9\times10^{-31}\text{ kg})(0.2\times1.6\times10^{-19}\text{ J})}}$

$= \frac{6.6}{2.4} \times 10^{-9} \text{ m} \approx 2.8 \times 10^{-9}$ m

So, $\lambda \geq 2.8 \times 10^{-9}$ m

S20. (c) Energy of the photon $E = \frac{hc}{\lambda}$ or $= \frac{hc}{E}$, where λ is the wavelength.

S21. (b) According to Einstein's photoelectric equation,

$eV_s = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$

$\therefore$ As per question, $eV = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$ ...(i)

$\frac{eV}{4} = \frac{hc}{2\lambda} - \frac{hc}{\lambda_0}$ ...(ii)

From equations (i) and (ii), we get

$\frac{hc}{2\lambda} - \frac{hc}{4\lambda} = \frac{hc}{\lambda_0} - \frac{hc}{4\lambda_0}$

$\Rightarrow \frac{hc}{4\lambda} = \frac{3hc}{4\lambda_0}$ or $\lambda_0 = 3\lambda$

ASSERTION AND REASONING

S1. (c) Mass of moving photon $m = \frac{hv}{c^2} = \frac{h}{c\lambda}$ and $E = mc^2$

S2. (c) Less work function means less energy is required for ejecting out the electrons.

S3. (b) Both statement I and II are true; but even it radiation of single wavelength is incident on photosensitive surface, electrons of different KE will be emitted.

S4. (a) de-Broglie wavelength associated with gas molecules varies as $\lambda \propto \frac{1}{\sqrt{T}}$

S5. (a) When a light of single frequency falls on the electrons of inner layer of metal, then this electron comes out of the metal surface after a large number of collisions with atom of it's upper layer

SHORT ANSWER QUESTIONS

S1. No, most electrons get scattered into the metal. Only a few come out of the surface of the metal

S2. In the first case, energy given out is less than the energy supplied. In the second case, the material has to supply the energy as the emitted photon has more energy. This cannot happen for stable substances.

S3. The photoelectric current increases proportionally with the increase in intensity of incident radiation. Larger the intensity of incident radiation, larger is the number of incident photons and hence larger is the number of electrons ejected from the photosensitive surface.

S4. Threshold frequency is defined as the minimum frequency of incident radiation which can cause photoelectric emission. It is different for different metal.

NUMERICAL TYPE QUESTIONS

S1. Momentum of the photon = $\frac{hv}{c}$

$\Rightarrow \frac{c}{v} = \frac{h}{p} = \lambda$

$v = \frac{c}{\lambda} = \frac{cp}{h} = 3 \times 10^8 \times \frac{3.3\times10^{-29}}{6.6\times10^{-34}} = 1.5 \times 10^{13}$ Hz

S2. $W_0 = \frac{hc}{\lambda_0}$ or $W_0 \propto \frac{1}{\lambda_0}$

$\Rightarrow \frac{W_1}{W_2} = \frac{\lambda_2}{\lambda_1} = \frac{600}{300} = \frac{2}{1}$

S3. Here, $\frac{hc}{\lambda} = 10^3$ eV and $hv = 10^6$ eV

Hence, $v = \frac{10^3 c}{\lambda} = \frac{10^3\times3\times10^8}{1.24\times10^{-9}} = 2.4 \times 10^{20}$ Hz

S4. The maximum kinetic energy is given as

$K_{\max} = hv - \phi_0 = hv - hv_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$

where λ_0 = threshold wavelength

or $\frac{1}{2}mv^2 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$

Here, $h = 4.14 \times 10^{-15}$ eV s, $c = 3 \times 10^8\ \mathrm{m\ s^{-1}}$

$\lambda_0 = 3250 \times 10^{-10}\ \mathrm{m} = 3250$ Å

$\lambda = 2536 \times 10^{-10}\ \mathrm{m} = 2536$ Å,

$m = 9.1 \times 10^{-31}$ kg

$hc = 4.14 \times 10^{-15}\ \mathrm{eV\ s} \times 3 \times 10^8\ \mathrm{m\ s^{-1}} =$ 12420 eV Å

$\therefore\ \frac{1}{2}mv^2 = 12420\left[\frac{1}{2536} - \frac{1}{3250}\right]$ eV $= 1.076$ eV

$v^2 = \frac{2.152\ \mathrm{eV}}{m} = \frac{2.152\times1.6\times10^{-19}}{9.1\times10^{-31}}$

$\therefore\ v \approx 6 \times 10^5\ \mathrm{m\ s^{-1}} = 0.6 \times 10^6\ \mathrm{m\ s^{-1}}$

S5. $\frac{h}{10^{-6}\ \mathrm{kg}\times v} = \frac{h}{9.1\times10^{-31}\ \mathrm{kg}\times3\times10^6\ \mathrm{m/s}}$

$\therefore\ v = 2.7 \times 10^{-18}$ m/s

S6. Kinetic energy (E) = 100 eV;

Mass of electron (m) = 9.1 × 10^{-31} kg;

1 eV = 1.6 × 10^{-19} J and

Planck's constant (h) = 6.6 × 10^{-34} J s

Energy of an electron (E) = 100 × (1.6 × 10^{-19}) J

Or $\lambda = \frac{h}{\sqrt{2mE}} = \frac{6.6\times10^{-34}}{\sqrt{2\times9.1\times10^{-31}\times100\times1.6\times10^{-19}}}$

$= 1.2 \times 10^{-10}\ \mathrm{m} = 1.2$ Å

S7. According to Einstein's photoelectric equation

$\frac{1}{2}mv_{\max}^2 = hv - \phi_0$

where $\frac{1}{2}mv_{\max}^2$ is the maximum kinetic energy of the emitted electrons, hv is the incident energy and ϕ_0 is the work function of the metal.

$\therefore\ \frac{1}{2}mv_{\max_1}^2 = 1\ \mathrm{eV} - 0.5\ \mathrm{eV} = 0.5\ \mathrm{eV}$ ...(i)

and $\frac{1}{2}mv_{\max_2}^2 = 2.5\ \mathrm{eV} - 0.5\ \mathrm{eV} = 2\ \mathrm{eV}$ ...(ii)

Divide (i) and (ii), we get

$\frac{v_{\max_1}^2}{v_{\max_2}^2} = \frac{0.5}{2}$ or $\frac{v_{\max_1}}{v_{\max_2}} = \sqrt{\frac{0.5}{2}} = \frac{1}{2}$

S8. Given, for proton,

Specific charge

$= \frac{e}{m} = 9.6 \times 10^7\ \mathrm{C\ kg^{-1}}$ ... (i)

As, α −particle $\left({}^4_2\mathrm{He}\right)$ have 2 electrons and its mass number is 4.

$\therefore$ Specific charge of α-particle $= \frac{2e}{4m} = \frac{1}{2}\frac{e}{m}$

$= \frac{1}{2} \times 9.6 \times 10^7$ [using Eq. (i)]

$= 4.8 \times 10^7\ \mathrm{C\ kg^{-1}}$

S9. Given, work-function of platinum,

$\phi_0 = hv_0 = 6.35\ eV = 6.35 \times 1.6 \times 10^{-19}$ J

where, v_0 is threshold frequency of platinum and h is Planck's constant.

$\Rightarrow\quad v_0 = \frac{\phi_0}{h} = \frac{6.35 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}}$

$= 15.32 \times 10^{14}$ Hz

S10. The work function of material is given by

$\phi = hv$

$\phi = \frac{hc}{\lambda}$ or $\lambda = \frac{hc}{\phi}$ ... (i) $\left[\because v = \frac{c}{\lambda}\right]$

where, h = Planck's constant $= 6.63 \times 10^{-34}$ J − s,

c = speed of light $= 3 \times 10^8\ \mathrm{ms^{-1}}$

and λ = threshold wavelength of light.

Given, $\phi = 4$ eV $= 4 \times 1.6 \times 10^{-19}$ J.

Substituting the given values in Eq. (i), we get

$\lambda = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{4 \times 1.6 \times 10^{-19}}$

$= 3.108 \times 10^{-7}\ m \simeq 310\ nm$

HOMEWORK EXERCISE SOLUTIONS

MCQ

S1. **(b)** Cathode rays are basically negatively charged particles (electrons). If the cathode rays are allowed to pass between two plates kept at a difference of potential, the rays are found to be deflected from the rectilinear path. The direction of deflection shows that the rays carry negative charges.

S2. (b) According to Einstein's photoelectric equation, $h\nu = \Phi_0 + K_{max}$

We have

$h\nu = \Phi_0 + 0.5$

and $1.2h\nu = \Phi_0 + 0.8$

Therefore, from above two equations $\Phi_0 = 1.0$ eV.

S3. (d) $W_0 = h\nu_1 - eV_1$

$= h\nu_2 - eV_2$

$eV_2 = h(\nu_2 - \nu_1) + eV_1$

$$V_2 = \frac{h(h_2 - n_1)}{e} + V_1$$

S4. (d) $h\upsilon - h\upsilon_0 = E_K$, according to photoelectric equations, when $\upsilon = \upsilon_0$, $E_K = 0$.

Graph (d) represents $E_K - \upsilon$ relationship.

S5. (b) $\lambda \propto \frac{1}{\sqrt{V}}$

$$\Rightarrow \frac{\lambda_1}{\lambda_2} = \sqrt{\frac{V_2}{V_1}} = \sqrt{\frac{100keV}{25keV}} = 2$$

$$\Rightarrow \lambda_2 = \frac{\lambda_1}{2}$$

S6. (b) Cathode rays get deflected in the electric field.

S7. (c) As we know

$\lambda \propto \frac{1}{\sqrt{V}}$

$$\therefore \frac{1}{\sqrt{100}} : \frac{1}{\sqrt{200}} : \frac{1}{\sqrt{300}} = 1 : \frac{1}{\sqrt{2}} : \frac{1}{\sqrt{3}}$$

S8. (d) $$\frac{hc}{\lambda} - \phi = eV_0$$

$$V_0 = \frac{hc}{e\lambda} - \frac{\phi}{e}$$

For metal A For metal B

$$\frac{\phi_A}{hc} = \frac{1}{\lambda} \qquad \frac{\phi_B}{hc} = \frac{1}{\lambda}$$

As the value of $\frac{1}{\lambda}$ (increasing and decreasing) is not specified hence we cannot say that which metal has comparatively greater or lesser work function (Φ).

S9. (c)

S10. (d) Potential difference = 100 V

K.E. acquired by electron = e (100)

$$\frac{1}{2}mv^2 = e(100) \Rightarrow v = \sqrt{\frac{2e(100)}{m}}$$

According to de Broglie's concept

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

$$\Rightarrow \lambda = \frac{h}{m\sqrt{\frac{2e(100)}{m}}}$$

$$= \frac{h}{\sqrt{2me(100)}} = 1.2 \times 10^{-10} = 1.2\text{Å}$$

S11. (d) Since $p = nh\nu$

$$\Rightarrow n = \frac{p}{h\nu} = \frac{2 \times 10^{-3}}{6.6 \times 10^{-34} \times 6 \times 10^{14}} = 5 \times 10^{15}$$

ASSERTION AND REASONING

S1. (d) To photons of equal wavelength will have equal momentum (magnitude), but direction of momentum may be different.

S2. (d) Total number of emitted photons depends on energy of each photon. The energy of photons of two sources may be different.

S3. (b) Less work function means less energy is required for ejecting out the electrons

S4. (d) Photoelectric saturation current is independent of frequency. It only depends on intensity of light

S5. (b) The kinetic energy of emitted photoelectrons varies from zero to a maximum value. Work function depends on metal used.

SHORT ANSWER QUESTIONS

S1. Work Function: The minimum energy required to free an electron from metallic surface is called the work function. Smaller the work function, larger the kinetic energy of emitted electron.

S2. The three characteristic features which cannot be explained by wave theory are:

(i) Kinetic energy of emitted electrons is found to be independent of the intensity of incident light.

(ii) There is no emission of electrons if frequency of incident light is below a certain frequency (threshold frequency).

(iii) Photoelectric effect is an instantaneous process.

S3. In photoelectric effect, a single photon interacts with a single electron. As individual photon has energy (2.5 eV) which is less than work function, hence emission of electron will not take place.

NUMERICAL TYPE QUESTIONS

S1. $\lambda = \frac{h}{mv}$

$\because v = \frac{c}{20} = \frac{3\times10^8}{20} = 1.5 \times 10^7$ m/sec

$h = 6.626 \times 10^{-34}$ J − s, $m = 1.67 \times 10^{-27}$ kg

$\therefore \lambda = \frac{6.626\times10^{-34}}{1.67\times10^{-27}\times1.5\times10^7}$

$\Rightarrow \lambda = 2.64 \times 10^{-14}$ m

S2. If the inciden light be of threshold wavelength (λ_0) then the stopping potential shall be zero. thus

$\lambda_0 = \frac{hc}{\phi}, \lambda_0 = \frac{6.6\times10^{-34}\times3\times10^8}{4.2\times1.6\times10^{-19}}$

$\lambda_0 = 2.946 \times 10^{-7}\ \mathrm{m} = 2946$ Å

S3. $\because 2d\sin\phi = n\lambda$

$\lambda_{max} = \frac{(2d\sin\phi)_{max}}{n_{min}} = \frac{2d\sin 90^\circ}{1} = 2 \times 10$ Å

$\lambda_{max} = 20$Å

∴ Possible wavelengths are 5Å, 10Å and 20Å.

S4. $hv = hv_0 + E_k$

$6.6 \times 10^{-34} \times 3 \times 10^{15} = 4 \times 1.6 \times 10^{-19} + E_k$

$19.8 \times 10^{-19} - 6.4 \times 10^{-19} = E_k$

$E_k = 13.4 \times 10^{-19}$ J

$\Rightarrow \frac{1}{2}mv_{max}^2 = 13.4 \times 10^{-19}$

$v_{max} = \sqrt{\frac{2\times13.4\times10^{-19}}{m}}$

$= \sqrt{\frac{2\times13.4\times10^{-19}}{9\times10^{-31}}} = 1.73 \times 10^6$ m/s

S5. Energy of incident light

$E(eV) = \frac{12375}{3320} = 3.72eV$

We know that, $E = W_0 + eV_0$

$V_0 = \frac{(E-W_0)}{e} = \frac{3.72eV-1.07eV}{e}$

$V_0 = 2.65$ Volt

S6. According to the Einstein's photoelectric equation,

$E = W_0 + \frac{1}{2}mv^2$

When frequency of incident light is $2v_0$.

$h(2v_0) = hv_0 + \frac{1}{2}mv_1^2 \Rightarrow hv_0 = \frac{1}{2}mv_1^2$ ...(i)

When frequency of incident light is $5v_0$

$h(5v_0) = hv_0 + \frac{1}{2}mv_2^2 \Rightarrow 4hv_0 = \frac{1}{2}mv_2^2$...(ii)

Dividing (i) by (ii), $\frac{1}{4} = \frac{v_1^2}{v_2^2}$ or $\frac{v_1}{v_2} = \frac{1}{2}$

S7. Given $V = 30\mathrm{kV} = 30 \times 10^3$ volt

Energy, $E = eV = 1.6 \times 10^{-19} \times 30 \times 10^3 = 4.8 \times 10^{-15}$ joule

(a) Maximum frequency v_{max} is given by, $E = hv_{max}$

$$v_{max} = \frac{E}{h} = \frac{4.8 \times 10^{-15}}{6.63 \times 10^{-34}} = \mathbf{7.24} \times 10^{18}\mathbf{Hz}$$

(b) Minimum wavelength, $\lambda_{min} = \frac{c}{v_{max}} = \frac{3\times10^8}{7.24\times10^{18}} = 4.1 \times 10^{-11}\ \mathrm{m} = \mathbf{0.041\ nm}$

S8. Total E is constant.

Let n_1 and n_2 be the number of photons of X-rays and visible region.

$n_1E_1 = n_2E_2 \Rightarrow n_1\frac{hc}{\lambda_1} = n_2\frac{hc}{\lambda_2}$

$\frac{n_1}{n_2} = \frac{\lambda_1}{\lambda_2} \Rightarrow \frac{n_1}{n_2} = \frac{1}{\mathbf{500}}$

S9. Give that, only 25% of 200 W converter electrical en into light of yellow colour

$\left(\frac{hc}{\lambda}\right) \times N = 200 \times \frac{25}{100}$

Where N is the No. of photons emitted per sec $h =$ plank's constant, c, speed of light.

$$N = \frac{200 \times 25}{100} \times \frac{\lambda}{hc}$$

$$= \frac{200 \times 25 \times 0.6 \times 10^{-6}}{100 \times 6.2 \times 10^{-34} \times 3 \times 10^8}$$

$=1.5 \times 10^{20}$

S10. $n \to 2 - 1$

$E = 10.2eV$

$kE = E - \phi$

$Q = 10.20 - 3.57$

$hv_0 = 6.63eV$

$v_0 = \frac{6.63\times1.6\times10^{-19}}{6.67\times10^{-34}} = 1.6 \times 10^{15}$ Hz