11

The Maxwell's equations of electromagnetism and Hertz experiments on generation and detection of electromagnetic waves established the wave nature of light in 1887. But the discoveries of photoelectric effect by Hertz, Compton effect by Compton, established the particle nature of light. Hence, it was concluded that light has **dual nature**.

DUAL NATURE OF RADIATION AND MATTER

CHAPTER CHECKLIST
- Photoelectric Effect
- Matter Wave

ELECTRON EMISSION

In metals, the electrons in the outer shells (valence electrons) are loosely bound to the atoms, hence they are free to move easily within the metal surface but cannot leave it. Such electrons are called **free electrons**.

These free electrons can be emitted from the metals, if they have sufficient energy to overcome the attractive pull of metal surface. The phenomenon of emission of electrons from the surface of a metal is called **electron emission**.

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

(i) **Thermionic Emission** Sufficient thermal energy can be imparted to the free electrons by suitable heating, so that they can come out of the metal. This process of emission of electrons is known as thermionic emission and the electrons so emitted are known as **thermions** or **thermal electrons** . The number of thermions emitted depends on the temperature of the metal surface.

(ii) **Field Emission or Cold Cathode Emission** It is the phenomenon of emission of electrons from the surface of a metal by applying a very strong electric field ($\sim 10^8$ Vm^{-1}) to a metal. One of the examples of cold emission is spark plug.

(iii) **Photoelectric Emission** It is the phenomenon of emission of electrons from the surface of metal when light radiations of suitable frequency fall on it. Here, the energy to the free electrons for their emission is being supplied by light photons. The emitted electrons are called **photoelectrons**. The number of photoelectrons emitted depends on the intensity of the incident light.

(iv) **Secondary Emission** It is the phenomenon of emission of electrons from the surface of metal in large number when fast moving electrons (called primary electrons) or other particles strike the metal surface.

Work Function

A certain minimum amount of energy is required to be given to an electron to pull it out from the surface of the metal. This minimum energy required by an electron to escape from the metal surface is called the **work function** of the metal. It is generally denoted by ϕ_0 or W_0 and measured in eV (electron volt). It depends on the properties of the metal and the nature of its surface. It decreases with the increase on temperature.

One electron volt (1 eV) is the energy gained by an electron when it has been accelerated by a potential difference of one volt (1 V), so that $1\ eV = 1.602 \times 10^{-19}$ J.

The values of work function of some metals are given below

Work Function of Some Metals

Metal	Work function, ϕ_0 (eV)	Metal	Work function, ϕ_0 (eV)
Cs	2.14	Al	4.28
K	2.30	Hg	4.49
Na	2.75	Cu	4.65
Ca	3.20	Ag	4.70
Mo	4.17	Ni	5.15
Pb	4.25	Pt	5.65

From the above table, it can be concluded that, the work function of platinum is the highest ($\phi_0 = 5.65$ eV), while it is the lowest for caesium ($\phi_0 = 2.14$ eV).

|TOPIC 1|
Photoelectric Effect

As discussed earlier, the phenomenon of emission of electrons from the surface of metal, when radiations of suitable frequency fall on it, is called photoelectric effect. The emitted electrons are called **photoelectrons** and the current, so produced is called **photoelectric current**.

Alkali metals like lithium, sodium, etc. show photoelectric effect with visible light, whereas the metals like zinc, cadmium, etc. are sensitive only to ultraviolet light.

Note Non-metals also show photoelectric effect. Liquids and gases can also show this effect but to limited extent.

Hertz's Observations

In 1887, Heinrich Hertz discovered the phenomenon of photoelectric emission while working with his electromagnetic wave experiment, by means of spark discharge. He observed that high voltage sparks across the detector loop were enhanced when the emitter plate was illuminated by ultraviolet light from an arc lamp. It was accounted as follows:

When suitable radiations fall on a metal surface, some electrons near the surface absorb enough energy from the incident radiations, to overcome the attraction of the positive ions in the material of the surface. This helps them to escape from the surface of the material to the surrounding space.

Hallwachs' and Lenard's Observations

During 1886-1902, Wilhelm Hallwachs and Philipp Lenard made a detailed study of photoelectric effect. Lenard observed that, if a potential difference is applied across the two metal plates enclosed in an evacuated tube, then there is no flow of current in the circuit. However, when one plate (called emitter plate) enclosed in the evacuated tube, kept at negative potential is exposed with ultraviolet radiations, current begins to flow in the circuit.

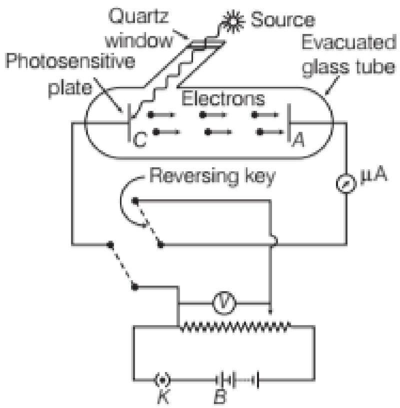
As soon as ultraviolet radiations falling on the emitter plate are stopped, the current flowing is also stopped. Thus, light falling on the surface of emitter causes current in the external circuit. From his observation, Hallwachs concluded that negatively charged particles were ejected out from the zinc plate under the action of ultraviolet radiations. After the discovery of electron in 1897, it became evident that the exposure of emitter plate with the incident light causes the electrons to emit also. Due to negative charge, the emitted electrons are pushed towards the collector plate by the applied electric field.

Hallwachs and Lenard also observed that when ultraviolet light fell on the emitter plate, no electrons were emitted, until the frequency of the incident light was smaller than a certain minimum value, called the threshold frequency. This minimum frequency depends on the nature of the material of the emitter plate.

EXPERIMENTAL STUDY OF PHOTOELECTRIC EFFECT

The figure given below shows the experimental setup for the study of photoelectric effect.

The setup consists of an evacuated glass or quartz tube which encloses a photosensitive plate C (called **emitter**) and a metal plate A (called **collector**). A transparent quartz window is sealed onto the glass tube which permits ultraviolet radiation to pass through it and irradiate the photosensitive plate *C*.



Experimental arrangement for the study of photoelectric effect

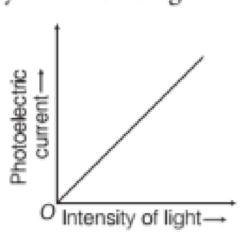
The electrons are emitted by the plate *C* and are collected by the plate *A*. When the collector plate *A* is positive with respect to the emitter plate *C*, then the electrons are attracted to it. Hence, photoelectric current is constituted. This emission of electrons causes flow of electric current in the circuit.

The potential difference between the emitter and collector plates is measured by a voltmeter (V), whereas the resulting photocurrent flowing in the circuit is measured by a microammeter (μA).

The experimental arrangement given above is used to study the variations of photocurrent with intensity of radiation, frequency of radiation and the potential difference between the plates *A* and *C*.

Effect of Intensity of Light on Photoelectric Current

For a fixed frequency of incident radiation and accelerating potential, the photoelectric current increases linearly with increase in intensity of incident light.

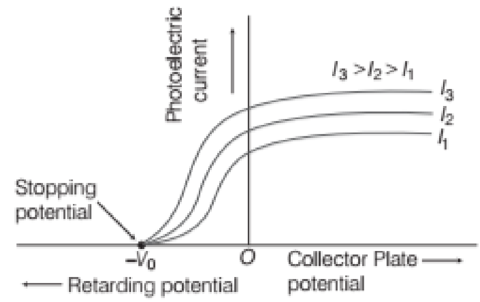


Variation of photoelectric current with intensity of light

As, the photoelectric current is directly proportional to the number of photoelectrons emitted per second. So, the number of photoelectrons emitted per second is directly proportional to the intensity of the incident radiation.

Effect of Potential on Photoelectric Current

For a fixed frequency and intensity of incident light, photoelectric current increases with increase in potential applied to the collector as shown in the graph.



Variation of photoelectric current *versus* potential for different intensities but constant frequency

From the above graph, we can observe that,

(i) After a certain value of accelerating potential, when all photo electrons reach the plate *A*, and the photocurrent ceases. On increasing the value of accelerating potential, this maximum value of photoelectric current is called **Saturation current.**

(ii) When the potential is decreased, the current decreases but does not become zero at zero potential. This shows that even in the absence of accelerating potential, few photoelectrons manages to reach the plate *A* on their own due to their kinetic energy.

(iii) For a particular frequency of incident radiation, when minimum negative potential V_0 is applied to the plate *A* w.r.t. *C*, photoelectric current becomes zero at a particular value of negative potential V_0 called **stopping potential** or **cut-off potential.**

In this condition, the stopping potential is sufficient to repel even the most energetic photoelectron with maximum kinetic energy K_{max}. Photoelectric current becomes zero whenever no electron even the fastest photoelectrons cannot reach the plate *A*. Hence, maximum kinetic energy is given as,

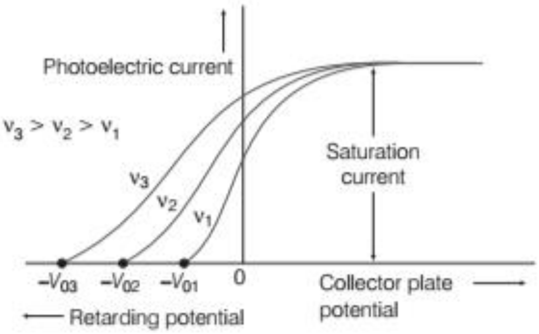
$$K_{max} = eV_0 = \frac{1}{2} m v_{max}^2$$

where, m is the mass of photoelectron and v_{max} is the maximum velocity of emitted photoelectron.

Note For the radiation of a given frequency and material of plate *C*, the value of stopping potential V_0 is independent of the intensity of the incident radiation. It means, the maximum kinetic energy of emitted photoelectron depends on the light source and the emitter plate material but is independent of intensity of incident radiation.

Effect of Frequency of Incident Radiation on Stopping Potential

If we take radiations of different frequencies but of same intensity. For each radiation, we study the variation of photoelectric current against the potential difference between the plates as shown in the graph below.



Variation of photoelectric current *versus* potential for different frequencies but constant intensity of incident radiation

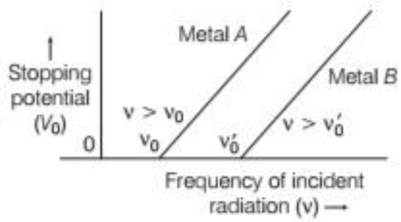
From the above graph, we observe that

(i) the value of stopping potential is different for radiation of different frequencies but the value of saturation current (for given intensity) remains constant.

(ii) the value of stopping potential is more negative for incident radiation of higher frequency. This means that the energy of the emitted electrons depends on the frequency of incident radiations. Greater the frequency of incident radiation, greater is the maximum kinetic energy of photoelectrons, consequently greater retarding potential or stopping potential is required to stop them completely.

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

If we plot a graph between stopping potential and the frequency of the incident radiation for two different metals *A* and *B*, we get the graph as shown below.



Variation of stopping potential *versus* frequency of incident radiation

From the graph, are observe that

(i) the stopping potential V_0 varies linearly with the frequency of incident radiation for a given photosensitive material.

(ii) there exists a certain minimum cut-off frequency ν_0 for which the stopping potential is zero. This frequency is called threshold frequency.

Note The minimum frequency of light which can emit photoelectrons from a material is called **threshold frequency** or **cut-off frequency** of that material. It is a characteristic property of material.

For a frequency lower than cut-off frequency, no photoelectric emission is possible even if the intensity is large. If frequency of incident radiation is more than the threshold frequency, the photoelectric emission starts instantaneously without any apparent time lag (-10^{-9} s or less) even when the incident radiation is very dim.

LAWS OF PHOTOELECTRIC EMISSION

The laws of photoelectric emission are as follows

(i) For a given material and a given frequency of incident radiation, the photoelectric current or number of photoelectrons ejected per second is directly proportional to the intensity of the incident light.

(ii) For a given material and frequency of incident radiation, saturation current is found to be proportional to the intensity of incident radiation, whereas the stopping potential is independent of its intensity.

(iii) For a given material, there exists a certain minimum frequency of the incident radiation below which no emission of photoelectrons takes place. This frequency is called **threshold frequency.**

Above the threshold frequency, the maximum kinetic energy of the emitted photoelectrons or equivalent stopping potential is independent of the intensity of the incident light but depends upon only the frequency (or wavelength) of the incident light.

(iv) The photoelectric emission is an instantaneous process. The time lag between the incidence of radiations and emission of photoelectrons is very small, less than even 10^{-9} s.

PHOTOELECTRIC EFFECT AND WAVE THEORY OF LIGHT

Huygens' wave theory of light could not explain the photoelectric emission due to the following main reasons:

(i) According to the wave nature of light, the free electrons at the surface of the metal absorb the radiant energy continuously.

The greater the intensity of radiation, the greater should be the energy absorbed by each electron. The maximum kinetic energy of the photoelectrons on the surface is then expected to increase with increase in intensity.

But according to experimental facts, the maximum kinetic energy of ejected photoelectrons is independent of intensity of incident radiation.

(ii) According to wave theory of light, no matter what the frequency of radiation is, a sufficiently intense beam of radiation should be able to impart enough energy to the electrons, so that they exceed the minimum energy needed to escape from metal surface.

A threshold frequency, therefore should not exist which contradicts the experimental fact that, no photoelectric emission takes place below that threshold frequency, no matter whatsoever may be its intensity.

(iii) According to the wave theory of light, the absorption of energy by electron takes place continuously over the entire wavefront of the radiation. Since, a large number of electrons absorb energy, the energy absorbed per electron per unit time turns out to be small.

Hence, it will take hours or more for a single electron to come out of the metal which contradicts the experimental fact that photoelectron emission is instantaneous.

EINSTEIN'S PHOTOELECTRIC EQUATION

Energy Quantum of Radiation

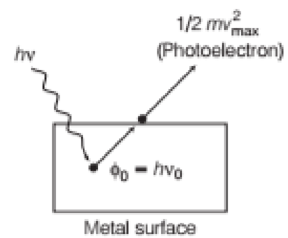
In 1905, Albert Einstein explained the various laws of photoelectric emission on the basis of Planck's quantum theory. According to that theory, the energy of an electromagnetic wave is not continuously distributed over the wavefront of waves. Instead of this, these waves travel in the form of discrete packets or bundels of energy called quanta of energy of radiation

Each quantum of energy radiate an energy, which is given by

$$E = h\nu$$

where, h is Planck's constant and ν is the frequency of light radiation.

When a quantum of light radiation of energy $h\nu$ falls on a metal surface, then this energy is absorbed by the electron and is used in following two ways



Emission of photoelectron by a metal surface when a quantum of light is absorbed by it

(i) A part of energy is used to overcome the surface barrier and come out of the metal surface. This part of energy is called **work function.** It is expressed as $\phi_0 = h\nu_0$.

(ii) The remaining part of the energy is used in giving a velocity v to the emitted photoelectron. This is equal to the maximum kinetic energy of the photoelectrons $\left(\frac{1}{2} mv^2_{max}\right)$, where m is the mass of the photoelectron.

According to the law of conservation of energy,

$$h\nu = \phi_0 + \frac{1}{2} mv^2_{max} = h\nu_0 + \frac{1}{2} mv^2_{max}$$

$$\therefore \quad \frac{1}{2} mv^2_{max} = K_{max} = h(\nu - \nu_0) = h\nu - \phi_0$$

$$\therefore \quad \boxed{K_{max} = h\nu - \phi_0}$$

This equation is called **Einstein's photoelectric equation**.

EXAMPLE |1| The electric field associated with a monochromatic beam of light becomes zero, with frequency 2.4×10^{15} times per second. Find the maximum kinetic energy of the photoelectrons when this light falls on a metal surface whose work function is 2.0 eV.

Sol. Given, $\phi_0 = 2.0$ eV, $h = 6.63 \times 10^{-34}$ J-s, $KE_{max} = ?$

In one complete vibration twice the electric field becomes zero, so the frequency of incident light is given by

$$\nu = \frac{1}{2} \times 2.4 \times 10^{15} = 1.2 \times 10^{15} \text{ Hz}$$

Hence, maximum kinetic energy,

$$KE_{max} = h\nu - \phi_0 = \frac{6.63 \times 10^{-34} \times 1.2 \times 10^{15}}{1.6 \times 10^{-19}} - 2 = 2.97 \text{ eV}$$

Relation between Stopping Potential (V_0) and Threshold Frequency (ν_0)

Maximum kinetic energy is given by

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

Also, $K_{max} = eV_0$

$$\therefore \quad \boxed{eV_0 = h(\nu - \nu_0)} \quad \ldots(i)$$

If λ = wavelength of the incident radiation,
λ_0 = threshold wavelength of the metal surface and
c = velocity of light.

Then, $\nu = \frac{c}{\lambda}$ and $\nu_0 = \frac{c}{\lambda_0}$

Putting these values in Eq. (i), we get

$$eV_0 = h\left(\frac{c}{\lambda} - \frac{c}{\lambda_0}\right)$$

$$\therefore \quad \boxed{eV_0 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)} \quad \ldots(ii)$$

EXAMPLE |2| The work function of caesium is 2.14 eV. Calculate

(i) the threshold frequency for caesium and
(ii) the wavelength of the incident light, if the photocurrent is brought to zero by a stopping potential of 0.60 V. Given, $h = 6.63 \times 10^{-34}$ J-s.

Sol. Here, $V_0 = 0.60$ V, $\phi_0 = 2.14$ eV $= 2.14 \times 1.6 \times 10^{-19}$ J

(i) Threshold frequency, $\nu_0 = \frac{\phi_0}{h}$ $\quad [\because \phi_0 = h\nu_0]$

$$= \frac{2.14 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$= 5.16 \times 10^{14} \text{ Hz}$$

(ii) We have, $eV_0 = \frac{hc}{\lambda} - \phi_0 \Rightarrow \lambda = \frac{hc}{(eV_0 + \phi_0)}$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{(1.6 \times 10^{-19} \times 0.60 + 2.14 \times 1.6 \times 10^{-19})}$$

$$= 454 \times 10^{-9} \text{ m} = 454 \text{ nm}$$

Verification of Laws of Photoelectric Emission Based on Einstein's Photoelectric Equation

Einstein's photoelectric equations is

$$K_{max} = \frac{1}{2} m v_{max}^2 = h(\nu - \nu_0)$$

This equation successfully explains the laws of photoelectric emission. These are as follows

(i) If $\nu < \nu_0$, then $\frac{1}{2} m v_{max}^2$ is negative which is not possible therefore, for photoelectric emission to take place, $\nu > \nu_0$.

(ii) Since, one photon emits one electron, so the number of photoelectrons emitted per second is directly proportional to the intensity of incident light.

(iii) It is clear that $\frac{1}{2} m v_{max}^2 \propto \nu$, as h and ν_0 are constants. This shows that kinetic energy of the photoelectrons is directly proportional to the frequency of the incident light.

(iv) Photoelectric emission is due to elastic collisions between a photon and an electron. As such there cannot be any significant time lag between the incidence of photon and emission of photoelectron.

Graphs Related to Photoelectric Effect From Einstein Photoelectric Equation

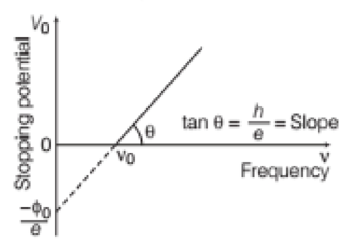
The important graphs related to photoelectric effect are as follows

(i) Frequency ν and stopping potential V_0 graph

We know that, $eV_0 = h\nu - \phi_0$

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

So, $V_0 \propto \nu$



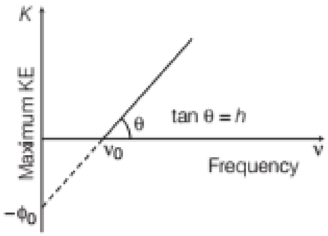
Graph of V_0 *versus* ν

It could be seen that, V_0 *versus* ν curve is a straight line with slope = (h/e) and is independent of the nature of material.

(ii) **Frequency ν and maximum kinetic energy graph**

As, $K_{max} = h\nu - \phi_0$

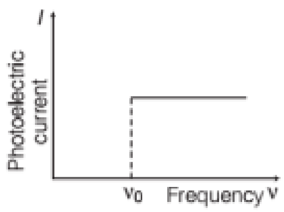
$\Rightarrow$ $K_{max} \propto \nu$



Graph of K_{max} *versus* ν

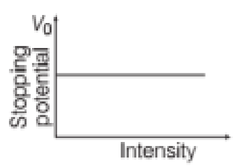
(iii) **Frequency ν and photoelectric current *I* graph**

The graph given below shows that, the photoelectric current I is independent of frequency of the incident light, till intensity remains constant.



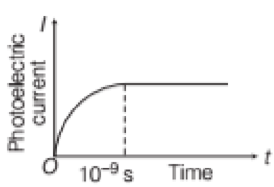
Graph of *I versus* ν

(iv) **Intensity and stopping potential V_0 graph**



Graph of V_0 *versus* intensity

(v) **Photoelectric current *I* and time lag *t* graph**



Graph of *I versus t*

PARTICLE NATURE OF LIGHT : THE PHOTON

Photoelectric effect thus gave evidence that light consists of packets of energy. These packets of energy were called **light quantum** that are associated with particles named as **photons**. So, photons confirm the particle nature of light.

Energy of a photon is given by

$$E = h\nu = \frac{hc}{\lambda}$$

where, h is the Planck's constant, ν is the frequency of radiation or photon, c is the speed of light and λ is the wavelength of photon.

The momentum of photon is given by

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda} \text{ kg ms}^{-1}$$

EXAMPLE |3| The momentum of photon of electromagnetic radiation is 3.3×10^{-29} kg ms^{-1}. Find out the frequency and wavelength of the wave associated with it.

Sol. Given, $p = 3.3 \times 10^{-29}$ kg ms^{-1}

$h = 6.63 \times 10^{-34}$ J-s

$c = 3 \times 10^8$ m/s, $\nu = ?$

and $\lambda = ?$

Since, $E = h\nu = mc^2 = mc \times c = p \times c$

$$\therefore \quad \nu = \frac{pc}{h} = \frac{3.3 \times 10^{-29} \times 3 \times 10^8}{6.63 \times 10^{-34}}$$

$$= 1.5 \times 10^{13} \text{ Hz}$$

and $$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8}{1.5 \times 10^{13}}$$

$$= 2 \times 10^{-5} \text{m}$$

Characteristic Properties of Photons

Different characteristic properties of photons are given below

(i) In interaction of radiation with matter, radiation behaves as if it is made up of particles called **photons**.

(ii) A photon travels at a speed of light c in vacuum (i.e. 3×10^8 m/s).

(iii) It has zero rest mass, i.e. the photon cannot exist at rest. According to the theory of relativity, the mass m of a particle moving with velocity v, comparable with the velocity of light c is given by

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \Rightarrow m_0 = m\sqrt{1 - \frac{v^2}{c^2}}$$

where, m_0 is the mass of the particle at rest.

As, a photon moves with the speed of light, i.e. $v = c$, hence $m_0 = 0$. So, rest mass of photon is zero.

(iv) The inertial mass of a photon is given by

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

(v) Photons travel in a straight line.

(vi) Irrespective of the intensity of radiation, all the photons of a particular frequency ν or wavelength λ have the same energy $E\left(= h\nu = \frac{hc}{\lambda}\right)$ and momentum, $p\left(= \frac{h\nu}{c} = \frac{h}{\lambda}\right)$.

(vii) Energy of a photon depends upon frequency of the photon, so the energy of the photon does not change when photon travels from one medium to another.

(viii) Wavelength of the photon changes in different media, so velocity of a photon is different in different media.

(ix) Photons are not deflected by electric and magnetic fields. This shows that photons are electrically neutral.

(x) In a photon-particle collision (such as photoelectron collision), the energy and momentum are conserved. However, the number of photons may not be conserved in a collision.

(xi) Photons may show diffraction under given conditions.

EXAMPLE |4| Monochromatic light of wavelength 632.8 nm is produced by a helium-neon laser. The power emitted is 9.42 mW.

(i) Find the energy and momentum of each photon in the light beam.

(ii) How many photons per second, on the average, arrive at a target irradiated by this beam?
(Assume the beam to have uniform cross-section, which is less than the target area.)

(iii) How fast does a hydrogen atom have to travel in order to have the same momentum as that of the photon?

NCERT

Sol. Given, wavelength of monochromatic light,

$$\lambda = 632.8 \text{ nm} = 632.8 \times 10^{-9} \text{ m}$$

$$\text{Power} = 9.42 \text{ mW} = 9.42 \times 10^{-3} \text{ W}$$

(i) Energy of each photon, $E = \frac{hc}{\lambda}$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{632.8 \times 10^{-9}}$$

$$= 3.14 \times 10^{-19} \text{ J}$$

We know that momentum of each photon, $p = \frac{h}{\lambda}$

$$p = \frac{6.63 \times 10^{-34}}{632.8 \times 10^{-9}} = 1.05 \times 10^{-27} \text{ kg-m/s}$$

(ii) Let n be the number of photons per second.

So, $n = \frac{\text{Power}}{\text{Energy of each photon}} = \frac{9.42 \times 10^{-3}}{3.14 \times 10^{-19}}$

$$= 3 \times 10^{16} \text{ photons/s}$$

(iii) Momentum, $p = mv$

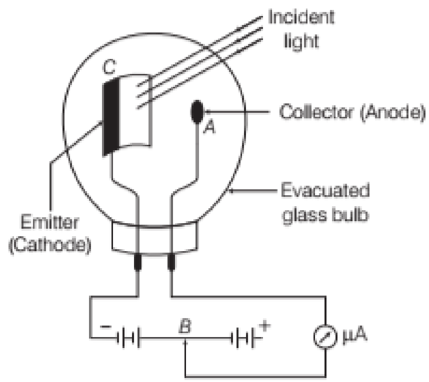
$\therefore$ Velocity of hydrogen atom, $v = \frac{p}{m} = \frac{1.05 \times 10^{-27}}{1.66 \times 10^{-27}}$

$$= 0.63 \text{ m/s}$$

$[\because m = 1.66 \times 10^{-27} \text{ kg (mass of electron)}]$

PHOTOCELL

It is a device which converts light energy into electrical energy. It is also called an **electric eye.** As, the photoelectric current sets up in the photoelectric cell corresponding to incident light, it provides the information about the objects as has been seen by our eye in the presence of light.



Photocell

A photocell consists of a semi-cylindrical photosensitive metal plate C (emitter) and a wire loop A (collector) supported in an evacuated glass or quartz bulb. When light of suitable wavelength falls on the emitter C, photoelectrons are emitted.

Applications of Photocell

Some applications of photocell are given below

(i) Used in television camera for telecasting scenes and in photo telegraphy.

(ii) Reproduction of sound in cinema film.

(iii) Used in counting devices.

(iv) Used in burglar alarm and fire alarm.

(v) To measure the temperature of stars.

(vi) Used for the determination of Planck's constant.

TOPIC PRACTICE 1

OBJECTIVE Type Questions

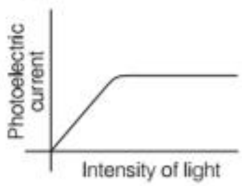
1. Lenard observed that no electrons are emitted when frequency of light is less than a certain minimum frequency. This minimum frequency depends on

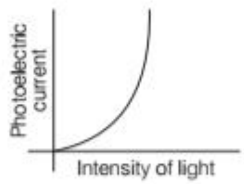
(a) potential difference of emitter and collector plates
(b) distance between collector and the emitter plate
(c) size (area) of the emitter plate
(d) material of the emitter plate

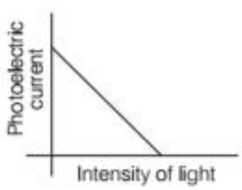
2. The work function of a metal is hc/λ_0. If light of wavelength λ is incident on its surface, then the essential condition for the electron to come out from the metal surface is

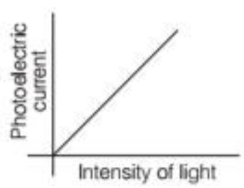
(a) $\lambda \geq \lambda_0$ (b) $\lambda \geq 2\lambda_0$
(c) $\lambda \leq \lambda_0$ (d) $\lambda \leq \lambda_0/2$

3. Variation of photoelectric current with intensity of light is

(a)


(b)


(c)


(d)


4. A photon of energy 3.4 eV is incident on a metal surface whose work function is 2 eV. Maximum kinetic energy of the photoelectron emitted by the metal surface will be

(a) 1.4eV (b) 1.7 eV
(c) 5.4 eV (d) 6.8 eV

5. If photons of frequency ν are incident on the surfaces of metals A and B of threshold frequencies $\frac{\nu}{2}$ and $\frac{\nu}{3}$ respectively, the ratio of the maximum kinetic energy of electrons emitted from A to that from B is

CBSE All India 2020

(a) $2:3$ (b) $3:4$
(c) $1:3$ (d) $\sqrt{3}:\sqrt{2}$

6. Consider a beam of electrons (each electron with energy E_0) incident on a metal surface kept in an evacuated chamber. Then, **NCERT Exemplar**

(a) no electrons will be emitted as only photons can emit electrons
(b) electrons can be emitted but all with an energy, E_0
(c) electrons can be emitted with any energy, with a maximum of $E_0 - \phi$ (ϕ is the work function)
(d) electrons can be emitted with any energy, with a maximum of E_0

7. The formula for kinetic mass of a moving photon is

(a) $h\nu/\lambda$ (b) $h\lambda/e$
(c) $h\nu/e$ (d) $h/c\lambda$

where, h is Planck constant and ν, λ, c are frequency, wavelength and speed of photon, respectively.

8. The wavelength of a photon needed to remove a proton from a nucleus which is bound to the nucleus with 1 MeV energy is nearly

NCERT Exemplar

(a) 1.2 nm
(b) 1.2×10^{-3} nm
(c) 1.2×10^{-6} nm
(d) 1.2×10 nm

9. A photocell connected in an electrical circuit is placed at a distance d from a source of light. As a result, current I flows in the circuit. What will be the current in the circuit when the distance is reduced to $d/2$? **CBSE All India 2020**

(a) I (b) $2I$
(c) $4I$ (d) $I/2$

10. A photocell connected in an electrical circuit is placed at a distance d from a source of light. As a result, current I flows in the circuit. What will be the current in the circuit when the distance is reduced to $d/3$?

(a) I (b) $6I$
(c) $9I$ (d) $\frac{1}{3}I$

ASSERTION AND REASON

11. Assertion Cathode rays produce fluorescence in glass and colour of glow depends on nature of glass.

Reason Cathode rays excite glass electrons and they on de-excitation emits radiation in visible region.

12. Assertion In photoelectric effect, cathode or emitter plate is usually coated with barium oxide, barium sulphide or strontium oxide.

Reason Coating prevents cathode from erosion.

13. Assertion According to wave theory of light, if intensity of incident radiation is increased, then energy of emitted photoelectrons increases.

Reason Energy of a wave is proportional to its intensity.

14. Assertion Photoelectric current depends on the intensity of incident light.

Reason Number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation.

15. Assertion Photosensitivity of a metal is high if its work-function is small.

Reason Work-function $= h\nu_0$ where, ν_0 is the threshold frequency.

16. Assertion In photon-particle collision, the total energy and total momentum are conserved.

Reason The number of photons are conserved in a collision.

17. Assertion Photocell is also called electric eye.

Reason Photocell can see the things placed in front of it.

CASE STUDY BASED QUESTIONS

18. Photoelectric Effect

When a beam of 10.6 eV photons of intensity $2.0\ \text{Wm}^{-2}$ falls on a surface of platinum of surface area $1.0 \times 10^{-4}\ \text{m}^2$ and the work-function of the material is 5.6 eV. Given that, 0.53% of the incident photons eject photoelectrons.

(i) What is the energy of incident photon in joules?

(a) 10.6 J (b) 1.6×10^{-19} J

(c) 16.96×10^{-19} J (d) 2×10^{-21} J

(ii) Find the number of photons incident on given area.

(a) 1.18×10^{18} (b) 1.18×10^{14}

(c) 2×10^{16} (d) 23×10^{18}

(iii) Find number of photoelectrons emitted per second.

(a) 7×10^{11} (b) 6.25×10^{11}

(c) 9×10^{10} (d) 11×10^{11}

(iv) Find maximum energy of photoelectrons emitted.

(a) 5.0 eV (b) 6.0 eV

(c) 2.5 eV (d) 0 eV

(v) Find minimum energy of photoelectrons emitted.

(a) 6.0 eV (b) 5.0 eV

(c) 5.8 eV (d) 0 eV

VERY SHORT ANSWER Type Questions

19. Define the term intensity in photon picture of electromagnetic radiation. **CBSE 2019**

20. Do all the electrons that absorb a photon come out as photoelectrons? **NCERT Exemplar**

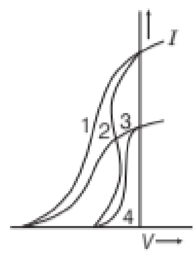
21. When radiations of frequency 10^{14} Hz is incident on certain surface, no photoemission takes place. What does this statement mean?

22. Two metals X and Y, when illuminated with appropriate radiation, emit photoelectrons. The work function of X is higher than of Y. Which metal will have higher value of threshold frequency?

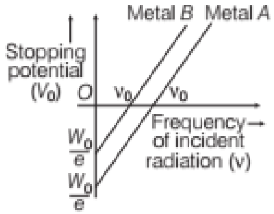
23. Two metals A and B have work functions 2 eV and 4 eV respectively. Which metal has lower threshold wavelength for photoelectric effect?

24. For a given photosensitive material and with a source of constant frequency of incident radiation, how does the photocurrent vary with the intensity of incident light? **All India 2011**

25. The given graph shows the variation of photoelectric current I *versus* applied voltage V for two different photosensitive materials and for two different intensities of the incident radiations. Identify the pairs of curves that correspond to different materials but same intensity of incident radiation. **Delhi 2013**



26. The graph shows the variation of stopping potential with frequency of incident radiation for two photosensitive metals *A* and *B*.



Which one of the two has higher value of work function? Justify your answer. **All India 2014**

27. Ultraviolet radiations of different frequencies ν_1 and ν_2 are incident on two photosensitive materials having work functions W_{O1} and W_{O2} ($W_{O1} > W_{O2}$) respectively. The kinetic energy of the emitted electrons is same in both the cases. Which one of the two radiations will be of higher frequency?

28. If the frequency of incident radiation is equal to the threshold frequency, what will be the value of stopping potential?

29. All the photoelectrons are not emitted with same energy. The energies of photoelectrons are distributed over a certain range. Why?

30. The photoelectric current at distances r_1 and r_2 of light source from photoelectric cell are I_1 and I_2, respectively . Find the value of $\frac{I_1}{I_2}$.

31. Draw graphs showing variation of photoelectric current with applied voltage for two incident radiations of equal frequency and different intensities. Mark the graph for the radiation of higher intensity. **CBSE 2018**

SHORT ANSWER Type Questions

32. 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. **NCERT Exemplar**

33. In the wave picture of light, intensity of light is determined by the square of the amplitude of the wave. What determines the intensity in the photon picture of light? **All India 2016**

34. Why does the existence of a cut-off frequency in the photoelectric effect favor a particle theory of light rather than a wave theory? Explain.

35. Two monochromatic beams *A* and *B* of equal intensity *I*, hit a screen. The number of photons hitting the screen by beam *A* is twice that by beam *B*. Then, what inference can you make about their frequencies? **NCERT Exemplar**

36. Two monochromatic radiations, blue and violet, of the same intensity are incident on a photosensitive surface and cause photoelectric emission. Would

(i) the number of electrons emitted per second and

(ii) the maximum kinetic energy of the electrons be equal in the two cases? Justify your answer. **Delhi 2010**

37. (i) In the explanation of photoelectric effect, we assume one photon of frequency ν collides with an electron and transfers its energy. This leads to the equation for the maximum energy E_{max} of the emitted electron as, $E_{max} = h\nu - \phi_0$, where ϕ_0 is the work function of the metal. If an electron absorbs 2 photons (each of frequency ν), what will be the maximum energy for the emitted electron?

(ii) Why is this fact (two photon absorption) not taken into consideration in our discussion of the stopping potential? **NCERT Exemplar**

38. Draw a graph to show the variation of stopping potential with frequency of radiation incident on a metal plate. How can the value of Planck's constant be determined from this graph?

39. Consider figure for photoemission. How would you reconcile with momentum conservation? Note light (photons) have momentum in a different direction than the emitted electrons. **NCERT Exemplar**

40. If light of wavelength 412.5 nm is incident on each of the metals given below, which ones will show photoelectric emission and why? **CBSE 2018**

Metal	Work Function (eV)
Na	1.92
K	2.15
Ca	3.20
Mo	4.17

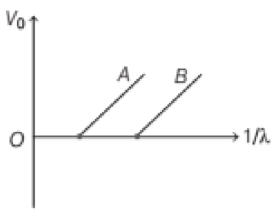
41. Why is wave theory of electromagnetic radiation not able to explain photoelectric effect? How does photon picture resolve this problem? **CBSE 2019**

LONG ANSWER Type I Questions

42. Light of same wavelength is incident on three photo-sensitive surfaces A, B and C. The following observations are recorded.
   (a) From surface A, photoelectrons are not emitted.
   (b) From surface B, photoelectrons are just emitted.
   (c) From surface C, photoelectrons with some kinetic energy are emitted.
   Compare the threshold frequencies of the three surfaces and justify your answer. **CBSE 2020**

43. (i) Describe briefly three experimentally observed features in the phenomenon of photoelectric effect.
   (ii) Discuss briefly how wave theory of light cannot explain these features. **Delhi 2015, 16**

44. Figure shows the stopping potential (V_0) for the photoelectron *versus* $\left(\frac{1}{\lambda}\right)$ graph, for two metals A and B, λ being the wavelength of incident light. **CBSE 2020**



   (a) How is the value of Planck's constant determined from the graph?
   (b) If the distance between the light source and the surface of metal A is increased, how will the stopping potential for the electrons emitted from it be effected? Justify your answer.

45. Predict and Explain
   Light of a particular wavelength does not eject electrons from the surface of a given metal.
   (i) Should the wavelength of the light be increased or decreased in order to make ejection of electrons possible?
   (ii) Choose the best explanation from among the following:
      (a) The energy of a photon is proportional to its frequency, i.e. inversely proportional to its wavelength. To increase the energy of the photons, so they can eject electrons, one must decrease their wavelength.
      (b) The photons have too little energy to eject electrons. To increase their energy, their wavelength should be increased.

46. Explain how does (i) photoelectric current and (ii) kinetic energy of the photoelectrons emitted in a photocell vary, if the frequency of incident radiation is doubled but keeping the intensity same? Show the graphical variation in the above two cases. **CBSE SQP Term-II**

47. Sketch the graphs showing variation of stopping potential with frequencies of incident radiations for two photosensitive materials A and B having threshold frequencies $\nu_A > \nu_B$.
   (i) In which case is the stopping potential more and why?
   (ii) Does the slope of the graph depend on the nature of the material used? Explain. **All India 2016**

48. Define the terms cut-off voltage and threshold frequency in relation to the phenomenon of photoelectric effect. Using Einstein's photoelectric equation, show how the cut-off voltage and threshold frequency for a given photosensitive material can be determined with the help of a suitable plot/graph. **All India 2012**

49. Define the term "cut-off frequency" in photoelectric emission. The threshold frequency of a metal is f. When the light of frequency $2f$ is incident on the metal plate, the maximum velocity of photo-electron is v_1. When the frequency of the incident radiation is increased to $5f$, the maximum velocity of photoelectrons is v_2. Find the ratio $v_1 : v_2$. **Foreign 2016**

50. Plot a graph showing the variation of stopping potential with frequency of incident radiation for two different photosensitive materials having work functions W_{01} and W_{02} ($W_{01} > W_{02}$). On what factors does the
   (i) slope and
   (ii) intercept of the lines depend?

51. (i) State two important features of Einstein's photoelectric equation.

(ii) Radiation of frequency 10^{15} Hz is incident on two photosensitive surfaces P and Q. There is no photoemission from surface P. Photoemission occurs from surface Q but photoelectrons have zero kinetic energy. Explain these observations and find the value of work function for surface Q.

Delhi 2017

52. (i) Write the important properties of photons which are used to establish Einstein's photoelectric equation.

(ii) Use this equation to explain the concept of
(a) threshold frequency and
(b) stopping potential. **Delhi 2015**

53. Write Einstein's photoelectric equation and mention which important features in photoelectric effect can be explained with the help of this equation.The maximum kinetic energy of the photoelectrons gets doubled when the wavelength of light incident on the surface changes from λ_1 to λ_2. Derive the expressions for the threshold wavelength λ_0 and work function for the metal surface.

All India 2015

54. In case of photoelectric effect experiment, explain the following facts, giving reasons.

(a) The wave theory of light could not explain the existence of the threshold frequency.

(b) The photoelectric current increases with increase of intensity of incident light.

CBSE 2020

55. If the frequency of light incident on the cathode of a photo-cell is increased, how will the following be affected? Justify your answer.

(a) Energy of the photoelectrons.

(b) Photocurrent. **CBSE 2020**

56. State the main implications of observations obtained from various photoelectric experiments. Can these implications be explained by wave nature of light? Justify your answer. **CBSE SQP**

NUMERICAL PROBLEMS

57. The photoelectric cut-off voltage in a certain experiment is 1.5 V. What is the maximum kinetic energy of photoelectrons emitted?

NCERT

58. The work function for a certain metal is 4.2 eV. Will this metal give photoelectric emission for incident radiation of wavelength 330 nm?

NCERT

59. The maximum kinetic energy of photoelectrons emitted from a surface, when photons of energy 6 eV fall on it is 4 eV. What is the stopping potential (in volt) for the fastest photoelectrons.

60. In an experiment on photoelectric effect, the slope of the cut-off voltage *versus* frequency of incident light is found to be 4.12×10^{-15} V-s. Calculate the value of Planck's constant. **NCERT**

61. Find the

(i) maximum frequency and

(ii) minimum wavelength of X-rays produced by 30 kV electrons. **NCERT**

62. (i) An X-ray tube produces a continuous spectrum of radiation with its short wavelength of 0.45 Å. What is the maximum energy of a photon in the radiation?

(ii) From your answer to (i), guess what order of accelerating voltage (for electrons) is required in such a tube? **NCERT**

63. The threshold frequency for a certain metal is 3.3×10^{14} Hz. If light of frequency 8.2×10^{14} Hz is incident on the metal, predict the cut-off voltage for the photoelectric emission. **NCERT**

64. If radiation of wavelength 5000 Å is incident on a surface of work function 1.2 eV, find the value of stopping potential. Given, $h = 6.62\times 10^{-34}$ J-s.

65. Light of frequency 7.21×10^{14} Hz is incident on a metal surface. Electrons with a maximum speed of 6×10^5 m/s are ejected from the surface. What is the threshold frequency for photoemission of electrons? **NCERT**

66. Consider a metal exposed to light of wavelength 600 nm. The maximum energy of the electron doubles when light of wavelength 400 nm is used. Find the work function in eV.

NCERT Exemplar

67. In an accelerator experiment on high energy collisions of electrons with positrons, a certain event is interpreted as annihilation of an electron-positron pair of total energy 10.2 BeV into two γ-rays of equal energy. What is the wavelength associated with each γ-ray?
($1\ \text{BeV} = 10^9\ \text{eV}$)

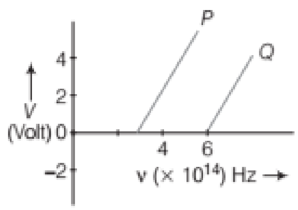
68. Aluminium and calcium have photoelectric work functions of $\phi_{Al} = 4.28$ eV and $\phi_{Ca} = 2.87$ eV, respectively.

(i) Which metal requires higher frequency light to produce photoelectrons? Explain.

(ii) Find out the minimum frequency that will produce photoelectrons from each surface.

69. The work functions for the following metals are given, Na = 2.75 eV, K = 2.30 eV, Mo = 4.17 eV, Ni = 5.15 eV. Which of these metals will not give photoelectric emission for a radiation of wavelength 3300 Å from a He-Cd laser placed 1 m away from the photocell? What happens if the laser is brought nearer and placed 50 cm away? **NCERT**

70. In the study of a photoelectric effect, the graph between the stopping potential *V* and frequency ν of the incident radiation on two different metals *P* and *Q* is shown below.



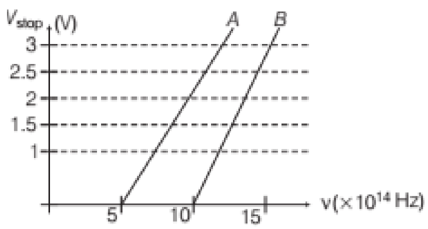
(i) Which one of the two metals has higher threshold frequency?

(ii) Determine the work function of the metal which has greater value.

(iii) Find the maximum kinetic energy of electron emitted by light of frequency 8×10^{14} Hz for this metal. **Delhi 2017**

71. A student performs an experiment on photoelectric effect, using two materials *A* and *B*. A plot of V_{stop} *versus* ν is given in the figure.

(i) Which material *A* or *B* has a higher work function?



(ii) Given the electric charge of an electron $= 1.6 \times 10^{-19}$ C, find the value of *h* obtained from the experiment for both *A* and *B*.

Comment on whether it is consistent with the Einstein's theory. **NCERT Exemplar**

72. The work function of caesium metal is 2.14 eV. When light of frequency 6×10^{14} Hz is incident on the metal surface, photoemission of electrons occurs. What is the

(i) maximum kinetic energy of the emitted electrons,

(ii) stopping potential and

(iii) maximum speed of the emitted photoelectrons? **NCERT**

73. When light with a frequency 547.5 THz illuminates a metallic surface, the most energetic photoelectrons have 1.260×10^{-19} J of kinetic energy. When light with a frequency of 738.8 THz is used instead, the most energetic photoelectrons have 2.480×10^{-19} J of kinetic energy. Using these experimental results, determine the approximate value of Planck's constant.

74. Monochromatic radiation of wavelength 640.2 nm ($1 \text{ nm} = 10^{-9}$ m) from a neon lamp irradiates a photosensitive material made of calcium or tungsten. The stopping voltage is measured to be 0.54 V. The source is replaced by an iron source and its 427.2 nm line irradiates the same photocell. Predict the new stopping voltage. **NCERT**

75. A mercury lamp is a convenient source for studying frequency dependence of photoelectric emission, since it gives a number of spectral lines ranging from the UV to the red end of the visible spectrum. In our experiment with rubidium photocell, the following lines from a mercury source were used

$\lambda_1 = 3650$ Å, $\lambda_2 = 4047$ Å, $\lambda_3 = 4358$ Å,
$\lambda_4 = 5461$ Å, $\lambda_5 = 6907$ Å

The stopping voltages respectively were measured to be

$V_{01} = 1.28$ V, $V_{02} = 0.95$ V,
$V_{03} = 0.74$ V, $V_{04} = 0.16$ V, $V_{05} = 0$

Determine the value of Planck's constant *h*, the threshold frequency and work function for the material. **NCERT**

76. What is the energy associated in joule with a photon of wavelength 4000 Å?

77. What is the energy of a photon in eV corresponding to the visible light of maximum wavelength?

78. The energy flux of sunlight reaching the surface of the earth is $1.388 \times 10^3\ W/m^2$. How many photons (nearly) per square metre are incident on the earth per second? Assume that the photons in the sunlight have an average wavelength of 550 nm. **NCERT**

79. There are two sources of light, each emitting with a power of 100 W. One emits X-rays of wavelength 1 nm and the other visible light at 500 nm. Find the ratio of number of photons of X-rays to the photons of visible light of the given wavelength. **NCERT Exemplar**

80. A 100 W sodium lamp radiates energy uniformly in all directions. The lamp is located at the centre of a large sphere that absorbs all the sodium light which is incident on it.

The wavelength of the sodium light is 589 nm.

(i) What is the energy per photon associated with the sodium light?

(ii) At what rate are the photons delivered to the sphere? **NCERT**

81. How many photons per second does a 100 W bulb emit if its efficiency is 10% and wavelength of light emitted is 500 nm?

82. Light of intensity $10^{-5}\ Wm^{-2}$ falls on a sodium photocell of surface area $2\ cm^2$. Assuming that, the top 5 layers of sodium absorb the incident energy, estimate the time required for photoelectric emission in the wave picture of radiation. The work function of the metal is given to be about 2 eV. What is the implication of your answer?

Effective atomic area $= 10^{-20} m^2$. **NCERT**

HINTS AND SOLUTIONS

1. (d) Hallwachs and Lenard also observed that when ultraviolet light fell on the emitter plate, no electrons were emitted at all when the frequency of the incident light was smaller than a certain minimum value, called the threshold frequency. This minimum frequency depends on the nature of the material of the emitter plate.

2. (c) When the wavelength of incident light is $\lambda \leq \lambda_0$, then the electrons will come out of the metal surface.

3. (d) Photocurrent varies linearly with intensity. The photocurrent is directly proportional to the number of photoelectrons emitted per second. This implies that, it is a straight line passing through origin.

4. (a) Given, work function = 2eV

Energy of incident photon = 3.4 eV

From Einstein's equation of photoelectric effect,

$$h\nu = h\nu_0 + k$$
$$3.4\ \text{eV} = 2\text{eV} + k$$
$$k = 3.4\ \text{eV} - 2.0\ \text{eV} = 1.4\ \text{eV}$$

5. (b) 3 : 4;

From Einstein's photoelectric equation, maximum kinetic energy of emitted electrons,

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

where, h is Planck's constant,

ν is frequency of incident radiation

and ν_0 is threshold frequency of metal surface.

For metal A,

$$K_{(max)A} = h\left(\nu - \frac{\nu}{2}\right)$$

or $$K_{(max)A} = \frac{h\nu}{2} \quad \text{... (i)}$$

Similarly, for metal B,

$$K_{(max)B} = h\left(\nu - \frac{\nu}{3}\right)$$

or $$K_{(max)B} = \frac{2h\nu}{3} \quad \text{... (ii)}$$

So, from Eqs. (i) and (ii), the ratio of the maximum kinetic energy of electrons emitted from A to that from B is given as,

$$\frac{K_{(max)A}}{K_{(max)B}} = \frac{\frac{h\nu}{2}}{\frac{2h\nu}{3}}$$
$$= \frac{1}{2} \times \frac{3}{2} = \frac{3}{4}$$

or $$K_{(max)A} : K_{(max)B} = 3:4$$

6. (d) When a beam of electrons of energy E_0 is incident on a metal surface kept in an evacuated chamber electrons can be emitted with maximum energy E_0 (due to elastic collision) and with any energy less than E_0, when part of incident energy of electron is used in liberating the electrons from the surface of metal.

7. (d) We know that, $E = h\nu$ and

$$E = mc^2 \quad \text{(Einstein mass energy equation)}$$

$\therefore\ mc^2 = h\nu \Rightarrow m = h\nu/c^2$

Moving mass, $$m = \frac{(hc/\lambda)}{c^2} = \frac{h}{c\lambda}$$

8. (b) Given in the question,

Energy of a photon, $E = 1\text{ MeV} \Rightarrow E = 10^6\text{ eV}$

Now, $$hc = 1240\text{ eVnm}$$

Now, $$E = \frac{hc}{\lambda}$$

$$\Rightarrow \lambda = \frac{hc}{E} = \frac{1240\text{ eVnm}}{10^6\text{ eV}}$$
$$= 1.24 \times 10^{-3}\text{ nm}$$

9. (c) The photoelectric current in a photocell is related to the distance of source of light as

$$I \propto \frac{1}{r^2}$$

$$\therefore \frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

Here, $r_1 = d, r_2 = \frac{d}{2}$ and $I_1 = I$

$$\therefore \frac{I}{I_2} = \frac{\left(\frac{d}{2}\right)^2}{(d)^2} = \frac{1}{4} \quad \text{or} \quad I_2 = 4I$$

10. (c) The photo electric current in a photocell is related to the distance of source of light as

$$I \propto \frac{1}{r^2}$$

$$\therefore \frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

Here $r_1 = d,\ r_2 = \frac{d}{3},\ I_1 = I$

$$\therefore \frac{I}{I_2} = \frac{\left(\frac{d}{3}\right)^2}{(d)^2} = \frac{1}{9}$$

$$\Rightarrow I_2 = 9I$$

11. (a) Cathode ray particles when strike the electrons of glass atom, the electrons of glass atom are excited and move to higher energy levels. On de-excitation, they fall to their ground state and release energy. As energy levels are characteristics of glass, glow depends on glass.

12. (c) Sensitivity of a photoelectric materials greatly depends on its surface characteristics. When emitter plate is coated with a materials of low work function, photoemission occurs even at low frequency.

13. (a) We know that, intensity is energy per unit area per unit time.

14. (a) The number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation and kinetic energy of photoelectrons depends on frequency of incident radiation.

15. (b) Work function is the minimum energy required to eject the photoelectron from photosensitive metal. Hence for metal to be photosensitive, the work-function should be small.

Work function $= h\nu_0$

where, ν_0 is the threshold frequency.

16. (c) 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.

17. (c) Photocell is a technical application of the photoelectric effect. It is a device which converts light energy into electric energy. It is also called an electric eye. Photocell are used in the reproduction of sound in motion picture and in the television camera.

18. (i) (c) Energy of the incident photons,

$$E_i = 10.6\text{ eV}$$
$$= 10.6 \times 1.6 \times 10^{-19}$$
$$E_i = 16.96 \times 10^{-19}\text{ J}$$

(ii) (b) Energy incident per unit area per unit time (intensity) = 2 J

$\therefore$ Number of photons incident on unit area in unit time

$$= \frac{2}{16.96 \times 10^{-19}} = 1.18 \times 10^{18}$$

Therefore, number of photons incident on given area $(1.0 \times 10^{-4}\text{ m}^2)$

$$= (1.18 \times 10^{18})(1.0 \times 10^{-4}) = 1.18 \times 10^{14}$$

(iii) (b) As, only 0.53% of incident photons emit photoelectrons.

$\therefore$ Number of photoelectrons emitted per second (n),

$$n = \left(\frac{0.53}{100}\right)(1.18 \times 10^{14}) = 6.25 \times 10^{11}$$

(iv) (a) $K_{max} = E_i$ − work-function $= (10.6 - 5.6) = 5.0\text{ eV}$

(v) (d) $K_{min} = 0$, kinetic energy of photoelectrons varies from 0 $(\text{KE})_{max}$. Hence, minimum possible KE of any photoelectron is zero.

19. **Intensity** It is the number of photons passing through an area in a given interval of time. Its SI unit is watt/steradian.

20. In photoelectric effect, we can observe that most electrons get scattered into the metal by absorbing a photon.

Thus, all the electrons that absorb a photon does not come out as photoelectron. Only a few comes out of metal whose energy becomes greater than the work function of metal.

21. The value of threshold frequency is more than 10^{14} Hz.

22. Since, work function is given as,

$$W_0 = h\nu_o$$
$$\Rightarrow W_0 \propto \nu_0$$

As work function of metal X is higher than metal Y, so metal X has higher threshold frequency than metal Y.

23. We know that,

$$\lambda_0 = \frac{hc}{\phi_0} \qquad \left[\because \phi_0 = \frac{hc}{\lambda_0}\right]$$

$\therefore$ $$\lambda_0 \propto \frac{1}{\phi_0}$$

Hence, metal B has lower threshold wavelength.

24. The photocurrent increases linearly with the intensity of incident radiation.

25. Curves 1 and 2 correspond to similar materials, while curves 3 and 4 represent different materials, since the value of stopping potential for the pair of curves (1 and 2) and (3 and 4) are the same. For given frequency of the incident radiation, the stopping potential is independent of its intensity. So, the pairs of curves (1 and 3) and (2 and 4) correspond to different materials but same intensity of incident radiation.

26. Metal A has higher value of work function because the slopes of both materials are constant and the intercept of the line depends on work function.

27. As, $K_{max} = h\nu - W_0$

$\therefore$ $$\nu = \frac{K_{max} + W_0}{h}$$

$\because W_{01} > W_{02}$ and K_{max} is same, hence $\nu_1 > \nu_2$.

28. We know that,

$$K_{max} = eV_0 = h(\nu - \nu_0)$$

Here, $\nu = \nu_0$

$\therefore$ $eV_0 = h(\nu_0 - \nu_0)$

$\Rightarrow$ $eV_0 = 0$

$\therefore$ $V_0 = 0$

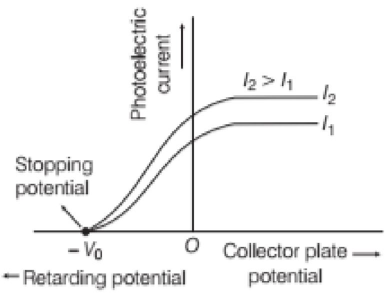
Hence, stopping potential becomes zero when frequency of incident radiation is equal to threshold frequency.

29. All the electrons in the photo-sensitive material do not belong to the highest level of energy. The energies of the free electrons in the material belongs to many different closely spaced levels. So, the energies of the photoelectrons emitted from the material are distributed over a certain range.

30. Since, $$I \propto \frac{1}{r^2}$$

So, $$\frac{I_1}{I_2} = \left(\frac{r_2}{r_1}\right)^2$$

31.



Variation of photoelectric current *versus* potential for different intensities.

32. According to first statement, when the materials which absorb photons of shorter wavelength has high energy of the incident photon on the material and low energy of emitted photon of longer wavelength.

But in second statement, the energy of the incident photon is low for the substances which has to absorb photons of larger wavelength and energy of emitted photon is high to emit light of shorter wavelength.

This means in this statement material has to supply the energy for the emission of photons. But this is not possible for a stable substances.

33. For a given frequency, intensity of light in the photon picture is determined by

$$I = \frac{\text{energy of photons}}{\text{area} \times \text{time}} = \frac{n \times h\nu}{A \times t}$$

where, n is the number of photons incident normally on cross-sectional area A in time t.

34. Refer to text on page 440.

35. The number of photons of beam $A = n_A$

The number of photons of beam $B = n_B$

According to the question, $n_A = 2n_B$

Let ν_A be the frequency of beam A and ν_B be the frequency of beam B.

$\therefore$ Intensity $\propto$ Energy of photons

$\Rightarrow$ $I \propto (h\nu) \times$ Number of photons

$\therefore$ $$\frac{I_A}{I_B} = \frac{n_A \nu_A}{n_B \nu_B}$$

According to the question, $I_A = I_B$

$\therefore$ $$n_A \nu_A = n_B \nu_B \text{ or } \frac{\nu_A}{\nu_B} = \frac{n_B}{n_A} = \frac{1}{2}$$

So, $\nu_B = 2\nu_A$

36. The intensities for both the monochromatic radiations are same but their frequencies are different. It represents

(i) the number of electrons ejected in two cases are same because it depends on the number of incident photons.

(ii) As, $KE_{max} = h\nu - \phi_0 = hc/\lambda - \phi_0$

[Einstein's photoelectric equation]

$\therefore$ The KE_{max} of violet radiation will be more.

37. (i) Here, it is given that, an electron absorbs 2 photons each of frequency ν, then $\nu' = 2\nu$

where, ν' is the frequency of emitted electron.

Given, $E_{max} = h\nu - \phi_0$

Now, maximum energy for emitted electrons,

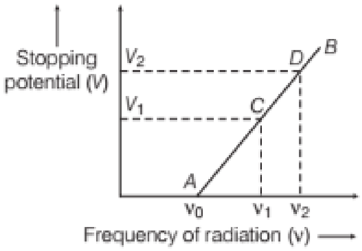
$$E'_{max} = h(2\nu) - \phi_0 = 2h\nu - \phi_0$$

(ii) The probability of absorbing 2 photons by the same electron is very low.

Hence, such emission will be negligible.

38. The variation of stopping potential with the frequency of radiation, incident on a metal plate is a straight line AB as shown in the figure.

Take two points C and D on the graph.



The corresponding frequency of radiation is ν_1, ν_2 and stopping potential is V_1, V_2.

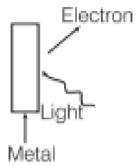
Then, $eV_1 = h\nu_1 - \phi_0$ and $eV_2 = h\nu_2 - \phi_0$

$\therefore \quad e(V_2 - V_1) = h(\nu_2 - \nu_1)$

or $$h = \frac{e(V_2 - V_1)}{\nu_2 - \nu_1}$$

Thus, Planck's constant can be determined.

39. During photoelectric emission, the momentum of incident photon is transferred to the metal. At microscopic level, atoms of a metal absorb the photon and its momentum is transferred mainly to the nucleus and electrons.



The excited electron is emitted. Therefore, the conservation of momentum is to be considered as the momentum of incident photon transferred to the nucleus and electrons.

40. Given, $\lambda = 412.5 \text{ nm} = 412.5 \times 10^{-9}$ m

$$\therefore \quad E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{412.5 \times 10^{-9} \times 1.6 \times 10^{-19}} \text{ eV}$$

$= 3.01$ eV

From the given question, work function (ϕ) of the following metals are given as

Na $\rightarrow$ 1.92, K $\rightarrow$ 2.15

Ca $\rightarrow$ 3.20, Mo $\rightarrow$ 4.17

As the given energy is greater than the work function of Na and K only, hence these metals shows photoelectric emission.

41. Refer to text on page 438 (Photoelectric Effect and Wave Theory of Light)

42. From Einstein's photoelectric equation,

$$K_{\text{max}} = \frac{1}{2}mv^2_{\text{max}} = h(\nu - \nu_0)$$

where, h = Planck's constant,

ν = frequency of incident light

and ν_0 = threshold frequency of the photosensitive surface.

So, for photoemission to takes place, $\nu > \nu_0$.

As the wavelength of light incident is same for all the three surfaces, so

(a) threshold frequency of surface A is higher than the frequency of incident light, as no emission takes place.

(b) threshold frequency of surface B is equal to the frequency of incident light, as photoelectrons are just emitted.

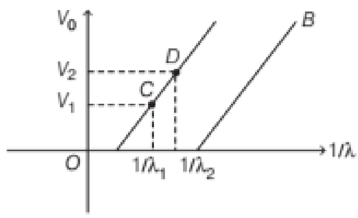
(c) threshold frequency of surface C is lower than the frequency of incident light, as the emitted photoelectrons have some kinetic energy.

$$\therefore \quad (\nu_0)_A > (\nu_0)_B > (\nu_0)_C$$

43. (i) Refer to the text on pages 435 to 437.

(ii) Refer to the text on page 438.

44. (a) The variation of stopping potential (V_0) for the photoelectron *versus* $\left(\frac{1}{\lambda}\right)$ graph is as shown below



Take any two points C and D on the graph as shown above.

According to Einstein's photoelectric equation, we can write,

$$eV_1 = \frac{hc}{\lambda_1} - \phi_0 \quad \text{...(i)}$$

where, ϕ_0 is the work function of metal A.

and $$eV_2 = \frac{hc}{\lambda_2} - \phi_0 \quad \text{...(ii)}$$

Subtracting Eq. (i) from Eq. (ii), we get

$$\Rightarrow \quad e(V_2 - V_1) = hc\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)$$

or $$h = \frac{e(V_2 - V_1)}{c\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)} = \frac{e(V_2 - V_1)\lambda_1\lambda_2}{c(\lambda_1 - \lambda_2)}$$

Thus, Planck's constant can be determined from graph.

Note Since, h is a constant, so it will be same for both metals A and B.

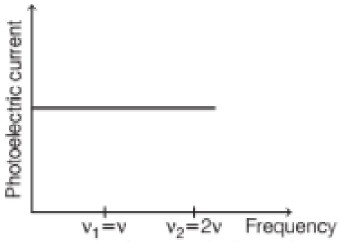
(b) Stopping potential (V_0) for the electrons emitted will not be affected by the increase in distance between light source and the metal surface A. This is because V_0 is independent of the intensity of the incident light but depends only upon the frequency (or wavelength) of incident light. So, increase in the given distance affects only the intensity of the light but not the frequency. Thus, V_0 remains same.

45. (i) Since, we know that, to eject an electron, a photon must have energy at least as great as work function (W_0) and thus the minimum or cut off frequency to eject an electron is $f_0 = \frac{W_0}{n}$.

If the incident light has the frequency below this cut off frequency, electrons are not ejected from the metal surface, so we have to increase the value of frequency, i.e. decrease the value of wavelength $\left(\text{as } \nu = \frac{c}{\lambda}\right)$.

(ii) (a) is the best explanation.

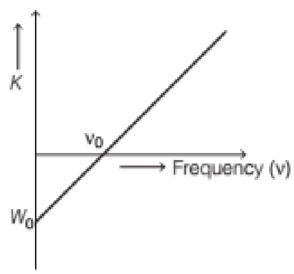
46. (i) Since, photoelectric current depends intensity of incident radiation and does not depend on the frequency of incident radiation. Therefore, when frequency of incident radiation is increased to double, then photoelectric current remains same. This is shown in the following graph



(ii) Kinetic energy of emitted photoelectrons,

$$K = \frac{1}{2}mv_{max}^2 = h\nu \Rightarrow K \propto \nu$$

Hence, on increasing the frequency of incident radiation to double, kinetic energy of emitted photoelectrons also will increase to double. This is shown below



where, ν_0 = threshold wavelength.

47. For the graph, refer to text on page 437.

(i) From the graph for the same value of ν, stopping potential is more for material *B*.

$$\text{As, } V = \frac{h}{e}(\nu - \nu_0)$$

$\therefore$ V is higher for lower value of ν_0. Here $\nu_B < \nu_A$, so $V_B > V_A$.

(ii) Slope of the graph is given by $\frac{h}{e}$ which is constant for all the materials. Hence, slope of the graph does not depend on the nature of the material used.

48. Cut-off voltage and threshold frequency

Refer to text on pages 436 and 437.

Graph between stopping potential (V_0) and frequency (ν).

Refer to text on page 437.

49. For cut-off frequency, refer to text on page 437.

Given that threshold frequency of metal is f and frequency of light is $2f$. Using Einstein's equation for photoelectric effect, we can write

$$h(2f - f) = \frac{1}{2}mv_1^2 \quad \text{... (i)}$$

Similarly, for light having frequency $5f$, we have

$$h(5f - f) = \frac{1}{2}mv_2^2 \quad \text{... (ii)}$$

Using Eqs. (i) and (ii), we find

$$\frac{f}{4f} = \frac{v_1^2}{v_2^2}$$

$$\Rightarrow \quad \frac{v_1}{v_2} = \sqrt{\frac{1}{4}} \Rightarrow \frac{v_1}{v_2} = \frac{1}{2}$$

50. Refer to the text and graph on page 437.

51. (i) Refer to text on page 438.

(ii) Energy of incident photon is less than work function of *P* but just equal to that of *Q*.

(i) For *Q*,

$$\text{Work function, } \phi_0 = \frac{h\nu}{e}(\text{eV})$$

$$= \frac{6.6 \times 10^{-34} \times 10^{15}}{1.6 \times 10^{-19}}$$

$$= 4.1 \text{ eV}$$

52. (i) Refer to text on page 474.

(ii) Since, Einstein's photoelectric equation is given by

$$\text{KE}_{max} = \frac{1}{2}mv_{max}^2 = h\nu - h\nu_0 = eV_0$$

(a) For a given material, there exist a certain minimum frequency of the incident radiation, below which no emission of photoelectron takes place. This frequency is called threshold frequency (ν_0). Above threshold frequency, the maximum kinetic energy of the emitted photoelectron or equivalent stopping potential is independent of the intensity of the incident light but depends only upon the frequency of the incident light.

(b) If the collecting plate in the photoelectric apparatus is made at high negative potential, then most of the high energetic electrons get repelled back along the same path and the photoelectric current in the circuit becomes zero. So, for a particular frequency of incident radiation, the minimum negative potential for which the electric current becomes zero is called cut-off or stopping potential (V_0).

53. Einstein's photoelectric equations and its features

Refer to theory on pages 438 and 439.

According to the photoelectric equation,

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

$$K_{max} = \frac{hc}{\lambda_1} - \phi_0 \quad ...(i)$$

Let the maximum kinetic energy for the incident radiation (of wavelength λ_2) be K'_{max}.

$$\Rightarrow \quad K'_{max} = \frac{hc}{\lambda_2} - \phi_0 \quad ...(ii)$$

From Eqs. (i) and (ii), we get

$$\frac{hc}{\lambda_2} - \phi_0 = 2\left(\frac{hc}{\lambda_1} - \phi_0\right) \quad [\because K'_{max} = 2K_{max}]$$

$$\Rightarrow \quad \phi_0 = hc\left(\frac{2}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$$\Rightarrow \quad h\nu_0 = hc\left(\frac{2}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$$\frac{c}{\lambda_0} = c\left(\frac{2}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$$\Rightarrow \quad \frac{1}{\lambda_0} = \left(\frac{2}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$$\Rightarrow \quad \lambda_0 = \left(\frac{\lambda_1\lambda_2}{2\lambda_2 - \lambda_1}\right)$$

54. (a) Refer to text on page 438.

Refer to text on page 436.

55. (a) The energy of photoelectrons in a photocell is given by,

$$E = \frac{hc}{\lambda} = h\nu \Rightarrow E \propto \nu$$

So, if the frequency of light incident on the cathode is increased, the energy of photoelectrons increases linearly.

(b) As, photoelectric current/photocurrent of the photocell is independent of frequency of the incident light, till intensity remains constant. So, when the frequency of light incident on the cathode of photo-cell is increased keeping other factors same, the photoelectric current remains the same.

56. Main implications of observations obtianed from various photoelectric experiments given as

(i) For a given material and a given frequency of incident radiation, the photoelectric current or number of photoelectrons ejected per second is directly proportional to the intensity of the incident light.

(ii) For a given material, there exists a certain minimum frequency of the incident radiation below which no emission of photoelectrons takes place. This frequency is called **threshold frequency.**

Above the threshold frequency, the maximum kinetic energy of the emitted photoelectrons or equivalent stopping potential is independent of the intensity of the incident light but depends upon only the frequency (or wavelength) of the incident light.

Photoelectric Effect and Wave Theory of Light

Huygens' wave theory of light could not explain the photoelectric emission due to the following main reasons

(i) According to the wave nature of light, the free electrons at the surface of the metal absorb the radiant energy continuously.

The greater the intensity of radiation, the greater should be the energy absorbed by each electron. The maximum kinetic energy of the photoelectrons on the surface is then expected to increase with increase in intensity.

But according to experimental facts, the maximum kinetic energy of ejected photoelectrons is independent of intensity of incident radiation.

(ii) According to wave theory of light, no matter what the frequency of radiation is, a sufficiently intense beam of radiation should be able to impart enough energy to the electrons, so that they exceed the minimum energy needed to escape from metal surface.

A threshold frequency, therefore should not exist which contradicts the experimental fact that, no photoelectric emission takes place below that threshold frequency, no matter whatsoever may be its intensity.

57. Given, cut-off voltage,

$$V_0 = 1.5\,V$$

Maximum kinetic energy is given by,

$$KE_{max} = eV_0 = 1.5\text{ eV}$$
$$= 1.5 \times 1.6 \times 10^{-19}$$
$$= 2.4 \times 10^{-19}\text{ J}$$

58. Given, $\phi_0 = 4.2$ eV

$$= 4.2 \times 1.6 \times 10^{-19}\text{ J}$$
$$= 6.72 \times 10^{-19}\text{ J}$$

and $\lambda = 330\text{ nm} = 330 \times 10^{-9}\text{ m}$

Energy of incident photon, $E = \frac{hc}{\lambda}$

$$= \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{330 \times 10^{-9}}$$
$$= 6.027 \times 10^{-19}\text{ J}$$

As energy of incident photon $E < \phi_0$, hence no photoelectric emission will take place.

59. We know that, $h\nu = h\nu_0 + eV_0$

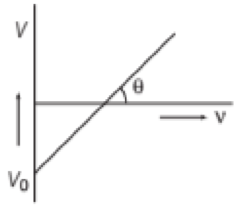
where, $eV_0 = \frac{1}{2}mv^2{}_{max}$

$= 4\text{eV}$ or $eV_0 = 4\text{eV}$

$\therefore \quad V_0 = 4\text{V}$

60. Given, slope of graph,

$$\tan\theta = 4.12\times10^{-15}\ \text{V-s}$$



Charge on electron, $e = 1.6\times10^{-19}$ C

Slope of graph of cut off voltage *versus* frequency is

$$\tan\theta = \frac{V}{\nu}$$

We know that, $h\nu = eV$ or $\frac{V}{\nu} = \frac{h}{e}$

$$\therefore \quad \frac{h}{e} = 4.12\times10^{-15}$$

$$\Rightarrow \quad h = 1.6\times10^{-19}\times4.12\times10^{-15}$$

$$= 6.592\times10^{-34}\text{J-s}$$

61. (i) Energy $= eV = h\nu$

or $\nu = \frac{eV}{h} = \frac{1.6\times10^{-19}\times30\times10^{3}}{6.63\times10^{-34}} = 7.24\times10^{18}$ Hz

(ii) As, $c = \nu\lambda$

$\therefore$ Wavelength, $\lambda = \frac{c}{\nu} = \frac{3\times10^{8}}{7.24\times10^{18}} = 0.0414$ nm

62. (i) As given in the question,
$\lambda_{min} = 0.45\ \text{Å} = 0.45\times10^{-10}$ m
The maximum energy of an X-ray photon is,

$$E_{max} = h\nu_{max} = \frac{hc}{\lambda_{min}}$$

$$= \frac{6.63\times10^{-34}\times3\times10^{8}}{0.45\times10^{-16}}\text{J}$$

$$= \frac{6.63\times3\times10^{-16}}{0.45\times1.6\times10^{-19}}\ \text{eV}$$

$$= 27.6\times10^{3}\ \text{eV}$$

$$= 27.6\ \text{keV}$$

(ii) In X-ray tube, accelerating voltage provides the energy to the electrons which produces X-rays. For getting X-rays, photon of 27.6 keV is required such that the incident electrons must possess kinetic energy 27.61 keV.

Energy $= eV = E$, $eV = 27.6$ keV
$V = 27.6\ \text{kV} \simeq 30\text{kV}$

So, the order of accelerating voltage is 30 kV.

63. Using the formula for kinetic energy,

Cut-off voltage, $V_0 = \frac{h(\nu-\nu_0)}{e}$

$$= \frac{6.63\times10^{-34}\ (8.2\times10^{14} - 3.3\times10^{14})}{1.6\times10^{-19}} = 2.03\ \text{V}$$

64. Given, $\lambda = 5000\text{Å} = 5\times10^{-7}$ m

and $\phi_0 = 1.2\text{eV} = 1.2\times1.6\times10^{-19}\text{J} = 1.92\times10^{-19}\text{J}$

We know that, $eV_0 = h\nu - h\nu_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$

$$= hc/\lambda - \phi_0 \qquad \left[\because \phi_0 = \frac{hc}{\lambda_0}\right]$$

$$\therefore \quad V_0 = \frac{hc}{e\lambda} - \frac{\phi_0}{e} = \frac{6.62\times10^{-34}\times3\times10^{8}}{1.6\times10^{-19}\times5\times10^{-7}} - \frac{1.92\times10^{-19}}{1.6\times10^{-19}}$$

$$= 2.4825 - 1.2 = 1.28\text{V}$$

65. Given,

$$\nu = 7.21\times10^{14}\ \text{Hz},\quad m = 9.1\times10^{-31}\ \text{kg}$$

$$v_{max} = 6\times10^{5}\ \text{m/s}$$

Let ν_0 be the threshold frequency.
Use the formula for kinetic energy,

$$\text{KE} = \frac{1}{2}mv^2_{max} = h\nu - h\nu_0$$

$$= \frac{1}{2}\times9.1\times10^{-31}\times(6\times10^{5})^2 = 6.63\times10^{-34}(\nu-\nu_0)$$

or $\nu - \nu_0 = \frac{36\times9.1\times10^{-21}}{2\times6.63\times10^{-34}} = 2.47\times10^{14}$ Hz

$$\therefore \quad \nu_0 = 4.74\times10^{14}\ \text{Hz}$$

66. Given, for the first condition, $\lambda = 600$nm

For the second condition, $\lambda' = 400$nm

$$K'_{max} = 2K_{max}$$

Here, $K'_{max} = \frac{hc}{\lambda} - \phi \Rightarrow 2K_{max} = \frac{hc}{\lambda'} - \phi_0$

$$\Rightarrow 2\left(\frac{1240}{600} - \phi\right) = \left(\frac{1240}{400} - \phi\right) \qquad [\because hc = 1240\ \text{eV-nm}]$$

$$\Rightarrow \quad \phi = \frac{1240}{1200} = 1.03\ \text{eV}$$

67. Total energy of 2 γ-rays = 10.2 BeV = 10.2×10^{9} eV

$\therefore$ Energy of each γ-rays,

$$E = \frac{1}{2}(10.2\times10^{9}\times1.6\times10^{-19})\ \text{J} = 8.16\times10^{-10}\ \text{J}$$

As energy of γ-rays, $E = h\nu = \frac{hc}{\lambda}$

$$\therefore \lambda = \frac{hc}{E} = \frac{6.63\times10^{-34}\times3\times10^{8}}{8.16\times10^{-10}} = 2.43\times10^{-16}\ \text{m}$$

68. Given, $\phi_{Al} = 4.28\text{eV}, \phi_{ca} = 2.87\text{eV}$

Also, $\phi = h\nu_0$

$$\therefore \quad \phi_{Al} = 4.28\text{eV} = h\nu_{0Al}$$

$$\Rightarrow \nu_{0Al} = \frac{4.28\times1.6\times10^{-19}}{6.62\times10^{-34}} = 1.03\times10^{15}\text{Hz}$$

Similarly, $\nu_{0ca} = \frac{2.87\times1.6\times10^{-19}}{6.62\times10^{-34}} = 6.93\times10^{14}\text{Hz}$

(i) Aluminium requires higher frequency of light to produce photoelectrons, i.e. 1.03×10^{15} Hz

(ii) Ca has minimum frequency, i.e. 6.93×10^{14} Hz that will produce photoelectrons from each surface.

69. Energy of the incident radiation of wavelength λ,

$$E=\frac{hc}{\lambda}=\frac{(6.63\times10^{-34})\times(3\times10^{8})}{3300\times10^{-10}\times1.6\times10^{-19}}$$

$$=3.76\text{ eV}$$

This energy of the incident radiation is greater than the work function of Na and K but less than those of Mo and Ni. So, photoelectric emission will occur only in Na and K metals and not in Mo and Ni.

If the laser is brought closer, the intensity of incident radiation increases. This does not affect the result regarding Mo and Ni metals, while photoelectric current from Na and K will increase in proportion to intensity.

70. (i) Since, Q has greater negative intercept, it will have greater ϕ (work function) and hence higher threshold frequency.

(ii) To know work function of Q, we put $V=0$ in the following equation.

$$V=\frac{h\nu}{e}-\frac{\phi}{e}$$

$$\Rightarrow\quad 0=\frac{h\nu}{e}-\frac{\phi}{e}\Rightarrow\phi=h\nu$$

$$\therefore\quad \phi=6.6\times10^{-34}\times6\times10^{14}\text{ J}$$

$$=\frac{6.6\times6\times10^{-20}}{1.6\times10^{-19}}\text{ eV}=2.5\text{ eV}$$

(iii) From the equation, $\nu\lambda=c$

$$\Rightarrow\quad\lambda=\frac{c}{\nu}=\frac{3\times10^{8}}{8\times10^{14}}=\frac{30}{8}\times10^{-7}\text{m}$$

$$=\frac{30}{8}\times10^{3}\times10^{-10}\text{m}=\frac{30}{8}\times10^{3}\text{ Å}=3750\text{ Å}$$

$$\text{Energy}=\frac{12375}{\lambda(\text{Å})}=\frac{12375}{3750}\text{ eV}=3.3\text{ eV}$$

$\therefore$ Maximum KE of emitted electron $=3.3-2.5$ eV $=0.8$ eV

71. (i) Refer to Q. 56.
Thus, work function of B is higher than A.

(ii) For metal A, slope $=\frac{h}{e}=\frac{2}{(10-5)\times10^{14}}$

or $$h=\frac{2\times e}{5\times10^{14}}=\frac{2\times1.6\times10^{-19}}{5\times10^{14}}$$

$$=6.4\times10^{-34}\text{ J-s}$$

For metal B, slope $=\frac{h}{e}=\frac{2.5}{(15-10)\times10^{14}}$

or $$h=\frac{2.5\times e}{5\times10^{14}}=\frac{2.5\times1.6\times10^{-19}}{5\times10^{14}}=8\times10^{-34}\text{ J-s}$$

Since, the value of h from experiment for metals A and B is different. Hence, experiment is not consistent with theory.

72. Given, work function of caesium metal, $\phi_0=2.14$ eV

Frequency of light, $\nu=6\times10^{14}$ Hz

(i) Work function, $\phi_0=2.14$ eV, $\nu=6\times10^{14}$ Hz

$$\therefore K_{max}=h\nu-\phi_0$$

$$=6.63\times10^{-34}\times6\times10^{14}-2.14$$

$$=\frac{6.63\times6\times10^{-20}}{1.6\times10^{-19}}\text{ eV}-2.14$$

$$=2.48-2.14=0.34\text{ eV}$$

(ii) Let stopping potential be V_0.

We know that, $KE_{max}=eV_0$

$$\Rightarrow\quad 0.35\text{ eV}=eV_0$$

$$\therefore\quad V_0=0.35\text{ V}$$

(iii) Maximum kinetic energy, $KE_{max}=\frac{1}{2}mv_{max}^2$

$$0.35\text{ eV}=\frac{1}{2}mv_{max}^2$$

(where, v_{max} is the maximum speed and m is the mass of electron)

$$\frac{0.35\times2\times1.6\times10^{-19}}{9.1\times10^{-31}}=v_{max}^2\qquad[\because e=1.6\times10^{-19}]$$

$$\Rightarrow\quad v_{max}^2=0.123\times10^{12}$$

$$\Rightarrow\quad v_{max}=350713.55\text{ m/s}$$

$$=350.7\text{ km/s}$$

73. Refer to Q. 59.

$h=6.377\times10^{-34}$ J-s

74. Here, for neon lamp, $\lambda=640.2$ nm $=640.2\times10^{-9}$ m

$$V_0=0.54\text{ V}$$

We know that, $eV_0=\frac{hc}{\lambda}-\phi_0$

$\therefore$ Work function, $\phi_0=\frac{hc}{\lambda}-eV_0$

$$=\frac{6.63\times10^{-34}\times3\times10^{8}}{640.2\times10^{-9}}-1.6\times10^{-19}\times0.54$$

$$=(3.1\times10^{-19}-0.864\times10^{-19})\text{ J}$$

$$=2.236\times10^{-19}\text{ J}=\frac{2.236\times10^{-19}}{1.6\times10^{-19}}\text{ eV}\simeq1.4\text{ eV}$$

For iron source, $\lambda=427.2$ nm $=427.2\times10^{-9}$ m

$$\therefore eV_0=\frac{hc}{\lambda}-\phi_0=\frac{6.63\times10^{-34}\times3\times10^{8}}{427.2\times10^{-9}}-2.236\times10^{-19}$$

$$=(4.656\times10^{-19}-2.236\times10^{-19})\text{ J}$$

$$=2.42\times10^{-19}\text{ J}$$

$\therefore$ Stopping potential, $V_0=\frac{2.42\times10^{-19}}{e}$

$$=\frac{2.42\times10^{-19}}{1.6\times10^{-19}}=1.51\text{ V}$$

75. Given, the following wavelengths from a mercury source were used

$$\lambda_1 = 3650 \text{ Å} = 3650 \times 10^{-10} \text{ m}$$
$$\lambda_2 = 4047 \text{ Å} = 4047 \times 10^{-10} \text{ m}$$
$$\lambda_3 = 4358 \text{ Å} = 4358 \times 10^{-10} \text{ m}$$
$$\lambda_4 = 5461 \text{ Å} = 5461 \times 10^{-10} \text{ m}$$
$$\lambda_5 = 6907 \text{ Å} = 6907 \times 10^{-10} \text{ m}$$

The stopping voltages are as follows:

$$V_{01} = 1.28 \text{ V}, V_{02} = 0.95 \text{ V}, V_{03} = 0.74 \text{ V}$$
$$V_{04} = 0.16 \text{ V and } V_{05} = 0$$

Frequencies corresponding to wavelengths,

$$\nu_1 = \frac{c}{\lambda_1} = \frac{3 \times 10^8}{3650 \times 10^{-10}} = 8.219 \times 10^{14} \text{ Hz}$$

Similarly,

$$\nu_2 = 7.412 \times 10^{14} \text{ Hz}, \quad \nu_3 = 6.884 \times 10^{14} \text{ Hz}$$
$$\nu_4 = 5.493 \times 10^{14} \text{ Hz}, \quad \nu_5 = 4.343 \times 10^{14} \text{ Hz}$$

As we know that, $eV_0 = h\nu - \phi_0$

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

As the graph between V_0 and frequency ν is a straight line.

The slope of this graph gives the values of $\frac{h}{e}$.

$$\therefore \frac{h}{e} = \frac{V_{01} - V_{04}}{\nu_1 - \nu_4} = \frac{1.28 - 0.16}{(8.219 - 5.493) \times 10^{14}} = \frac{1.12}{2.726 \times 10^{14}}$$

$$h = \frac{1.12 \times 1.6 \times 10^{-19}}{2.726 \times 10^{14}} = 6.573 \times 10^{-34} \text{ J-s}$$

As, $\nu_{average} = 5 \times 10^{14} \text{Hz}$ [given]

$\therefore$ Work function, $\phi_0 = h\nu_0 = 6.573 \times 10^{-34} \times 5 \times 10^{14}$

$$= 32.865 \times 10^{-20} \text{ J} = 2.05 \text{ eV}$$

76. We have, $E = h\nu \Rightarrow \frac{hc}{\lambda}$

$$\therefore E = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{4000 \times 10^{-10}} = 4.96 \times 10^{-19} \text{ J}$$

77. Maximum wavelength of visible light (i.e. of red light) is 7800 Å.

$\therefore$ Energy of red light, $E = \frac{hc}{\lambda} \cong \frac{12400 \text{ (eV - Å)}}{7800 \text{ (Å)}} = 1.6 \text{ eV}$

78. Energy of a photon, $E = \frac{hc}{\lambda}$

$\therefore$ Number of photons incident per square metre per second,

$$n = \frac{p}{E} = \frac{p}{\frac{hc}{\lambda}} = \frac{p\lambda}{hc} = \frac{(1.388 \times 10^3) \times 550 \times 10^{-9}}{(6.63 \times 10^{-34}) \times (3 \times 10^8)}$$

$$= 3.84 \times 10^{21} \text{ photons/m}^2\text{-s}$$

79. Suppose wavelength of X-rays is λ_1 and the wavelength of visible light is λ_2.

Given, $P = 100 \text{W}, \lambda_1 = 1 \text{ nm}, \lambda_2 = 500 \text{ nm}$

Also, n_1 and n_2 represent number of photons of X-rays and visible light emitted from the two sources per second.

So, $$\frac{E}{t} = P = n_1 \frac{hc}{\lambda_1} = n_2 \frac{hc}{\lambda_2}$$

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

80. Refer to example 4 on page 475.

(i) $E = 2.11 \text{eV}$ (ii) $n = 3 \times 10^{20} \text{ photon / s}$

81. Here, $\lambda = 500 \text{ nm} = 5 \times 10^{-7} \text{ m}$

Energy of one photon

$$= \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{5 \times 10^{-7}}$$
$$= 3.98 \times 10^{-19} \text{ J}$$

A bulb of 100 W supplied 100 J of energy per second.

$\therefore$ Energy released per second as visible photons

$$= \frac{100 \times 10}{100} = 10 \text{ J}$$

$\therefore$ Number of photons emitted per second as visible light

$$= \frac{10}{3.98 \times 10^{-19}} = 2.5 \times 10^{19}$$

82. Here, $I = 10^{-5} \text{ Wm}^{-2}, A = 2 \times 10^{-4} \text{ m}^2$

$$n = 5, t = ?,$$
$$\phi_0 = 2 \text{ eV} = 2 \times 1.6 \times 10^{-19} \text{ J}$$

Sodium has one conduction electron per atom and effective atomic area $= 10^{-20} \text{m}^2$

Number of conduction electrons in five layers

$$= \frac{5 \times \text{Area of one layer}}{\text{Effective atomic area}} = \frac{5 \times 2 \times 10^{-4}}{10^{-20}} = 10^{17}$$

Incident power, $P = \text{Intensity} \times \text{Area}$

$$= 10^{-5} \times 2 \times 10^{-4} = 2 \times 10^{-9} \text{ W}$$

According to wave picture, the incident power is uniformly absorbed by all the electrons continuously.

Hence, energy absorbed per second per electron

$$= \frac{\text{Incident power}}{\text{Number of electrons of five layers}}$$

$$= \frac{2 \times 10^{-9}}{10^{17}} = 2 \times 10^{-26} \text{ W}$$

$\therefore$ Time required for photoelectric emission will be,

$$t = \frac{\text{Energy required per electron for ejection}}{\text{Energy absorbed per second per atom}}$$

$$= \frac{2 \times 1.6 \times 10^{-19}}{2 \times 10^{-26}} = 1.6 \times 10^7 \text{s}$$

|TOPIC 2|

Matter Wave

Wave theory of electromagnetic radiations explained the phenomenon of interference, diffraction and polarisation of light.

On the other hand, quantum theory of electromagnetic radiations successfully explained the photoelectric effect, Compton effect, black body radiation, X-rays spectra, etc.

From photoelectric and Compton effects, it is clear that a particle (photon of radiation) is colliding against another particle (electron). It is due to this reason it was concluded that, in photoelectric effect and Compton effect, the radiation possesses particle nature.

It means radiation sometimes behaves as a wave and sometimes as a particle. Therefore, Louis Victor de-Broglie suggested that the particles like electrons, protons, neutrons, etc., have dual nature, i.e. they can have particle as well as wave nature.

Note Matter cannot exist both as a particle and as a wave simultaneously. At a particular instant of time, it is either the one or the other aspect, i.e. the two aspects are complementary to each other.

WAVE NATURE OF PARTICLES: (DE-BROGLIE HYPOTHESIS)

According to de-Broglie, a wave is associated with moving material particle which controls the particle in every respect. The wave associated with moving material particle is called **matter wave** or **de-Broglie wave** whose wavelength is called **de-Broglie wavelength** which is given by $\lambda = \frac{h}{mv}$

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

According to Planck's quantum theory, the energy of the photon is given by

$$E = h\nu = \frac{hc}{\lambda} \quad \text{...(i)}$$

According to Einstein's theory, the energy of the photon is given by

$$E = mc^2 \quad \text{...(ii)}$$

Therefore, from Eqs. (i) and (ii), we get

$$\lambda = \frac{h}{mc} \text{ or } \boxed{\lambda = \frac{h}{p}}$$

where, $p = mc$ is momentum of a photon.

If a material particle of mass m is moving with velocity v, then momentum of the particle, $p = mv$.

According to de-Broglie hypothesis, the wavelength of wave associated with moving material particle becomes

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

which is the expression for de-Broglie wavelength.

From the above expression following observations we made

(i) The de-Broglie wavelength $\lambda \propto \frac{1}{v}$. If the particle moves faster, then the wavelength will be smaller and *vice-versa*.

(ii) If the particle is at rest $(v = 0)$, then the de-Broglie wavelength is infinite $(\lambda = \infty)$. Such a wave cannot be visualised.

(iii) The de-Broglie waves cannot be electromagnetic in nature because electromagnetic waves are produced by motion of charged particles.

(iv) The wavelength of a wave associated with moving particle defines a region of uncertainty, within which the whereabouts of the particle are unknown.

These facts lead to Heisenberg's uncertainty principle. According to this principle, it is not possible to measure both the position and momentum of a particle at the same time exactly. There is always some uncertainty (Δx) in the specification of position and some uncertainty (Δp) in the specification of momentum. The product of Δx and Δp is of the order of $\hbar$, (with $\hbar = \frac{h}{2\pi}$),

i.e. $\Delta x \, \Delta p \approx \hbar = \frac{h}{2\pi}$.

Common Features of Matter Waves

Some common features of matter waves are as given below

(i) Matter waves can travel in vacuum and hence they are not mechanical waves.

(ii) Matter waves are probability waves, amplitude of which gives the probability of existence of the particle at the point. If at a point, the amplitude of the wave is A, then probability of the particle being found in a small volume dV around that point is $|A|^2 \, dV$.

EXAMPLE |1| An electron and a photon each have a wavelength 1.00 nm. Calculate

(i) their momenta,

(ii) the energy of the photon and

(iii) the kinetic energy of electron. **NCERT**

Sol. Given, $\lambda = 1$ nm $= 1\times 10^{-9}$ m, $h = 6.63\times 10^{-34}$ J-s,

$c = 3\times 10^{8}$ m/s, $p = ?$, $E = ?$, $K = ?$

(i) Momentum of the photon, $p_p = \dfrac{h}{\lambda}$

$$= \frac{6.63\times 10^{-34}}{1\times 10^{-9}} = 6.63\times 10^{-25} \text{ kg-m/s}$$

Momentum of the electron, $p_e = \dfrac{h}{\lambda}$

$$= \frac{6.63\times 10^{-34}}{1\times 10^{-9}} = 6.63\times 10^{-25} \text{ kg-m/s}$$

(ii) Energy of the photon,

$$E = \frac{hc}{\lambda} = \frac{6.63\times 10^{-34}\times 3\times 10^{8}}{1\times 10^{-9}} = 1.99\times 10^{-16}\text{ J}$$

(iii) Kinetic energy of the electron,

$$K = \frac{p^2}{2m_e} = \frac{(6.63\times 10^{-25})^2}{2\times 9.1\times 10^{-31}} = 2.41\times 10^{-19}\text{ J}$$

EXAMPLE |2| A proton and an electron have same de-Broglie wavelength. Which of them moves fast and which possesses more kinetic energy? Justify your answer.

Sol. Kinetic energy of particle of mass m having momentum p is given by

$$K = \frac{p^2}{2m} \Rightarrow p = \sqrt{2mK}$$

The de-Broglie wavelength, $\lambda = \dfrac{h}{p} = \dfrac{h}{\sqrt{2mK}}$

$\therefore \quad p = \dfrac{h}{\lambda}$ ...(i)

and $\quad K = \dfrac{h^2}{2m\lambda^2}$ ...(ii)

If λ is constant, then from Eq. (i), we get

p = constant, i.e. $m_p v_p = m_e v_e$

or $\quad \dfrac{v_p}{v_e} = \dfrac{m_e}{m_p} < 1$

or $\quad v_p < v_e$

If λ is constant, then from Eq. (ii), $K \propto \dfrac{1}{m}$

$\therefore \dfrac{K_p}{K_e} = \dfrac{m_e}{m_p} < 1$ or $K_p < K_e$.

It means that the velocity of electron is greater than that of proton. Kinetic energy of electron is greater than that of proton.

Relation between de-Broglie Wavelength (λ) and Temperature (T)

From kinetic theory of matter, the average kinetic energy of a particle at a given temperature T kelvin is given by

$$K = \frac{3}{2}kT$$

where, k = Boltzmann constant.

If a particle of mass m is moving with velocity v, then its kinetic energy is,

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

Momentum of particle is

$$p = mv = \sqrt{2mK}$$

$$= \sqrt{2m\times \frac{3}{2}kT} = \sqrt{3mkT}$$

$\Rightarrow$ de-Broglie wavelength, $\lambda = \dfrac{h}{p} = \dfrac{h}{\sqrt{3mkT}}$

EXAMPLE |3| Find de-Broglie wavelength of neutron at 127° C. Given, mass of neutron $= 1.66\times 10^{-27}$ kg, Boltzmann constant, $k = 1.38\times 10^{-23}$ J mol^{-1} K^{-1}, and Planck's constant, $h = 6.63\times 10^{-34}$ J-s.

Sol. Here,

$T = 127°\text{C} = 127 + 273 = 400$ K

Energy of neutron at 127° C,

$$E = \frac{3}{2}kT = \frac{3}{2}\times 1.38\times 10^{-23}\times 400$$

$$= 8.28\times 10^{-21}\text{ J}$$

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

$$= \frac{6.63\times 10^{-34}}{\sqrt{2\times 1.66\times 10^{-27}\times 8.28\times 10^{-21}}}$$

$$= 1.264\times 10^{-10}\text{ m}$$

$$= 1.264\text{ Å}$$

de-Broglie Wavelength of an Electron

Let an electron of charge e having mass m be accelerated from rest through a potential difference V, then

Gain in kinetic energy of an electron $= \dfrac{1}{2}mv^2$

Work done on the electron $= eV$

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

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

Momentum is given by $p = mv = \sqrt{2eVm}$

The wavelength associated with moving charge is given by

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}} \qquad \dots \text{(i)}$$

If accelerated charge is electron, then $\lambda = \frac{h}{\sqrt{2eVm_e}}$

where, m_e = mass of electron.

Substituting the numerical values of h, m_e and e in Eq. (i) we get

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9 \times 10^{-31} \times 1.6 \times 10^{-19} \times V}}$$

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

$$= \frac{12.27}{\sqrt{V}} \text{Å}$$

$$= \frac{1.227}{\sqrt{V}} \text{nm}$$

EXAMPLE |4| Determine the de-Broglie wavelength associated with an electron, accelerated through a potential difference of 100 V.

Sol. Given, potential difference $(V) = 100$ V

$\therefore$ de-Broglie wavelength $(\lambda) = \frac{12.27}{\sqrt{V}} = \frac{12.27}{\sqrt{100}} = 1.227$ Å

In this case, the wavelength associated with an electron is of the order of wavelength of X-rays.

TOPIC PRACTICE 2

OBJECTIVE Type Questions

1. The de-Broglie wave of a moving particle does not depend on

(a) mass (b) charge
(c) velocity (d) momentum

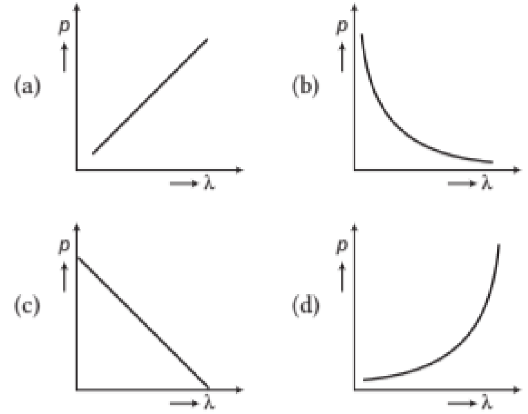
2. The de-Broglie wavelength of a particle of KE, K is λ. What will be the wavelength of the particle, if it's kinetic energy is $\frac{K}{9}$?

(a) λ (b) 2λ
(c) 3λ (d) 4λ

3. A proton, a neutron, an electron and an α-particle have same energy. Then, their de-Broglie wavelengths compare as

(a) $\lambda_p = \lambda_n > \lambda_e > \lambda_\alpha$ (b) $\lambda_\alpha < \lambda_p = \lambda_n > \lambda_e$
(c) $\lambda_e < \lambda_p = \lambda_n > \lambda_\alpha$ (d) $\lambda_e = \lambda_p = \lambda_n = \lambda_\alpha$

4. Which of the following figures represent the variation of particle momentum and the associated de-Broglie wavelength? **CBSE 2020**



5. The kinetic energy of a proton and that of an α-particle are 4 eV and 1 eV, respectively. The ratio of the de-Broglie wavelengths associated with them, will be

(a) 2 : 1 (b) 1 : 1
(c) 1 : 2 (d) 4 : 1

VERY SHORT ANSWER Type Questions

6. What consideration led de-Broglie to suggest that material particles can also show wave property?

7. Are the matter waves electromagnetic in nature?

8. Show graphically the variation of de-Broglie wavelength λ with the potential V through which an electron is accelerated from rest. **Delhi 2011**

9. Write the expression for the de-Broglie wavelength associated with a charged particle having charge q and mass m, when it is accelerated by a potential V. **Delhi 2013**

10. A photon and an electron have the same de-Broglie wavelength, which one has higher total energy?

11. A proton and an electron have same kinetic energy. Which one has greater de-Broglie wavelength and why? **All India 2012**

12. A photon and a proton have the same de-Broglie wavelength λ. Prove that the energy of the photon is $(2m\lambda c/h)$ times the kinetic energy of the proton. **CBSE 2019**

13. A particle with rest mass m_0 is moving with velocity c. What is the de-Broglie wavelength associated with it?

14. Plot a graph showing variation of de-Broglie wavelength (λ) associated with a charged particle of mass m, versus $\frac{l}{\sqrt{V}}$, where V is the potential difference through which the particle is accelerated. How does this graph give us the information regarding the magnitude of the charge of the particle?

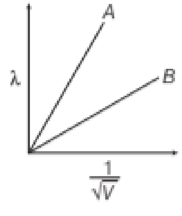
SHORT ANSWER Type Questions

15. Why is the wave nature of matter not more apparent to our daily observations?

16. Show that the wavelength of electromagnetic radiation is equal to the de-Broglie wavelength of its quantum (photon). **NCERT**

17. A proton and an α-particle are accelerated through the same potential. Which one of the two has
   (i) greater value of de-Broglie wavelength associated with it and
   (ii) less kinetic energy?
   Give reasons to justify your answer. **Delhi 2014**

18. The two lines marked A and B in the given figure, show a plot of de-Broglie wavelength λ versus $\frac{1}{\sqrt{V}}$, where V is the accelerating potential for two nuclei ^2_1H and ^3_1H.



   (i) What does the slope of the lines represent?
   (ii) Identify, which of the lines corresponded to these nuclei. **All India 2010**

19. Assuming an electron is confined to a 1 nm wide region, find the uncertainty in momentum using Heisenberg uncertainty principle $(\Delta x \times \Delta p = h)$. You can assume the uncertainty in position Δx as 1 nm. Assuming $p = \Delta p$, find the energy of the electron in eV. **NCERT Exemplar**

LONG ANSWER Type I Questions

20. An electron, α-particle and a proton have the same de-Broglie wavelengths. Which of these particle has
   (i) minimum kinetic energy?
   (ii) maximum kinetic energy and why?
   In what way has the wave nature of electron beam exploited in electron microscope?

21. Electrons are emitted from the cathode of a photocell of negligible work function, when photons of wavelength λ are incident on it. Derive the expression for the de-Broglie wavelength of the electrons emitted on terms of the wavelength of the incident light. **All India 2017 C**

22. (a) Explain de-Broglie argument to propose his hypothesis. Show that de-Broglie wavelength of photon equals electromagnetic radiation.
   (b) If deuterons and alpha particle are accelerated through same potential, find the ratio of the associated de-Broglie wavelengths of two.

NUMERICAL PROBLEMS

23. A particle is moving three times as fast as an electron. The ratio of the de-Broglie wavelength of the particle to that of the electron is 1.813×10^{-4}. Calculate the particle's mass and identify the particle. **All India 2011**

24. de-Broglie postulated that the relationship, $\lambda = \frac{h}{p}$ is valid for relativistic particles. Find out the de-Broglie wavelength for an (relativistic) electron whose kinetic energy is 3 MeV.

25. The wavelength of light from the spectral emission line of sodium is 589 nm. Find the kinetic energy at which
   (i) an electron and
   (ii) a neutron would have the same de-Broglie wavelength? **NCERT**

26. What is the
   (i) momentum (ii) speed and
   (iii) de-Broglie wavelength of an electron with kinetic energy of 120 eV? **NCERT**

27. (i) Determine the de-Broglie wavelength of a proton whose kinetic energy is equal to the rest mass energy of an electron. Mass of proton is 1836 times that of electron.
(ii) In which region of electromagnetic spectrum does this wavelength lie? **All India 2011**

28. What is the de-Broglie wavelength of
(i) a bullet of mass 0.040 kg travelling at the speed of 1.0 km/s
(ii) a ball of mass 0.060 kg moving at a speed of 1.0 m/s
(iii) a dust particle of mass 1.0×10^{-9} kg drifting with a speed of 2.2 m/s? **NCERT**

29. Obtain the de-Broglie wavelength of an electron of kinetic energy 100 eV. Mass of electron $= 9.1 \times 10^{-31}$ kg, $e = 1.6 \times 10^{-19}$ C, $h = 6.63 \times 10^{-34}$ J-s.

30. The wavelength of light from the spectral emission line of sodium is 590 nm. Find the kinetic energy at which the electron would have the same de-Broglie wavelength. **CBSE 2019**

31. (i) For what kinetic energy of a neutron will associated de-Broglie wavelength be 1.40×10^{-10} m?
(ii) Also, find the de-Broglie wavelength of a neutron, in thermal equilibrium with matter, having an average kinetic energy of (3/2) kT and temperature is 300 K. **NCERT**

32. Calculate the
(i) momentum and
(ii) de-Broglie wavelength of the electrons accelerated through a potential difference of 56 V. **NCERT**

33. Find the ratio of the de-Broglie wavelength, associated with protons, accelerated through a potential of 128 V and α-particles, accelerated through a potential of 64 V. **Delhi 2010C**

34. A proton and an α-particle have the same de-Broglie wavelength. Determine the ratio of
(i) their accelerating potentials
(ii) their speeds. **All India 2015**

35. An electron microscope uses electrons accelerated by a voltage of 50 kV. Determine the de-Broglie wavelength associated with the electrons.

Taking other factors, such as numerical aperture, etc., to be same, how does the resolving power of an electron microscope compare with that of an optical microscope which uses yellow light? **NCERT, All India 2014**

36. Crystal diffraction experiments can be performed using X-rays or electrons accelerated through appropriate voltage. Which probe has greater energy? (For quantitative comparison, take the wavelength of the probe equal to 1 Å, which is of the order of interatomic spacing in the lattice.) ($m_e = 9.11 \times 10^{-31}$ kg) **NCERT**

37. An electron is accelerated through a potential difference of 64 V. What is the de-Broglie wavelength associated with it? To which part of the electromagnetic spectrum does this value of wavelength correspond?

38. Compute the typical de-Broglie wavelength of an electron in a metal at 27 °C and compare it with the mean separation between two electrons in a metal which is given to be about 2×10^{-10} m. **NCERT**

39. Find the typical de-Broglie wavelength associated with a He atom in helium gas at room temperature (27° C) and 1 atm pressure and compare it with the mean separation between two atoms under these conditions. **NCERT**

40. The de-Broglie wavelength associated with an electron accelerated through a potential difference V is λ. What will be its wavelength when the accelerating potential is increased to 4 V?

41. An electron gun with its collector at a potential of 100 V fires out electrons in a spherical bulb containing hydrogen gas at low pressure ($\sim 10^{-2}$ mm of Hg). A magnetic field of 2.83×10^{-4} T curves the path of the electrons in a circular orbit of radius 12.0 cm. (The path can be viewed because the gas ions in the path focus, the beam by attracting electrons and emitting light by electron capture, this method is known as the fine beam tube method.) Determine e/m from the data. **NCERT**

42. (i) Estimate the speed with which electrons emitted from a heated emitter of an evacuated tube impinge on the collector maintained at a potential difference of 500 V with respect to the emitter. Ignore the small initial speeds of the electrons.

The specific charge of the electron, i.e. its e/m is given to be 1.76×10^{11} C/kg.

(ii) Use the same formula you employ in (i) to obtain electron speed for a collector potential of 10 MV. Do you see what is wrong? In what way is the formula to be modified? **NCERT**

HINTS AND SOLUTIONS

1. (b) de-Broglie wavelength, $\lambda = \frac{h}{p} = \frac{h}{mv}$

So, the de-Broglie wavelength does not depend on charge.

2. (c) de-Broglie wavelength, $\lambda = \frac{h}{\sqrt{2mK}}$ ...(i)

When the KE is $\frac{K}{9}$, then

$$\lambda' = \frac{h}{\sqrt{2m\left(\frac{K}{9}\right)}} = \frac{3h}{\sqrt{2mK}} = 3\lambda \quad \text{[using Eq. (i)]}$$

3. (b) We know that the relation between λ and K is given by

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

or $\lambda \propto \frac{1}{\sqrt{m}}$

Since, $m_p = m_n$, hence $\lambda_p = \lambda_n$

As, $m_\alpha > m_p$, therefore $\lambda_\alpha < \lambda_p$

As, $m_e < m_n$, therefore $\lambda_e > \lambda_n$

Hence, $\lambda_\alpha < \lambda_p = \lambda_n < \lambda_e$

4. (b) The de-Broglie wavelength is given by

$\lambda = h/p \Rightarrow p\lambda = h$

This equation is in the form of $yx = c$, which is the equation of a rectangular hyperbola. Hence, the graph given in option (b) is the correct one.

5. (b) The de-Broglie wavelength associated with a particle is given by

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

Given, $K_p = 4\,\text{eV}$ and $K_\alpha = 1\,\text{eV}$

$$\therefore \frac{\lambda_p}{\lambda_\alpha} = \sqrt{\frac{m_\alpha K_\alpha}{m_p K_p}} = \sqrt{\frac{4}{1} \times \frac{1}{4}} = 1 \quad \left[\because \frac{m_\alpha}{m_p} = 4\right]$$

or $\lambda_p : \lambda_\alpha = 1:1$

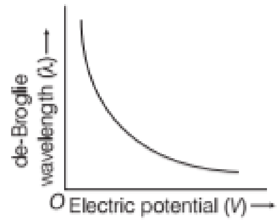
6. The following considerations led de-Broglie to suggest that material particles can also show wave property

(i) The Einstein's mass-energy relationship $E = mc^2$, i.e. matter can be converted into energy and *vice-versa*.

(ii) Wave nature loves symmetry, hence from symmetry, consideration particles like electrons, protons should exhibit wave nature when in motion.

7. No, matter waves are not electromagnetic in nature, because electromagnetic waves are only associated with accelerated charged particles, but de-Broglie wavelength $\lambda = \frac{h}{p}$, i.e. associated with momentum

8. We know that, $\lambda \propto \frac{1}{\sqrt{V}}$



$\Rightarrow \lambda^2 V = \text{constant}$ $\left[\because \text{constant} = \frac{1}{\sqrt{2me}}\right]$

9. de-Broglie wavelength,

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

10. Total energy of an electron, $E_e = mc^2$

Total energy of a photon, $E_p = \frac{hc}{\lambda}$

de-Broglie wavelength of electron of mass m moving with velocity v,

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

$$\Rightarrow m = \frac{h}{\lambda v}$$

$\therefore$ Energy of an electron, $E_e = mc^2 = \frac{hc^2}{\lambda v}$

$$\therefore \frac{E_e}{E_p} = \frac{\frac{hc^2}{\lambda v}}{\frac{hc}{\lambda}} = \frac{c}{v}$$

As $c >> v$, therefore the total energy of electron is more than the total energy of photon.

11. de-Broglie wavelength,

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}}, \text{ where } K = \text{kinetic energy}$$

For given KE, $\lambda \propto \frac{1}{\sqrt{m}}$

Since, electrons have smaller mass, i.e. $\lambda_e > \lambda_p$.
For given kinetic energy, electrons have greater de-Broglie wavelength as these have smaller mass.

12. Energy of photon, $E_p = \dfrac{hc}{\lambda}$

Energy of electron (moving particle),

$$E_e = \frac{1}{2}\frac{p^2}{m}$$

de-Broglie wavelength associated with the moving particle is

$$\lambda = h/p \text{ or } p = h/\lambda$$

$$E_e = \frac{1}{2}\frac{(h/\lambda)^2}{m} = \frac{1}{2}\frac{h^2}{\lambda^2 m}$$

$$\therefore \quad \frac{E_p}{E_e} = \frac{hc/\lambda}{\frac{1}{2}\frac{h^2}{\lambda^2 m}} = \frac{2m\lambda c}{h}$$

13. de-Broglie wavelength,

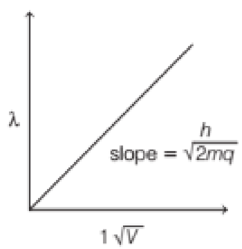
$$\lambda = \frac{h}{mv} = \frac{h\sqrt{1 - v^2/c^2}}{m_0 v}$$

$$= \frac{h\sqrt{1 - c^2/c^2}}{m_0 c} = 0 \qquad [\because v = c]$$

14. The de-Broglie wavelength is given by

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

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



Thus, it gives a straight line graph.

$$\lambda\sqrt{V} = \frac{h}{\sqrt{2mq}} = \text{slope of graph}$$

Knowing the mass of particle (m) and slope of graph, we can calculate charge (q) on a particle.

15. The de-Broglie wavelength associated with a body of mass m, moving with velocity v is given by $\lambda = \dfrac{h}{mv}$.

Since, the mass of the objects used in our daily life is very large, hence the de-Broglie wavelength associated with them is quite small and is not visible. Hence, the wave nature of matter is not more apparent to our daily observations.

16. The momentum of an electromagnetic wave of frequency ν, wavelength λ is given by

$$p = \frac{h\nu}{c} = \frac{h}{\lambda}$$

or

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

de-Broglie wavelength of photon,

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

Thus, wavelength of electromagnetic radiation is equal to the de-Broglie wavelength.

17. (i) The de-Broglie wavelength of a particle is given

$$\lambda = \frac{h}{\sqrt{2mV_0 q}}$$

So, potential V_0 is same.
Since, α-particle and proton both are accelerated through the same.

$$\therefore \quad \lambda \propto \frac{1}{\sqrt{mq}}$$

or

$$\frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{m_p q_p}{m_\alpha q_\alpha}}$$

As, charge on α-particle $= 2 \times$ charge on proton

$$q_\alpha = 2q_p \Rightarrow \frac{q_p}{q_\alpha} = \frac{1}{2}$$

Mass of α-particle $= 4 \times$ mass of proton

$$m_\alpha = 4 \times m_p \Rightarrow \frac{m_p}{m_\alpha} = \frac{1}{4}$$

$$\therefore \quad \frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{1}{4}\cdot\frac{1}{2}} = \frac{1}{2\sqrt{2}}$$

$$\Rightarrow \quad \lambda_p = 2\sqrt{2}\lambda_\alpha$$

i.e. proton has greater de-Broglie wavelength than that of α-particle.

(ii) KE $\propto q$ (for same accelerating potential)
The charge of an α-particle is more as compared to a proton. So, it will have a greater value of KE. Hence, proton will have lesser KE.

18. de-Broglie wavelength of accelerating charged particle is given by

$$\lambda = \frac{h}{\sqrt{2mqV}} \Rightarrow \lambda\sqrt{V} = \frac{h}{\sqrt{2mq}} = \text{constant}$$

(i) The slope of the lines represents $\dfrac{h}{\sqrt{2mq}}$

where, $h =$ Planck's constant, $q =$ charge and $m =$ mass of charged particle.

(ii) ${}_1H^2$ and ${}_1H^3$ carry same charge (as they have same atomic number).

$$\therefore \quad \lambda\sqrt{V} \propto \frac{1}{\sqrt{m}}$$

The lighter mass, i.e. ${}_1H^2$ is represented by line of greater slope, i.e. A and similarly, ${}_1H^3$ by line B.

19. Here, $\Delta x = 1$ nm $= 10^{-9}$ m, $\Delta p = ?$ As, $\Delta x \Delta p = \hbar$

$$\therefore \quad \Delta p = \frac{\hbar}{\Delta x} = \frac{h}{2\pi\Delta x} = \frac{6.6 \times 10^{-34} \text{ J-s}}{2 \times (22/7)(10^{-9}) \text{ m}}$$

$$= 1.05 \times 10^{-25} \text{ kg-m/s}$$

$$\therefore \quad \text{Energy } (E) = \frac{p^2}{2m} = \frac{(\Delta p)^2}{2m} \quad [\because p = \Delta p]$$

$$= \frac{(1.05 \times 10^{-25})^2}{2 \times 9.1 \times 10^{-31}} \text{ J}$$

$$= \frac{(1.05 \times 10^{-25})^2}{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19}} \text{ eV}$$

$$= 3.8 \times 10^{-2} \text{ eV}$$

20. de-Broglie matter wave equation,

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}} \quad \left[\because K = \frac{p^2}{2m}\right]$$

where, K is kinetic energy and m is mass of particle.

$$K = \frac{h^2}{2m\lambda^2} \quad \text{[for same wavelength } \lambda]$$

$$\Rightarrow \quad K \propto \frac{1}{m} \quad \Rightarrow \quad K_e : K_\alpha : K_p = \frac{1}{m_e} : \frac{1}{m_\alpha} : \frac{1}{m_p}$$

where, m_e, m_p and m_α are masses of electron, proton and α-particle, respectively.

Also, K_e, K_α and K_p are their respective kinetic energies.

$\because \quad m_\alpha > m_p > m_e$

$\Rightarrow \quad m_\alpha m_p > m_e m_\alpha > m_e m_p$

$\Rightarrow \quad K_e > K_p > K_\alpha$

(i) α-particle possesses minimum kinetic energy.

(ii) Electron has maximum kinetic energy.

The magnifying power of an electron microscope is inversely related to wavelength of radiation used. Smaller wavelength of electron beam in comparison to visible light increases the magnifying power of microscope.

21. We know that, $\quad \dfrac{hc}{\lambda} = \dfrac{hc}{\lambda_0} + \dfrac{1}{2}mv^2$

Neglecting the work function, we get

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

de-Broglie wavelength is given by, $\lambda_e = \dfrac{h}{mv}$

$$\therefore \quad \lambda_e = \frac{h\sqrt{\lambda}}{\sqrt{2mhc}} = \sqrt{\frac{h\lambda}{2mc}}$$

22. (a) **de-Broglie Hypothesis** According to de-Broglie, a wave is associated with moving material particle which controls the particle in every respect. The wave associated with moving material particle is called **matter wave** or **de-Broglie** wave whose wavelength is called de-Broglie wavelength which is given by

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

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

This means the mass and radiation are symmetrical in nature.

According to de-Broglie equation, wavelength,

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

where, p = momentum of photon.

$$= mc = \frac{h\nu}{c}$$

$$\therefore \quad \lambda = \frac{hc}{h\nu} = \frac{c}{\nu}$$

which is equal to the wavelength of an electromagnetic radiation.

(b) The de-Broglie wavelength of a particle is given by

$$\lambda = \frac{h}{\sqrt{2mV_0 q}}$$

Since, V_0 is same, so $\lambda \propto \dfrac{1}{\sqrt{mq}}$

For deuteron, $q_d = +e$, $m_d = 2m_p$

For α-particle, $q_\alpha = +2e$, $m_\alpha = 4m_p$

$$\therefore \quad \frac{\lambda_d}{\lambda_\alpha} = \sqrt{\frac{m_\alpha q_\alpha}{q_d m_d}} = \sqrt{\frac{2e \times 4m_p}{e \times 2m_p}}$$

$$= 2:1$$

23. Given, $\quad v_{\text{particle}} = 3\,v_{\text{electron}} \quad$ ...(i)

and $\quad \lambda_{\text{particle}} = 1.813 \times 10^{-4}\,\lambda_{\text{electron}}$

As, $\quad \lambda = \dfrac{h}{mv} \quad$ [de-Broglie equation]

$$\Rightarrow \quad \frac{m_{\text{particle}}}{m_{\text{electron}}} = \frac{\lambda_{\text{electron}} \times v_{\text{electron}}}{\lambda_{\text{particle}} \times v_{\text{particle}}}$$

$$= \frac{\lambda_{\text{electron}} \times v_{\text{electron}}}{1.813 \times 10^{-4} \times \lambda_{\text{electron}} \times 3v_{\text{electron}}}$$

$$\therefore \quad m_{\text{particle}} = 1839\, m_{\text{electron}} \quad \text{[given][from Eq. (i)]}$$

$$= 1839 \times 9.1 \times 10^{-31}$$

$$= 1.673 \times 10^{-27} \text{ kg}$$

$\therefore$ Particle is either a proton or a neutron.

24. de-Broglie wavelength,

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

Substituting the given values, we get

$$\lambda = 3.58 \times 10^{-3} \text{m}$$

25. Given, wavelength of light,

$$= 589 \text{ nm} = 589 \times 10^{-9} \text{ m}$$

Mass of electron, $m_e = 9.1 \times 10^{-31}$ kg

Mass of neutron, $m_n = 1.675 \times 10^{-27}$ kg

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

(i) Using formula, $\lambda = \frac{h}{\sqrt{2mK}}$

Kinetic energy of electron,

$$K_e = \frac{h^2}{2\lambda^2 m_e} = \frac{(6.63\times 10^{-34})^2}{2\times(589\times 10^{-9})^2 \times 9.1\times 10^{-31}}$$
$$= 6.96\times 10^{-25}\text{ J}$$

(ii) Kinetic energy of neutron,

$$K_n = \frac{h^2}{2\lambda^2 m_n} = \frac{(6.63\times 10^{-34})^2}{2\times(589\times 10^{-9})^2 \times 1.675\times 10^{-27}}$$
$$= 3.81\times 10^{-28}\text{ J}$$

26. Given, kinetic energy = KE = 120 eV

(i) Momentum, $p = \sqrt{2\,eVm} = \sqrt{2\,\text{KE}\cdot m}$ [$\because$ KE = eV]

$$= \sqrt{2\times 120\times 1.6\times 10^{-19}\times 9.1\times 10^{-31}}$$
$$= 5.91\times 10^{-24}\text{g-m/s}$$

(ii) We know that momentum, $p = mv$

or $$v = \frac{p}{m} = \frac{5.91\times 10^{-24}}{9.1\times 10^{-31}}$$
$$= 6.5\times 10^{6}\text{ m/s}$$

(iii) de-Broglie wavelength associated with electron,

$$1 = \frac{12.27}{\sqrt{V}}\text{ Å} = \frac{12.27}{\sqrt{120}}\text{Å}$$
$$= 0.112\times 10^{-9}\text{m} = 0.112\,\text{nm}$$

27. (i) de-Broglie matter wave equation is given by

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

$\because$ $$p = \sqrt{2mK}$$

where, m = mass of proton and

K = kinetic energy of proton.

According to the question, kinetic energy of proton,

$K = m_e c^2$ [using Einstein's mass-energy relation]

$$\Rightarrow \lambda = \frac{h}{\sqrt{2m\,(m_e c^2)}}$$
$$= \frac{h}{\sqrt{2}c\cdot\sqrt{m\cdot m_e}}$$
$$= \frac{h}{\sqrt{2}\;c\cdot m_e\sqrt{1836}} \quad [\because\; m = 1836\,m_e]$$
$$= \frac{6.63\times 10^{-34}}{1.414\times(3\times 10^{8})\times 9.1\times 10^{-31}\times 42.8}$$
$$= 4\times 10^{-14}\text{ m}$$

(ii) This region of electromagnetic spectrum is γ-ray.

28. (i) Given, mass of bullet, $m = 0.040$ kg

Speed of bullet, $v = 1000$ m/s

de-Broglie wavelength, $\lambda = \frac{h}{mv} = \frac{6.63\times 10^{-34}}{0.040\times 1\times 10^{3}}$

$$= 1.66\times 10^{-35}\text{ m}$$

(ii) Mass of the ball, $m = 0.060$ kg and speed of the ball, $v = 1$ m/s

$$\lambda = \frac{h}{mv} = \frac{6.63\times 10^{-34}}{0.060\times 1}$$
$$= 1.1\times 10^{-32}\text{ m}$$

(iii) Mass of a dust particle, $m = 1\times 10^{-9}$ kg and speed of the dust particle, $v = 2.2$ m/s

$$\lambda = \frac{h}{mv} = \frac{6.63\times 10^{-34}}{1\times 10^{-9}\times 2.2}$$
$$= 3.0\times 10^{-25}\text{ m}$$

29. Refer to Q.28 on page 461, $\lambda = 1.2\times 10^{-10}\text{m}$

30. Given, $\lambda = 590\text{ nm} = 590\times 10^{-9}\text{m}$

de-Broglie wavelength $(\lambda) = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$

where, m is the mass of electron.

Thus, $$590\times 10^{-9} = \frac{6.626\times 10^{-34}}{\sqrt{2\times 9.11\times 10^{-31}\times E}}$$

$$\Rightarrow \sqrt{2\times 9.11\times 10^{-31}\times E} = \frac{6.626\times 10^{-34}}{590\times 10^{-9}}$$
$$= 0.112\times 10^{-25}$$
$$\Rightarrow 2\times 9.11\times 10^{-31}\times E = (0.112\times 10^{-25})^2$$
$$\Rightarrow E = \frac{0.00012544\times 10^{-50}}{2\times 9.11\times 10^{-31}}$$
$$= 6.884\times 10^{-25}\text{ J}$$

31. (i) Refer to Q. 26 on page 460.

KE $= 6.714\times 10^{-21}$ J, using $K = \frac{h^2}{2m\lambda^2}$

(ii) Kinetic energy associated with temperature,

$$\text{KE} = \frac{3}{2}kT = \frac{3}{2}(1.38\times 10^{-23})\times 300$$
$$= 6.21\times 10^{-21}\text{ J}$$

[$\because$ absolute temperature, $T = 300$ K and Boltzmann's constant, $k = 1.38\times 10^{-23}$ J / K]

$$\text{KE} = 6.21\times 10^{-21}\text{ J}$$

de-Broglie wavelength associated with kinetic energy,

$$\lambda = \frac{h}{\sqrt{2m_n\,\text{KE}}} = \frac{6.63\times 10^{-34}}{\sqrt{2\times 1.675\times 10^{-27}\times 6.21\times 10^{-21}}}$$
$$= 1.45\times 10^{-10}\text{ m} = 1.45\text{ Å}$$

32. Given, potential difference, $V = 56$ V

(i) Use the formula for kinetic energy,

$$eV = \frac{1}{2}mv^2 \Rightarrow \frac{2\,eV}{m} = v^2$$
$$\Rightarrow v = \sqrt{\frac{2eV}{m}}$$

where, m is mass and v is velocity of electron.

Momentum associated with accelerated electron,

$$p = mv = m\sqrt{\frac{2eV}{m}} = \sqrt{2\,eVm}$$

$$= \sqrt{2 \times 1.6 \times 10^{-19} \times 56 \times 9 \times 10^{-31}}$$

$$= 4.02 \times 10^{-24} \text{ kg-m/s}$$

(ii) $\lambda = 0.164$ nm; refer to example 4 on page 459.

33. de-Broglie wavelength is given by

$$\lambda = \frac{h}{\sqrt{2mK}} = \frac{h}{\sqrt{2mqV}} \quad [\because K = qV]$$

$$\Rightarrow \quad \lambda \propto \frac{1}{\sqrt{mqV}}$$

Ratio of de-Broglie wavelengths of proton and α-particle is given by

$$\frac{\lambda_p}{\lambda_\alpha} = \sqrt{\frac{m_\alpha q_\alpha V_\alpha}{m_p q_p V_p}} = \sqrt{\left(\frac{m_\alpha}{m_p}\right)\left(\frac{q_\alpha}{q_p}\right)\left(\frac{V_\alpha}{V_p}\right)}$$

Here, $\frac{m_\alpha}{m_p} = 4$, $\frac{q_\alpha}{q_p} = 2$,

$$\Rightarrow \quad \frac{V_\alpha}{V_p} = \frac{64}{128} = \frac{1}{2}$$

[∵ α-particle is 4 times heavier than proton and it has double the charge than that of proton]

$$\Rightarrow \quad \frac{\lambda_p}{\lambda_\alpha} = \sqrt{4 \times 2 \times \frac{1}{2}} = 2$$

$$\Rightarrow \quad \lambda_p : \lambda_\alpha = 2 : 1$$

34. (i) The de-Broglie wavelength of a particle is given by

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

[where, V is the accelerating potential of the particle]

$$\because \quad \lambda_p = \lambda_\alpha \quad \text{[given]}$$

$$\Rightarrow \quad \frac{12.27}{\sqrt{V_p}} = \frac{12.27}{\sqrt{V_\alpha}}$$

$$\Rightarrow \quad \frac{V_p}{V_\alpha} = 1$$

(ii) The de-Broglie wavelength of a particle is given by

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

$$\therefore \quad \lambda_p = \frac{h}{m_p \cdot v_p} \text{ and } \lambda_\alpha = \frac{h}{m_\alpha v_\alpha}$$

We know that, $m_\alpha = 4\,m_p$

$$\because \quad \lambda_p = \lambda_\alpha \quad \text{[given]}$$

$$\therefore \quad \frac{h}{m_p \cdot v_p} = \frac{h}{4\,m_p \cdot v_\alpha}$$

$$\Rightarrow \quad \frac{v_p}{v_\alpha} = 4$$

35. $\lambda = 0.0548$ Å; refer to Example 4 on page 459.

Resolving power of a microscope, $R = \frac{2\mu \sin\theta}{\lambda}$

From the formula, it is clear that, if other factors remain same, then resolving power is inversely proportional to wavelength of the radiation used. Wavelength of moving electron is very small as compared to that of yellow light, so it has greater resolving power than optical microscope.

36. Given, wavelength of X-rays, $\lambda = 1\text{ Å} = 10^{-10}$ m

Mass of electron, $m_e = 9.11 \times 10^{-31}$ kg

As, $\lambda = \frac{h}{\sqrt{2m\text{KE}}}$ or $\text{KE} = \frac{h^2}{2\lambda^2 m}$

$$= \frac{(6.63 \times 10^{-34})^2}{2 \times (10^{-10})^2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19}}$$

$$= 150.78 \text{ eV}$$

$$\therefore \text{Energy of photon} = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{1 \times 10^{-10} \times 1.6 \times 10^{-19}}$$

$$= 12.4 \times 10^3 \text{ eV}$$

Thus, for the same wavelength, a X-ray photon has greater kinetic energy than an electron.

37. Given that, $V = 64$V

Now, from the de-Broglie equation,

$$\lambda = \frac{12.27}{\sqrt{V}} \text{Å} = \frac{12.27 \text{Å}}{\sqrt{64}} \quad [\because V = 64\text{V}]$$

$$= \frac{12.27}{8} \text{Å}$$

$$= 0.153 \text{ nm}$$

This wavelength belongs to the X-ray part of the electromagnetic radiation.

38. Given, temperature,

$$T = 27\,°\text{C} = 27 + 273 = 300 \text{ K}$$

Separation, between two electrons,

$$r = 2 \times 10^{-10} \text{ m}$$

Momentum $p = \sqrt{3m\,kT}$

$$= \sqrt{3 \times 9.11 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}$$

$$[\because k = 1.38 \times 10^{-23} \text{ J/K}]$$

$$= 1.06 \times 10^{-25} \text{ kg-m/s}$$

de-Broglie wavelength, $\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{1.06 \times 10^{-25}}$

$$= 62.6 \times 10^{-10} \text{ m}$$

Mean separation, $r = 2 \times 10^{-10}$ m

$$\therefore \quad \frac{\lambda}{r} = \frac{62.6 \times 10^{-10}}{2 \times 10^{-10}} = 31.3$$

We can see that de-Broglie wavelength is much greater than the electron separation.

39. Mass of helium atom,

$$m = \frac{\text{Atomic weight}}{\text{Avogadro's number}} = \frac{4 \times 10^3}{6 \times 10^{23}} \text{ g}$$

Boltzmann constant, $k = 1.38 \times 10^{-23} \text{ J mol}^{-1} \text{ K}^{-1}$

de-Broglie wavelength, $\lambda = \frac{h}{\sqrt{3\,mkT}}$

$$= \frac{6.63 \times 10^{-34}}{\sqrt{3 \times \frac{4 \times 10^3}{6 \times 10^{23}} \times 1.38 \times 10^{-23} \times 300}} \quad \left[\begin{aligned} \because T &= 27^\circ \text{ C} \\ &= (27 + 273)\text{K} \\ &= 300 \text{ K} \end{aligned}\right]$$

$$= 0.73 \times 10^{-10} \text{ m}$$

Now, $pV = RT = kNT$

or $\frac{V}{N} = \frac{kT}{p}$

Mean separation, $r = \left(\frac{V}{N}\right)^{1/3} = \left(\frac{kT}{p}\right)^{1/3}$

$$= \left[\frac{1.38 \times 10^{-23} \times 300}{1.01 \times 10^5}\right]^{1/3}$$

$$= 3.4 \times 10^{-9} \text{ m}$$

$\therefore$ $\frac{\lambda}{r} = \frac{0.73 \times 10^{-10}}{3.4 \times 10^{-9}} = 0.021$

40. $\frac{\lambda}{2}$; refer to example 4 on page 459.

41. Given, potential at anode, $V = 100 \text{ V}$

Magnetic field, $B = 2.83 \times 10^{-4} \text{ T}$

Radius of circular path, $r = 12 \text{ cm} = 0.12 \text{ m}$

Kinetic energy, $\text{KE} = \frac{1}{2} mv^2$ $\quad \left[\begin{aligned} &\because m_e = 9.1 \times 10^{-31} \text{ kg} \\ &\text{and } e = 1.6 \times 10^{-19} \text{ C} \end{aligned}\right]$

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

$$\Rightarrow 1.6 \times 10^{-19} \times 100 = \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2$$

$$\Rightarrow \quad v^2 = \frac{2 \times 1.6 \times 10^{-17}}{9.1 \times 10^{-31}}$$

$$= 5.93 \times 10^6 \text{ m/s}$$

As, the angle between $\mathbf{v}$ and $\mathbf{B}$ is 90°.

The magnetic force ($F_m = evB$) is balanced by the centripetal force.

i.e. $evB = \frac{mv^2}{r}$

or $\frac{e}{m} = \frac{v}{Br} = \frac{5.93 \times 10^6}{2.83 \times 10^{-4} \times 0.12}$

$\therefore$ Specific charge of an electron,

$$\frac{e}{m} = 1.74 \times 10^{11} \text{ C/kg}$$

42. (i) Given, potential difference, $V = 500 \text{ V}$

Specific charge of the electron,

$$e/m = 1.76 \times 10^{11} \text{ C/kg}$$

Kinetic energy of an electron,

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

$$\Rightarrow \quad v = \sqrt{\frac{e}{m} \times 2V} \quad \text{...(i)}$$

$$= \sqrt{1.76 \times 10^{11} \times 2 \times 500}$$

$$= 1.326 \times 10^7 \text{ m/s}$$

(ii) Potential, $V = 10 \text{ MV} = 10^7 \text{ V}$

Again from Eq. (i), $v = \sqrt{\frac{2e}{m} V}$

$$= \sqrt{2 \times 1.76 \times 10^{11} \times 10^7}$$

$$= 1.8762 \times 10^9 \text{ m/s}$$

This speed is greater than the speed of light, which is not possible. As v approaches to c, then mass

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

SUMMARY

- **Electron Emission** The phenomenon of emission of electrons from metal surface is called electron emission.
- **Work Function** It is the minimum energy required by an electron to just escape from metal surface, so as to overcome the attractive pull of the ions.
- **Photoelectric Effect** It is the phenomenon of emission of electrons from the metal surface, when the radiations of suitable frequency falls on it.
- **Hertz's Observation** He observed that high voltage sparks across the detector loop were enhanced when the emitter plate was illuminated by UV light from an arc lamp.
- **Hallwachs and Lenard's Observations** They also observed that UV light falls on the emitter plate, no electrons were emitted at all when the frequency of incident light was smaller than a certain minimum value is called threshold frequency.
- **Effect of Intensity of Light on Photoelectric Current** For a fixed frequency of incident radiation photoelectric current increases linearly with increase in intensity of incident light.
- **Effect of Potential on Photoelectric Current** For a fixed frequency and intensity of incident light, photoelectric current increases with increase in potential applied to the collector.
- **Effect of Incident Photon Energy and Kinetic Energy**

  $$K_{max} = \frac{1}{2}mv^2_{max} = (h\nu - \phi_0)$$

  This equation is called Einstein's photoelectric equation.
- **Relation between Stopping Potential and Threshold Wavelength** The relation between stopping potential and threshold wavelength is $eV_0 = hc\left[\frac{1}{\lambda} - \frac{1}{\lambda_0}\right]$
- **Particle Nature of Light Photon** Photoelectric effect gave the evidence that light consists of packets of energy and these packets of energy are called light quanta, that are associated with photons.
- **Characteristic Properties of Photon**

  Photons has zero rest mass.

  Photons travel in a straight line.

  Photons may show diffraction under given conditions

  The inertial mass of a photon is $m = \frac{hc}{\lambda}$.
- **Photocell** It is a device which converts light energy into electrical energy.
- **Dual Nature of Radiation** Wave theory of electromagnetic radiations explained the phenomenon of interference, diffraction, etc, whereas quantum theory successfully explained the photoelectric effect, Compton effect, etc. So, Louis de-Broglie suggested that the particles like electrons, protons, etc. have dual nature of radiation.
- **Wave Nature of Particles (de-Broglie Hypothesis)** According to de-Broglie, a wave is associated with moving material particle which control the particle in every respect. The wave associated with moving material particle is called matter wave. It is given by,

  $$\lambda = \frac{h}{p} = \frac{h}{mv}$$
- **Relation between de-Broglie Wavelength and Temperature** It is given by

  $$\lambda = \frac{h}{\sqrt{3mkT}}$$
- **de-Broglie Wavelength of an Electron** It is given by $\lambda = \frac{h}{\sqrt{2eVm}}$.

CHAPTER PRACTICE

OBJECTIVE Type Questions

1. Work-function is
(a) maximum possible energy acquired by an electron
(b) energy of electrons in valence shell
(c) minimum energy required by an electron to move out of metal surface
(d) maximum energy which is given to electron to move it out of metal surface

2. The work function of platinum is 6.35 eV. The threshold frequency of platinum is
(a) 15.32×10^{14} Hz
(b) 15.32×10^{16} Hz
(c) 15.32×10^{19} Hz
(d) 15.32×10^{18} Hz

3. With the increase in potential difference of emitter and collector, the photoelectric current
(a) increases
(b) decreases
(c) remains constant
(d) increases initially and then become constant

4. The photoelectric threshold frequency of a metal is ν. When light of frequency 6ν is incident on the metal, the maximum kinetic energy of the emitted photo electron is
(a) $4h\nu$ (b) $5h\nu$
(c) $3h\nu$ (d) $(3/2)\, h\nu$

5. Light of wavelengths λ_A and λ_B falls on two identical metal plates A and B respectively. The maximum kinetic energy of photoelectrons is K_A and K_B respectively, then which one of the following relations is true? $(\lambda_A = 2\lambda_B)$
(a) $K_A < \frac{K_B}{2}$ (b) $2K_A = K_B$
(c) $K_A = 2K_B$ (d) $K_A > 2K_B$

6. All photons present in a light beam of single frequency have
(a) same frequency but different momentum
(b) same momentum but different frequency
(c) different frequency and different momentum
(d) same frequency and same momentum

7. The linear momentum of a 6 MeV photon is
(a) 0.01 eV sm^{-1}
(b) 0.02 eV s m^{-1}
(c) 0.03 eV s m^{-1}
(d) 0.04 eV s m^{-1}

8. A photocell converts
(a) change in current into change in light intensity
(b) change in intensity of light into change in current
(c) change in current into change in voltage
(d) change in intensity into change in potential difference

9. The de-Broglie wavelength (λ) of equal mass particles depends upon the mass in the following way
(a) $\lambda \propto m$ (b) $\lambda \propto m^{1/2}$
(c) $\lambda \propto m^{-1}$ (d) $\lambda \propto m^{-1/2}$

VERY SHORT ANSWER Type Questions

10. Define the term stopping potential in relation to photoelectric effect.

11. Show graphically the variation of photoelectric current with frequency of the incident photons.

12. Two metals M_1 and M_2 have work functions 2 eV and 4 eV, respectively. Which of the two has a higher threshold wavelength for photoelectric emission?

13. The frequency ν of incident radiation is greater than threshold frequency ν_0 in a photocell. How will the stopping potential vary, if frequency ν is increased, keeping other factors constant.

14. The de-Broglie wavelength associated with an electron accelerated through a potential difference V is λ. What will be its wavelength when the accelerating potential is increased to 5 V?

SHORT ANSWER Type Questions

15. What are the energies of photons at the (i) violet and (ii) red ends of the visible spectrum? The wavelength of light is about 390 nm for violet and about 760 nm for red.

16. An electron is accelerated through a potential difference of 250 V. What is the de-Broglie wavelength associated with it? To which part of electromagnetic spectrum does this wavelength correspond?

17. The de-Broglie wavelength of a body moving with speed v is λ. On its way, it losses some of its mass and gains twice the speed. Kinetic energy also increases to twice of its initial value. What will be the new value of de-Broglie wavelength?

18. For what kinetic energy of a neutron, will the associated de-Broglie wavelength be 2.64×10^{-10} m?

19. The de-Broglie wavelength of a particle of kinetic energy K is λ. What would be the wavelength of the particle, if its kinetic energy were $\frac{K}{4}$?

20. Ultraviolet light of wavelength 200 nm is incident on polished surface of iron. Work function of the surface is 4.71 eV. Calculate its stopping potential.

LONG ANSWER Type I Questions

21. Write Einstein's photoelectric equation relating the maximum kinetic energy of the emitted electron to the frequency of the radiation incident on a photosensitive surface. State clearly, the basic elementary process involved in photoelectric effect.

22. Define the terms threshold frequency and stopping potential in the study of photoelectric emission. Explain briefly the reasons, why wave theory of light is not able to explain the observed features in photoelectric effect?

23. Light of wavelength 2500 Å falls on a metal surface of work function 3.5 eV. What is the kinetic energy (in eV) of
   (i) the fastest and
   (ii) the slowest electrons emitted from the surface? If the same light falls on another surface of work function 5.5 eV, what will be the energy of emitted electrons?

24. Light of wavelength 2000 Å falls on a metal surface of work function 4.2 eV.
   (i) What is the kinetic energy (in eV) of the fastest electrons emitted from the surface?
   (ii) What will be the change in the energy of the emitted electrons, if the intensity of light with same wavelength is doubled?
   (iii) If the same light falls on another surface of work function 6.5 eV, what will be the energy of emitted electrons? **CBSE SQP (Term-II)**

ANSWERS

1. (c) 2. (a) 3. (d) 4. (b) 5. (a)
6. (d) 7. (b) 8. (b) 9. (c)

10. For a particular frequency of incident radiation, the minimum negative (retarding) potential V_0 given to plate A for which the photoelectric current becomes zero, is called cut-off or stopping potential.

11. Refer to plot on page 437.

12. We know that, $E_0 = h\nu_0 = \frac{hc}{\lambda_0}$

Thus, λ_0 or threshold wavelength is inversely proportional to the energy or work-function. So, metal M_1 has higher threshold wavelength for photoelectric emission.

13. We know that, $\frac{1}{2}mv^2_{\max} = eV_0 = h(\nu - \nu_0)$

Here, the frequency of the incident radiation is greater than the threshold frequency. Therefore, the value of stopping potential (V_0) increases with increase in frequency (ν) of the incident radiation and KE will also increases.

14. Refer to Q. 3 on page 461.

$$\lambda' = \frac{\lambda}{\sqrt{5}}$$

15. We know that, $E = \frac{hc}{\lambda}$ joule

or $$E = \frac{hc}{\lambda \times 1.6 \times 10^{-19}} \text{eV}$$

$$\therefore \quad \lambda_V = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{390 \times 10^{-9} \times 1.6 \times 10^{-19}} = 3.17 \text{eV}$$

$$\therefore \quad \lambda_R = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{760 \times 10^{-9} \times 1.6 \times 10^{-19}} = 1.63 \text{eV}$$

16. Refer to Q. 37 on page 461. [**Ans.** 49.5 Å]

17. **Hint** $\lambda = \frac{h}{\sqrt{2mK}}$

de-Broglie wavelength remains same.

18. Refer to the Q. 31 (i) on page 461.

19. As we know, de-Broglie wavelength, $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}}$

Hence, $$K_1 = \frac{h^2}{2m\lambda_1^2} \quad \text{...(i)}$$

If according to the question, $K_2 = \frac{K_1}{4}$

$$K_2 = \frac{h^2}{2\lambda_2^2}$$

$$\frac{K_1}{4} = \frac{h^2}{2m\lambda_2^2} \quad \text{..(ii)}$$

From Eqs. (i) and (ii), we get

$$\frac{\frac{K_1}{4}}{K_1} = \frac{h^2}{2m\lambda_2^2} \times \frac{2m\lambda_1^2}{h^2}$$

$$\frac{1}{4} = \frac{\lambda_1^2}{\lambda_2^2}$$

$$\Rightarrow \quad \frac{\lambda_1}{\lambda_2} = \frac{1}{2}$$

Hence, wavelength of the particle double the wavelength when kinetic energy is $\frac{1}{4}$ th.

20. Given, $\lambda = 200 \text{ nm} = 200 \times 10^{-9} \text{m}$

$$\text{KE}_{\text{max}} = h\nu - \phi$$
$$\text{KE}_{\text{max}} = eV_0$$
$$eV_0 = h\nu - \phi$$
$$eV_0 = \frac{hc}{\lambda} - \phi$$

$$\therefore 1.6 \times 10^{-19} V_0 = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{200 \times 10^{-9}} - 4.71 \times 1.6 \times 10^{-19}$$

$$V_0 = 6.19 - 4.17 = 1.48 = 1.50 \text{V}$$

21. Refer to the text on page 438.

22. Refer to the text on pages 436, 437 and 438.

23. Refer to Q. 72 (iii) on page 447.

24. Wavelength of light, $\lambda = 2000$ Å $= 2 \times 10^{-7}$ m

Work function, $\phi_0 = 4.2$ eV

$$h = 6.63 \times 10^{-34} \text{ J-s}$$

(i) Using Einstein's photoelectric equation, kinetic energy of fastest electron,

$$K_{\text{max}} = h\nu - \phi_0 = h\frac{c}{\lambda} - \phi_0$$
$$= \left(\frac{6.63 \times 10^{-34} \times 3 \times 10^8}{2 \times 10^{-7} \times 1.6 \times 10^{-19}} - 4.2\right) \text{eV}$$
$$= 6.2 \text{ eV} - 4.2 \text{ eV}$$
$$= 2.0 \text{ eV}$$

(ii) Since the energy of emitted electron does not depend upon intensity of incident light, hence the energy of emitted electrons remains unchanged.

(iii) For this surface, electrons will not be emitted as the energy of incident light (6.2 eV) is less than the work function ($\phi' = 6.5$ eV) of the surface.