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As we have already discussed, Newton regarded light as a beam of particles, called corpuscles. Newton's corpuscular theory could explain the phenomena of reflection and refraction, but had to be discarded because it could not explain the interference and diffraction of light. Since such phenomena could only be explained by Huygens' wave theory, light began to be regarded as a wave phenomenon. However, in the latter part of the 19th century and the beginning of the 20th century, phenomena such as black-body radiation, the Compton effect, Stark effect and photoelectric effect[1] made scientists realize that light does indeed consist of a stream of particles. These developments led to the acceptance of the dual (particle and wave) nature of light.

It was the French physicist Louis de Broglie (pronounced: de Broy) who first pointed out that if light, which is basically a wave phenomenon, sometimes behaves as particles then it should be possible for particles to sometimes behave as a wave. In other words, all material particles should also show dual behaviour. This concept, known as the **wave–particle duality** or the **de Broglie hypothesis**, earned de Broglie the Nobel prize in 1929. The de Broglie hypothesis was used by Erwin Schrödinger to formulate wave mechanics.

◆ ◆ ELECTRON EMISSION:

A metal contains a number of free electrons, which, however, cannot escape From its surface under ordinary conditions. If they try to escape, they are Pulled back by the surface. In other words, there is a kind of barrier , known as SURFACE barrier Or Potential Barrier ,which does not allow electron to escape from the surface . The amount of energy that must be imparted to an electron to let it escape from the surface of a metal is termed the Surface-energy Barrier (E_B) and it depends upon the nature of the metals And its surface conditions.

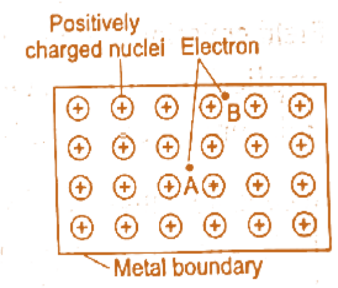


Fig. 1.1

ILLUSTRATION :

To Understand the origin of Potential barrier, Consider the Electron A in fig 1.1. It is far away from the surface of **and is symmetrically surrounded by positively charged Nuclei, so that the net force** on it is zero, However, the electron B near the surface is not surrounded symmetrically by positively charged nuclei, so there is a net force on it acting towards the interior of the metal, and it can escape only if it overcomes this pull, or the surface barrier. Ordinarily, electrons move too slowly, or do not have kinetic energy to overcome the surface barrier. But they may do so if they acquire a minimum amount of energy from some external source. This minimum energy required by an electron from the surface of a metal is known as **WORK FUNCTION, ϕ_o of the metal, and is generally expressed in "electronVolts(eV)'.**

One electronvolt is the energy required by an electron when it moves through a Potential difference of 1V.

$$1\text{ eV} = \text{charge on an electron} \times 1\text{ V} = 1.6\times10^{-19}\text{ C}\times 1\text{ V} = 1.6\times10^{-19}\text{ J.}$$

□□ The external energy required for electrons to be emitted from a metal may be provided by

(i) heating, (ii) illuminating it with light

(iii) subjecting it to an electric field (IV) Bombarding it with electron

◆ **THERMIONIC EMISSION:** (i) heating, : In this method, the metals is heated to a high temperature and **this increases the kinetic energy of the free electrons, causing a large number of them attains the energy needed to escape from the surface.**

Metal	Work function ϕ_0 (eV)	Metal	Work function ϕ_0 (eV)
Cs	2.14	Pb	4.25
K	2.30	Al	4.28
Li	2.40	Hg	4.49
Ba	2.50	Cu	4.65
Sr	2.70	Ag	4.70
Na	2.75	Ni	5.15
Ca	3.20	Pt	5.65
Mo	4.17		

- **PHOTO ELECTRIC EMISSION** (ii) illuminating it with light : When light of suitable frequency is incident on the metal surface, the free electrons of the metal acquire the energy required to enable them to escape. Electrons liberated this way are known as PHOTOELECTRONs.

- **FIELD EMISSION** (COLD CATHODE EMISSION): When a strong electric field is applied to a metal the electrons are pulled out of its surface . The stronger the field, the greater is field emission from the surface.

- **SECONDARY EMISSION**: When high speed electron strikes a metallic surface, they transfer a part of their kinetic energy to the electrons in the metal. Some of the bombarding electrons collide directly with free electrons on the metal surface and may knock them out. The liberated electrons are known as Secondary − emission electrons, since primary electrons from some other source must be available to bombard the electron-emitting surface.

PHOTOELECTRIC EFFECT:

The photoelectric effect (or photoelectric emission or photo-emission) was first observed in 1887 by Heinrich Hertz while he was conducting experiments for the production of electromagnetic waves. In these experiments, a spark was generated between two small metal spheres in the transmitter to induce a similar spark between two metal spheres in the receiver. Hertz found that the high-voltage sparks across the receiving device were enhanced by illuminating the device with visible or ultraviolet light from an arc lamp. After Thomson's discovery of electrons, it was concluded that the enhancement or increased sensitivity was the result of electrons being knocked out from the surface of the device by the incident light.

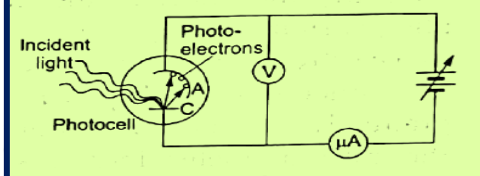


Fig. 1.2

Wilhelm Hallwachs and Lenard Philipp, an assistant of Hertz, investigated the phenomenon of photoelectric emission in detail during the period 1886–1902. Lenard used two metal plates enclosed in an evacuated glass tube, as shown in Figure 1.2. He illuminated the metal plate C, called the emitter. The electrons emitted by the plate were collected by the positive collector plate A. (Such a tube is called a **photocell** or more informally, an **electric eye.**) Lenard used light of different frequencies and intensities and observed that when ultraviolet light was allowed to fall on the emitter plate, a current flowed in the circuit.

Hallwachs, who connected a zinc plate to a gold-leaf electroscope and illuminated it with ultraviolet light, made the following observations.

1. When the zinc plate was negatively charged, it lost its charge (which became evident from the fact that the leaves of the gold-leaf electroscope came closer) upon being illuminated.
2. When the zinc plate was uncharged, it became positively charged and when it was positively charged, the charge on it increased upon being illuminated.

◈ CONCLUSION:

These observations led him to conclude that negatively charged particles were emitted from the zinc plate when it was illuminated by ultraviolet light. The negatively charged particles emitted by the zinc plate were later identified as electrons. They were termed photoelectrons since their emission is caused by light.

Robert Millikan, showed that light with frequencies below a certain cut-off value, called the **threshold frequency**, does not eject photoelectrons, no matter how bright the source. The threshold frequency depends on the nature of the material of the emitter surface. Materials with the lowest threshold frequencies are semiconductors, some with threshold frequencies in the infrared region. Metals such as zinc, cadmium and magnesium respond only to ultraviolet light, while some alkali metals, such as lithium, sodium, potassium, caesium and rubidium, respond to visible light also.

◈ EXPERIMENTAL STUDIES (PHOTO EFFECTRIC EFFECT) :

The experimental arrangement for studying the photoelectric effect is shown in Figure 1.3. It consists of two electrodes, A and C, enclosed in an evacuated glass tube. The electrode C is made of a **photoemissive material**, or a material which emits photoelectrons when irradiated by light and A is the collecting plate which collects the photoelectrons emitted by C. A side tube T, made of quartz[2] and covered with a filter, is connected to the evacuated tube. Light enters through this tube and falls on the photoemissive electrode. A potential difference can be applied between the electrodes A and C and their polarity may be reversed.

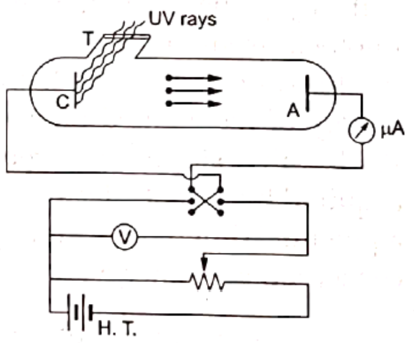


Fig. 1.3

When the electrode A is maintained at a positive potential with respect to the electrode C and ultraviolet light is allowed to fall on C, the photoelectrons emitted from C are collected by the positively charged plate A. This photocurrent is measured by a microammeter connected in the circuit and the potential difference between the two electrodes is measured by a voltmeter.

◈ EFFECT OF INTENSITY OF LIGHT:

To study the effect of the intensity of the incident light on the photocurrent, a constant potential difference is applied between the two electrodes and the frequency of the ultraviolet light incident on the cathode is also kept constant. As the intensity of the light is gradually increased, it is found that the photocurrent measured by the microammeter increases linearly with the intensity of the incident light, as shown in Figure 1.4. As the photoelectric current is directly proportional to the number of photoelectrons emitted per second, it follows that *the number of photoelectrons emitted per second is directly proportional to the intensity of the incident light.*

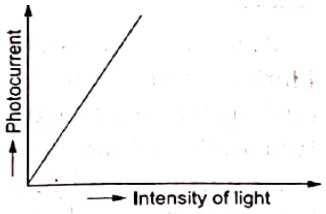


Fig. 1.4

Quartz is used as it allows ultraviolet light to pass through easily.

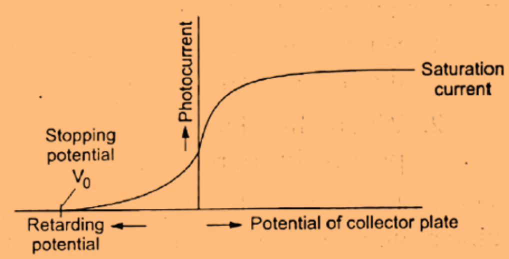


Fig. 1.5

When light of frequency greater than the threshold frequency is incident on the cathode C, photoelectrons are emitted. If the intensity and frequency of the incident light are kept constant, and the positive potential of A is gradually increased, the photoelectric current initially increases and then reaches a maximum value, called the **saturation current,** at a definite value of the potential (Figure 1.5). This happens because once the rate of emission of photoelectrons by C becomes equal to the rate at which they are collected by A, increasing the potential of A further has no effect on the magnitude of the photoelectric current.

If the potential of A is then decreased, the photoelectric current decreases. Even after the potential of A is made negative with respect to the potential of C, a small current flows in the circuit because a few electrons have sufficient energy to reach A despite its being at a negative potential. There comes a point, however, when no current flows. The minimum value of the negative potential applied to A, at which no photoelectrons reach A and the photoelectric current is zero, is called the **cut-off potential** or **stopping potential.**

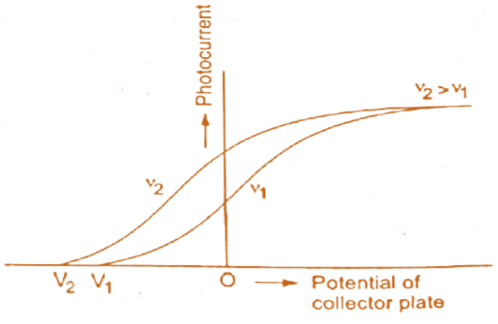


Fig. 1.6

If $v_{\max}$ be the maximum velocity of the photoelectrons emitted by the electrode C and m be the mass of an electron then the maximum kinetic energy of the emitted photoelectrons is $mv_{\max}^2/2$. If V_0 be the stopping potential then the energy acquired by a photoelectron when it moves through a potential difference V_0 is eV_0. From the principle of conservation of energy,

$$\frac{1}{2}mv_{\max}^2 = eV_0. \qquad \ldots 1.1$$

Equation 1.1 can be used to determine the maximum kinetic energy and hence, the maximum velocity of the photoelectrons. If the intensity of the light is increased without changing its frequency, the photoelectric current increases, but the stopping potential remains the same.

Conclusion:

1. The saturation current depends on the intensity of the incident radiation.
2. The stopping potential is independent of the intensity of the incident radiation.

◈ EFFECT OF FREQUENCY:

If the experiment is repeated with lights of the same intensity but different frequencies, the saturation current is the same in each case, but the stopping potential increases with the frequency of the light (Figure 1.6). If V be the stopping potential for radiation of frequency ν then

$$V \propto \nu \Rightarrow \frac{V_1}{V_2} = \frac{\nu_1}{\nu_2}. \qquad \ldots 1.2$$

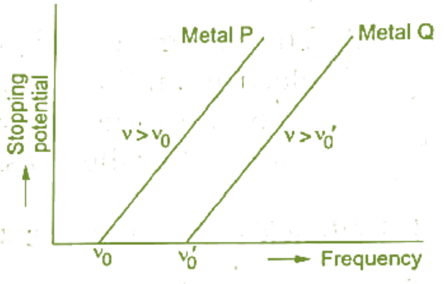


Fig. 1.7

A graph plotted between the frequency of incident radiation and the stopping potential comes out to be a straight line that does not pass through the origin, as shown in Figure 1.7. This shows that there is a particular value of frequency (of the incident radiation denoted as ν_0 and ν_0' in the above figure), called the threshold frequency, below which photoelectric emission is not possible. The threshold frequency depends on the material of the photoemissive surface. We can sum up the

Conclusion:

1. Photoelectric emission from the surface of a photoemissive material is not possible if the frequency of the incident radiation is less than the threshold frequency for that material. At this frequency, also known as the cut-off frequency, the stopping potential is zero.
2. The stopping potential varies linearly with the frequency of the incident radiation.

◆ ◆ LAWS OF PHOTOELECTRIC EMISSION:

1. For a given photosensitive material, there exists a certain minimum frequency of the incident radiation, called the threshold frequency or cut-off frequency, below which photoelectrons are not emitted, whatever be the intensity of the radiation. The maximum kinetic energy of the emitted photoelectrons, or equivalently the stopping potential, is directly proportional to the frequency of the incident radiation, but is independent of its intensity.
2. Different photosensitive materials respond differently to light. For example, selenium is more sensitive than zinc or copper.
3. So long as the frequency of the incident radiation is greater than the threshold frequency, photoelectric emission starts almost instantaneously without any apparent time lag (10^{-9} s or less), whatever be the intensity of the radiation.
4. For a given photosensitive material and frequency of incident radiation (> than the threshold frequency), the photocurrent is directly proportional to the intensity of the incident radiation.
5. For a given photosensitive material and frequency of incident radiation (> than the threshold frequency), the saturation current is proportional to the intensity of the incident radiation.

◆ ◆ PHOTOELECTRIC EFFECT AND WAVE THEORY:

[The wave theory of light failed to explain several observations related to photoelectric emission.]

1. According to the wave theory, the free electrons in the surface of the emitter absorb radiant energy continuously. The greater the intensity of the incident radiation, the greater are the magnitudes of the electric and magnetic fields and the greater is the energy density of radiation. Hence, a high-intensity beam of light should liberate more energetic photoelectrons than a low-intensity beam does. However, this is contrary to experimental observations. The kinetic energy of photoelectrons does not depend on the intensity of the incident radiation.
2. According to the wave theory, a light wave of sufficient intensity should knock out electrons from the surface of a metal, irrespective of the frequency of the wave. Hence, the wave theory fails to account for the existence of a threshold frequency.
3. The energy of a light wave is evenly distributed over its advancing wavefront. An electron on the surface on which the light is incident intercepts an insignificantly small amount of this energy. Hence, it should require a finite time to escape from the metal surface. But the emission of photoelectrons is almost instantaneous.

◆ ◆ PLANCK'S QUANTUM THEORY OF RADIATION:

To account for the discrepancies between the theoretical and experimental results relating to the radiation emitted by hot bodies, Max Planck proposed that radiation is not emitted or absorbed continuously, but in discrete packets, or **quanta.** One quantum of light radiation is called a **photon.** The energy of a photon (E) is proportional to the frequency (ν) of the radiation, i.e.,

$$E \propto \nu \Rightarrow E = h\nu. \qquad \ldots 1.3$$

The constant of proportionality h, is called the **Planck constant.** The SI unit of h can be obtained from the preceding equation.

$$h=\frac{E}{\nu}=\frac{\text{unit of energy}}{(\text{unit of time})^{-1}}=\frac{\text{J}}{\text{s}^{-1}}=\text{J s}.$$

The accepted value of the Planck constant is 6.6262×10^{-34} J s and its dimensions are

$$[h]=\left[\frac{E}{\nu}\right]=\frac{\text{ML}^2\text{T}^{-2}}{\text{T}^{-1}}=\text{ML}^2\text{T}^{-1}.$$

◆ ◆ EINSTEIN'S PHOTOELECTRIC EQUATION:

In 1905, Albert Einstein elaborated the concept of photons and used it to provide an explanation for the photoelectric effect. The photon picture of light may be summarized as follows.

1. In an interaction between radiation and matter, radiation behaves as if it were made of particles or photons.
2. From Planck's theory, the energy of a photon, $E=h\nu$, and from Einstein's mass–energy equivalence relation (which we will discuss later), $E=mc^2$. Hence, $mc^2=h\nu$, which means the momentum of a photon,

$$mc=\frac{h\nu}{c}. \qquad \text{... 1.4}$$

3. All photons of light of a particular frequency have the same energy ($h\nu$) and the same momentum ($h\nu/c$), irrespective of the intensity of the radiation. Increasing the intensity of light of a particular frequency has the effect of increasing the number of photons crossing per unit area, with each photon having the same energy.
4. Photons are electrically neutral and hence, are not deflected by either an electric field or a magnetic field.
5. In a collision between a photon and a material particle, the total energy as well as the total momentum of the system remains conserved. However, the number of photons may or may not be conserved, i.e., a photon may be absorbed or created.

◆ EINSTEIN'S POSTULATE:

Einstein postulated that when a photon of energy $h\nu$ collides with an electron on the surface of a metal, it transfers its energy to the electron. If the energy of the photon is greater than the minimum energy required by the electron to leave the metal surface, the electron is emitted instantaneously. He held that an electron absorbs either a whole photon or none. The chance that an electron may absorb more then one photon is negligible because the number of photons is much smaller than that of the electrons.

Increasing the intensity of the incident light has no impact on the energy of the photons. It merely increases the number of photons and hence, the number of photoelectrons emitted. Increasing the frequency of the incident light, on the other hand, increases the energy of the photons, and hence, of the photoelectrons. If the energy ($h\nu$) of a photon is greater than the minimum energy required to pull out an electron from the metal surface, a part of its energy ($=h\nu_0$) is used in liberating the electron and the rest is used in imparting kinetic energy ($=mv_{\max}^2/2$) to the electron, where $v_{\max}$ is the maximum velocity of the electron. Applying the principle of conservation of energy,

$$h\nu=h\nu_0+\frac{1}{2}mv_{\max}^2 \qquad \text{... 1.5}$$

$$h(\nu-\nu_0)=\frac{1}{2}mv_{\max}^2. \qquad \text{... 1.6}$$

In Equation 1.6, if $\nu < \nu_0$, $v^2_{\max}$ is negative, which is impossible. Hence, no electron is emitted from the metallic surface if $\nu < \nu_0$. If $\nu = \nu_0$, electrons are ejected with zero initial velocity, i.e., ν_0 is the minimum frequency of the incident radiation for which electrons can be emitted from the metallic surface. This accounts for the threshold frequency observed in experiments. The wavelength corresponding to this frequency is known as the threshold wavelength.

Since the minimum amount of energy required to remove an electron from the surface of a metal is equal to the work function ϕ_0 of the metal, $\phi_0 = h\nu_0$, and Equation 1.5 can be expressed as

$$h\nu = \phi_0 + \frac{1}{2}mv^2_{\max}. \qquad \text{... 1.7}$$

Einstein's photoelectric equations.

EXAMPLE 1 **The work function for a photosensitive surface is 3.3×10^{-19} J. Taking the Planck constant to be 6.2×10^{-34} J s, find the threshold frequency. [ISC]**

Solution The threshold frequency is given by

$$\nu_0 = \frac{\phi_0}{h}.$$

Inserting the appropriate values in the preceding equation,

$$\nu_0 = \frac{3.3 \times 10^{-19}\ \text{J}}{6.2 \times 10^{-34}\ \text{J s}} = 5.32 \times 10^{14}\ \text{Hz}.$$

EXAMPLE 2 **Light of wavelength 500 nm falls on a metal surface with a work function of 1.9 eV. Find (a) the energy of the photons in eV, (b) the kinetic energy of the photoelectrons emitted, and (c) the stopping potential.**

Solution (a) The energy of the photon is

$$E = h\nu = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}\ \text{J s})(3 \times 10^{8}\ \text{m s}^{-1})}{500 \times 10^{-9}\ \text{m}}\ \text{J} = 3.978 \times 10^{-19}\ \text{J}.$$

$$\Rightarrow \quad E = \frac{3.978 \times 10^{-19}}{1.6 \times 10^{-19}}\ \text{eV} = 2.49\ \text{eV}.$$

Alternatively

The standard value of hc is 12420 eV Å.

$$\therefore \quad E = \frac{hc}{\lambda} = \frac{12420\ \text{eV Å}}{5000\ \text{Å}} = 2.48\ \text{eV}.$$

(b) The kinetic energy of the photons emitted is

$$\frac{1}{2}mv^2 = h\nu - \phi_0 = E - \phi_0 = (2.49 - 1.9)\ \text{eV} = 0.59\ \text{eV}.$$

(c) The stopping potential V_0 is given by

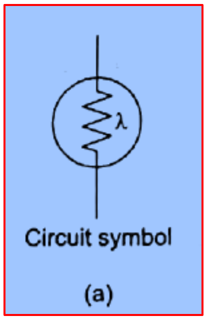
$$eV_0 = \frac{1}{2}mv^2 = 0.59\ \text{eV} \Rightarrow V_0 = 0.59\ \text{V}.$$

◈ ◈ PHOTOELECTRIC CELL:

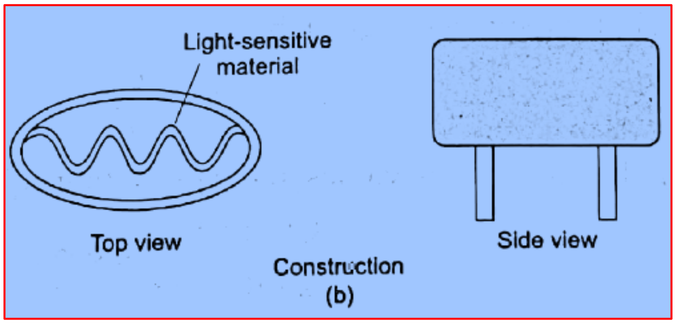
A photoelectric cell is a device that is activated by light. Photoelectric cells are used for many purposes. The most familiar use is as an automatic door-opener. In this case, when a person approaches a door, he/she blocks a beam of light which is incident on a photocell. This causes a change in the photocurrent, which starts a motor that opens the door. Photoelectric cells are of three basic kinds—**photoconductive cell, photoemissive cell,** and **photovoltaic cell.**

PHOTO-CONDUCTIVE CELL:

This device, also known as a **photoresistor,** makes use of the fact that the electrical conductivity of a photosensitive material increases when it is exposed to light due to the production of additional charge carriers by the incident photons. The essential elements of a photoconductive cell are a ceramic substrate, over which a layer of the photoconductive material is laid, metallic electrodes to connect the device to a circuit and a moisture-resistant cover. The circuit symbol and construction of a typical photoconductive cell are shown in Figure 1.8. The light-sensitive material is laid in a zigzag manner over the ceramic base in order to reduce the current in the dark. At room temperature, the number of free charges in a semiconductor is relatively limited. However, when exposed to light, the light-released electrons raise its conductivity (therefore, reduce its resistance). The resistance may change from several hundred thousand ohms in the dark to a few hundred ohms in sunlight. Photoconductive cells are used in turning street lights on and off automatically, in various alarm systems, and in sensors that scan codes on items bought in stores and super markets.



Circuit symbol
(a)



Construction
(b)

PHOTO-EMISSIVE CELL:

The photoemissive cell, also known as **phototube,** is shown in Figure 1.9. It consists of an evacuated glass envelope that contains a light-sensitive cathode *C* and an anode *A*. A battery *B* is connected across the terminals *P* and *Q* of the anode and cathode respectively with a galvanometer *G* in series. (Monatomic layers of caesium, potassium, or rubidium are used as cathode surfaces.) When light strikes the cathode, electrons are emitted. These electrons are attracted by the positive anode. The value of the current is proportional to the intensity of the light falling on the cathode. These cells are used as 'electric eyes' that trigger the automatic opening of doors. They can also be used the way photoconductive cells are used. In astronomy, they are used to measure electromagnetic radiation from celestial objects.

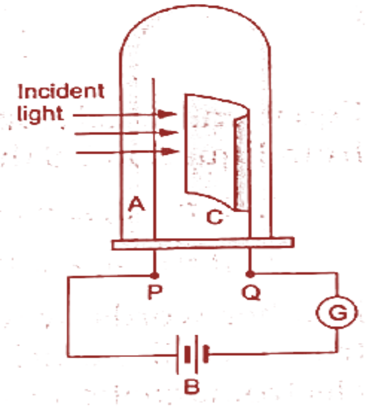


Fig. 1.9

◆ ◆ MATTER WAVE:

After the dual nature of radiation was established, de Broglie argued that since radiation behaves like matter, matter should also behave like radiation because nature is symmetrical.[3] He proposed that a material particle of mass m moving with a speed v has a wavelength λ associated with it and that the wavelength is

$$\lambda = \frac{h}{mv} = \frac{h}{p} \quad \text{... 1.8}$$

Equation 1.8 is known as the **de Broglie relation,** and λ as the **de Broglie wavelength.** It follows from Equation 1.8 that

1. if $v = 0, \lambda = \infty$, and
2. if $v = \infty, \lambda = 0$.

In other words, waves are associated with material particles *only if* they are in motion. This is true for all particles, whether charged or uncharged. Thus, de Broglie waves cannot be electromagnetic in nature as electromagnetic waves are produced by the motion of charged particles.

It is also evident from Equation 1.8 that the wavelength associated with a heavier particle (greater m) is much smaller than that associated with a lighter particle. Consider, for example, a ball of mass 1 kg moving with a speed of 25 m s^{-1}. The wavelength associated with this ball is

$$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}\ \text{J s}}{(1\ \text{kg})(25\ \text{m s}^{-1})} = 2.65\times10^{-35}\ \text{m}.$$

This wavelength is so small that it cannot be measured. This is why macroscopic objects do not show wavelike characteristics.

DE-BROGLIE WAVELENGTH ASSOCIATED WITH CHARGED PARTICLE:

Consider a charged particle of mass m at rest being accelerated by a potential difference V. If v be the velocity acquired by the particle then its kinetic energy is $mv^2/2$, while the energy imparted to it is eV. Applying the principle of conservation of energy,

$$\frac{1}{2}mv^2 = eV. \qquad \text{... 1.9}$$

If p be the momentum of the particle,

$$p = mv \Rightarrow p^2 = m^2v^2 = m(mv^2) = 2meV \qquad \text{[from Equation 1.9]}$$

$$\Rightarrow \quad p = \sqrt{2meV}. \qquad \text{... 1.10}$$

The wavelength associated with the moving charged particle is, thus,

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}. \qquad \text{... 1.11}$$

Let us consider some charged particles.

For an electron, $h = 6.63\times10^{-34}$ J s, $m = 9.11\times10^{-31}$ kg and $e = 1.60\times10^{-19}$ C. Thus,

$$\lambda = \frac{1.227}{\sqrt{V}}\ \text{nm} = \frac{12.27}{\sqrt{V}}\ \text{Å}. \qquad \text{... 1.12}$$

For a proton, $h = 6.63\times10^{-34}$ J s, $m = 1.67\times10^{-27}$ kg and $e = 1.60\times10^{-19}$ C. Hence,

$$\lambda = \frac{0.286}{\sqrt{V}}\ \text{Å}. \qquad \text{... 1.13}$$

For a deutron, $h = 6.63\times10^{-34}$ J s, $m = 2\times1.67\times10^{-27}$ kg and $e = 1.60\times10^{-19}$ C. Hence,

$$\lambda = \frac{0.202}{\sqrt{V}}\ \text{Å}. \qquad \text{... 1.14}$$

For an α-particle, $h = 6.63\times10^{-34}$ J s, $m = 4\times1.67\times10^{-27}$ kg and $e = 1.60\times10^{-19}$ C. Therefore,

$$\lambda = \frac{0.101}{\sqrt{V}}\ \text{Å}. \qquad \text{... 1.15}$$

DE-BROGLIE WAVELENGTH ASSOCIATED WITH UNCHARGED PARTICLE:

If m be the mass and v be the velocity of a material particle then its momentum is $p = mv$ and its kinetic energy is

$$E = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$

$$\Rightarrow \quad p = \sqrt{2mE}. \qquad \text{... 1.16}$$

Hence, the de Broglie wavelength associated with it is

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}} \cdot \qquad \text{... 1.17}$$

For a neutron, $m = 1.67 \times 10^{-27}$ kg. Hence,

$$\lambda = \frac{0.286}{\sqrt{E(\text{in eV})}}\ \text{Å}. \qquad \text{... 1.18}$$

◆ ◆ DE-BROGLIE WAVELENGTH ASSOCIATED WITH UNCHARGED PARTICLE:

When gas molecules are in thermal equilibrium at the absolute temperature T, their velocities follow the Maxwellian distribution and their average kinetic energy,

$$E = \frac{1}{2}mv_{\text{rms}}^2 = \frac{p^2}{2m} = \frac{3}{2}kT$$

$$\Rightarrow \qquad p = \sqrt{3mkT}, \qquad \text{... 1.19}$$

where k is the Boltzmann constant with a value of 1.38×10^{-23} J K^{-1}.

◆ ◆ HEISENBERG UNCERTAINTY PRINCIPLE:

The concept of matter waves fits well with the Heisenberg uncertainty principle, which draws a limit upon the precision with which certain pairs of physical properties of a particle, known as **complementary variables,** can be measured simultaneously. The position (x) and momentum (p) of a particle is one such pair. The Heisenberg uncertainty principle states that *it is impossible to measure both the position and the momentum of a particle simultaneously with equal accuracy.* The more precisely the position of a particle is determined, the less precisely its momentum can be known, and vice versa. We could also say that there is always some uncertainty in the specification of the position of a particle and some uncertainty in the specification of its momentum. If Δx be the uncertainty in the measurement of its position and Δp that in its momentum then according to the uncertainty principle,

$$(\Delta x)(\Delta p) \geq \hbar, \qquad \text{... 1.20}$$

where $\hbar = h/2\pi$ is known as the **reduced Planck constant** (or **Dirac constant**).[4]

CONCLUSION:

1. If the position of the particle is accurately measured then $\Delta x = 0$, which means that the uncertainty in the measurement of its momentum is

$$\Delta p = \frac{\hbar}{\Delta x} = \frac{\hbar}{0} = \infty.$$

In other words, the momentum of the particle cannot be measured.

2. On the other hand, if the momentum of the particle is accurately measured then $\Delta p = 0$, which means that the uncertainty in the measurement of its position is

$$\Delta x = \frac{\hbar}{\Delta p} = \frac{\hbar}{0} = \infty.$$

Thus, the position of the particle cannot be measured, but its momentum has a definite value ($p = \hbar/\lambda$). The wavelength of such a particle is $\lambda = h/p$ and the wave extends throughout space, as shown in Figure 1.11(a), which means that the particle is not confined to any finite region of space and that the uncertainty in its position is infinite.

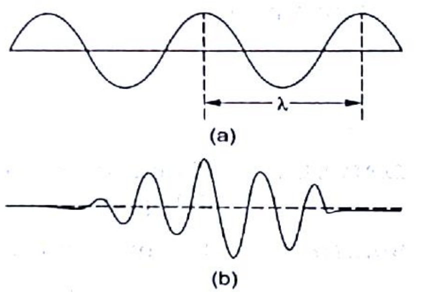


Fig. 1.11

◈◈ ELECTRON MICROSCOPE:

An electron microscope uses an electron beam to illuminate a specimen and produce a magnified image. Its resolving power is much greater than that of a light microscope and it is used to investigate the ultrastructure of a wide range of biological and inorganic specimens, including microorganisms, cells, large molecules, biopsy samples, viruses, metals, and crystals. Industrially, the electron microscope is often used for quality control and failure analysis.

The resolving power of an optical microscope is inversely proportional to the wavelength of the light used. This means the magnification produced by an optical microscope is below 2000 X. On the other hand, the de Broglie wavelength associated with electrons accelerated through a potential difference of V is $12.27/\sqrt{V}$. This means by selecting a suitable value of V, we can have an electron beam of as small a wavelength as desired, so an electron microscope can produce a magnification of up to about 10,000,000×.

The beam of electrons can be focused by using electric and magnetic fields, the way a beam of light is focused by using lenses.

◆◆

SOLVED EXAMPLES

EXAMPLE 1 **Calculate the photon energy (in eV) for radiation of wavelength 1 m.** **[CBSE]**

Solution The energy of a photon of frequency ν is

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

Substituting the appropriate values in the preceding equation,

$$E = \frac{(6.6\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}{1\ \text{m}} = 19.8\times10^{-26}\ \text{J}.$$

But $1\ \text{eV} = 1.6\times10^{-19}\ \text{J}$. Hence, the required energy in eV is

$$E = \frac{19.8\times10^{-26}}{1.6\times10^{-19}}\ \text{eV} = 12.38\times10^{-7}\ \text{eV}.$$

Alternatively

The standard value of $hc = 12420\ \text{eV Å}$.

$$\therefore\quad E = \frac{hc}{\lambda} = \frac{(12420\ \text{eV Å})}{1\ \text{m}} = \frac{(12420\ \text{eV Å})}{10^{10}\ \text{Å}} = 12.42\times10^{-7}\ \text{eV}.$$

EXAMPLE 2 **Light of wavelength 4000 Å and intensity 100 W m^{-2} is incident on a plate of threshold frequency 5.5×10^{14} Hz. Find the maximum kinetic energy of the photoelectrons and the number of photons incident per m^{2} per second.** **[CBSE]**

Solution The energy of the photons of the incident radiation,

$$E = h\nu = \frac{hc}{\lambda} = \frac{(6.6\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}{4000\ \text{Å}} = \frac{(6.6\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}{4000\times10^{-10}\ \text{m}}$$

$$\Rightarrow\quad E = 4.95\times10^{-19}\ \text{J}. \qquad \textbf{(1)}$$

The work function of the plate is

$$\phi_0 = h\nu_0 = (6.6\times10^{-34}\ \text{J s})(5.5\times10^{14}\ \text{Hz}) = 3.63\times10^{-19}\ \text{J}. \qquad \textbf{(2)}$$

Using Einstein's photoelectric equation, the maximum kinetic energy of the photoelectrons is

$$\frac{1}{2}mv_{\max}^{2} = E - h\nu_0 = h\nu - h\nu_0.$$

Substituting the appropriate values from equations 1 and 2,

$$\frac{1}{2}mv_{\max}^2 = 4.95\times10^{-19}\ \text{J} - 3.63\times10^{-19}\ \text{J} = 1.32\times10^{-19}\ \text{J}.$$

The intensity I is defined as the number of photons incident per m^2 per second.

If n be the number of photons incident per m^2 per second then

$$I = nh\nu \ \Rightarrow\ n = \frac{I}{h\nu}.$$

Inserting the appropriate values in the preceding equation,

$$n = \frac{100\ \text{W m}^{-2}}{4.95\times10^{-19}\ \text{J}} = 2.0\times10^{20}.$$

EXAMPLE 3 **The photoelectric work function of a metal is 1 eV. Light of wavelength 3000 Å falls on it. What is the velocity of the ejected photoelectrons? [CBSE]**

Solution Given: $\phi_0 = 1\ \text{eV} = 1.6\times10^{-19}\ \text{J}$, $\lambda = 3000\ \text{Å} = 3000\times10^{-10}\ \text{m} = 3\times10^{-7}\ \text{m}$.

The energy of the photons of the incident light is

$$E = \frac{(6.6\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}{3\times10^{-7}\ \text{m}} = 6.6\times10^{-19}\ \text{J}. \qquad \textbf{(1)}$$

The kinetic energy of the ejected photoelectrons is

$$\frac{1}{2}mv^2 = h\nu - \phi_0 = 6.6\times10^{-19}\ \text{J} - 1.6\times10^{-19}\ \text{J} = 5.0\times10^{-19}\ \text{J}$$

$$\Rightarrow \quad v = \sqrt{\frac{2\times5.0\times10^{-19}\ \text{J}}{m}} = \sqrt{\frac{2\times5.0\times10^{-19}\ \text{J}}{9.1\times10^{-31}\ \text{kg}}} = 1.05\times10^{6}\ \text{m s}^{-1}.$$

EXAMPLE 4 **When light of wavelength 400 nm is incident on the cathode of a photocell, the stopping potential is recorded as 6 V. If the wavelength of the incident light is increased to 600 nm, calculate the new stopping potential. [CBSE]**

Solution For λ_1, $h\nu_1 = \phi_0 + eV_0 \ \Rightarrow\ \dfrac{hc}{\lambda_1} = \phi_0 + eV_0$

For λ_2, $\dfrac{hc}{\lambda_2} = \phi_0 + eV_0'$

Subtracting, $hc\left(\dfrac{1}{\lambda_1} - \dfrac{1}{\lambda_2}\right) = e(V_0 - V_0')$.

Taking $hc = 12420\ \text{eV Å}$, $\lambda_1 = 4000\ \text{Å}$, $\lambda_2 = 6000\ \text{Å}$ and $V_0 = 6\ \text{V}$,

$$(12420\ \text{eV Å})\left(\frac{1}{4000\ \text{Å}} - \frac{1}{6000\ \text{Å}}\right) = e(6\ \text{V} - V_0')$$

$$\Rightarrow \quad \frac{(12420\ \text{eV Å})(1)}{(12000\ \text{Å})} = 6\ \text{V} - V_0' \quad \Rightarrow \quad \frac{12420}{12000}\ \text{V} = 6\ \text{V} - V_0'$$

$$\Rightarrow \quad V_0' = 6\ \text{V} - 1.035\ \text{V} = 4.965\ \text{V} \approx \mathbf{4.97\ V}.$$

EXAMPLE 5 **Calculate the de Broglie wavelength of an electron accelerated through a potential difference of 60 V. [CBSE]**

Solution The de Broglie wavelength of an electron accelerated through a potential difference V is

$$\lambda = \frac{12.27}{\sqrt{V}}\ \text{Å}. \quad = \frac{12.27}{\sqrt{60}}\ \text{Å} = \frac{12.27}{7.75}\ \text{Å} = 1.58\ \text{Å}.$$

EXAMPLE 6 **The wavelength of a photon and the de Broglie wavelength of an electron have the same value. Show that the energy of the photon is ($2\lambda mc/h$) times the kinetic energy of the electron, where m, c, and h have their usual meanings.** **[CBSE]**

Solution The energy of the photon is

$$E_p = \frac{hc}{\lambda}. \tag{1}$$

The de Broglie wavelength of the electron is

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

The kinetic energy of the electron is

$$E_0 = \frac{1}{2}mv^2 = \frac{(mv)^2}{2m} = \frac{h^2}{2m\lambda^2}. \tag{2}$$

Dividing Equation 1 by Equation 2,

$$\frac{E_p}{E_0} = \frac{(hc/\lambda)}{(h^2/2m\lambda^2)} = \frac{2mc\lambda}{h} \Rightarrow E_p = \frac{2mc\lambda}{h}E_0.$$

EXAMPLE 7 **The photoelectrons ejected from a metal surface are fully stopped by a retarding potential of 3 V. Find the frequency of light incident on the metal surface. The minimum frequency at which photoemission from the surface begins is 6×10^{14} Hz. Determine the work function for the metal.**

Solution From Einstein's photoelectric equation,

$$h\nu = h\nu_0 + eV_0 \Rightarrow \nu = \frac{h\nu_0 + eV_0}{h} = \frac{eV_0}{h} + \nu_0.$$

Inserting the appropriate values in the preceding equation,

$$\nu = \frac{(1.6\times10^{-19}\ \text{C})(3\ \text{V})}{6.62\times10^{-34}\ \text{J s}} + 6\times10^{14}\ \text{Hz} = (7.2+6)\times10^{14}\ \text{Hz} = 1.32\times10^{15}\ \text{Hz}.$$

The work function of the metal is

$$\phi_0 = h\nu_0 = (6.62\times10^{-34}\ \text{J s})(6\times10^{14}\ \text{Hz})$$

$$\Rightarrow \quad \phi_0 = \frac{(6.62\times10^{-34}\ \text{J s})(6\times10^{14}\ \text{Hz})}{1.6\times10^{-19}\ \text{C}} = 2.48\ \text{eV}.$$

EXAMPLE 8 **Light of wavelength 2000 Å falls on an aluminium surface. It requires 4.2 eV to remove an electron from aluminium. What is the kinetic energy of (a) the fastest, and (b) the slowest photoelectron?** **[MNR]**

Solution (a) The maximum kinetic energy of the ejected photoelectron is

$$\frac{1}{2}mv_{\max}^2 = h\nu - \phi_0 = \frac{hc}{\lambda} - \phi_0.$$

Substituting the appropriate values in the preceding equation,

$$\frac{1}{2}mv_{\max}^2 = \frac{(6.62\times10^{-34}\ \text{J s})(3\times10^8\ \text{m s}^{-1})}{2000\times10^{-10}\ \text{m}} - 4.2\ \text{eV}$$

$$\Rightarrow \frac{1}{2}mv_{\max}^2 = \frac{(6.62\times10^{-34}\ \text{J s})(3\times10^8\ \text{m s}^{-1})}{(2000\times10^{-10}\ \text{m})\times(1.6\times10^{-19}\ \text{C})} - 4.2\ \text{eV}$$

$$\Rightarrow \frac{1}{2}mv_{\max}^2 = 6.2\ \text{eV} - 4.2\ \text{eV} = 2\ \text{eV}.$$

(b) The kinetic energy of the slowest photoelectron is zero.

◆◆◆ MEMORY PLUS

- The amount of energy that must be imparted to an electron to let it escape from the surface of a metal is termed its surface-barrier energy, E_B, and depends upon the particular metal and its surface conditions.
- The minimum energy required to liberate an electron from a metal is known as the work function (ϕ_0) of the material.
- The four principal ways in which electron emission from the surface of a metallic conductor occurs are thermionic emission, photoelectric emission, field emission and secondary emission.
- A photoelectric cell is a device that is activated by light. Photoelectric cells are of three basic kinds—photoconductive cells, photoemissive cells, and photovoltaic cells.
- When light radiation is incident on a metal surface, the energy of the photons is transferred to the free electrons within the metal and speeds them up sufficiently to enable them to leave the surface. Electrons liberated this way are known as photoelectrons.
- Light is emitted and absorbed as localized packets, or quanta (called photons). Each quantum has an energy $h\nu$, where ν is the frequency of the light and h is the Planck constant.
- The minimum frequency of incident radiation that causes electrons to be emitted from a metallic surface is known as the threshold frequency. The wavelength corresponding to this frequency is known as the threshold wavelength.
- When a photon strikes a metallic surface, a part of its energy is used up in pulling an electron out of the metallic surface and the rest is used up in imparting kinetic energy to the emitted electron.
- Louis de Broglie hypothesized that a material particle of mass m moving with a speed v has a wave of wavelength $\lambda = h/mv$ associated with it.
- The Davisson–Germer experiment demonstrated the wave nature of the electron, confirming de Broglie's hyphothesis.
- According to the uncertainty principle of Heisenberg, if Δx be the uncertainty in determining the position of a particle and Δp be the uncertainty in knowing its momentum, $\Delta x \Delta p \geq \hbar$, where $\hbar = h/2\pi$.
- An electron microscope is a type of microscope that uses an electron beam to illuminate a specimen and produce a magnified image.

Objective Questions

I. Choose the correct option.

1. Light of wavelength 0.6 μm from a sodium lamp falls on a photocell and causes the emission of photoelectrons for which the stopping potential is 0.5 V. With light of wavelength 0.4 μm from a sodium lamp, the stopping potential is 1.5 V. From this data, the value of h/e is

3. The number of electrons ejected from a photosensitive surface depends upon [CET]
   (a) the intensity of the incident light
   (b) the frequency of the incident light
   (c) the wavelength of the incident light
   (d) none of these

4. Photons of energy 6 eV are incident on a metal surface whose work function is 4 eV. The minimum kinetic energy of the emitted photoelectrons is [MP]
   (a) 0 eV (b) 1 eV
   (c) 2 eV (d) 10 eV

5. The work function of three metals A, B and C are 4.5 eV, 4.3 eV and 3.5 eV respectively. If light of wavelength 4000 Å is incident on the metal then photoelectrons are emitted from [IIT]
   (a) A (b) B
   (c) C (d) all three

(a) 4×10^{-59} V s (b) 0.25×10^{15} V s
(c) 4×10^{-15} V s (d) 4×10^{-8} V s

2. If the threshold frequency for the emission of photoelectrons from a metal is ν_0, and light of frequency ν is incident on it then for emission to take place [IIT]
   (a) $\nu = \nu_0$ (b) $\nu = 2\nu_0$
   (c) $\nu < \nu_0$ (d) $\nu > \nu_0$

6. What is the approximate kinetic energy of the photoelectrons emitted when light of wavelength 4000 Å is incident on a metal of work function 2 eV? [IIT]
   (a) 0.5 eV (b) 1.1 eV
   (c) 2.5 eV (d) 3 eV

7. The work function of a substance is 4.0 eV. The largest wavelength of light that can cause photoelectron emission from the substance is approximately [UP]
   (a) 540 nm (b) 400 nm
   (c) 310 nm (d) 220 nm

8. Light of frequency $4\nu_0$ is incident on a metal of threshold frequency ν_0. The maximum kinetic energy of the emitted photoelectrons is [MP]
   (a) $3h\nu_0$ (b) $2h\nu_0$
   (c) $\frac{3}{2}h\nu_0$ (d) $\frac{1}{2}h\nu_0$

9. The photoelectric effect can be explained by assuming that light
   (a) is a form of electromagnetic wave
   (b) is a form of longitudinal wave
   (c) can be polarized
   (d) consists of quantas of energy

10. The stopping potential depends on
   (a) the intensity of the incident light
   (b) the frequency of the incident light
   (c) both (a) and (b)
   (d) neither (a) nor (b)

11. The momentum of a photon of wavelength λ is
   (a) $h\lambda$ (b) h/λ
   (c) λ/h (d) hc/λ

12. When radiation of wavelength λ is incident on a metallic surface, the stopping potential is 4.8 V. If the same surface is illuminated with radiation of double the wavelength, the stopping potential becomes 1.6 V. The threshold wavelength for the surface is
   (a) 2λ (b) 4λ
   (c) 6λ (d) 8λ

13. If an electron and a proton are propagating in the form of waves that have the same λ, they have the same [DCE]
   (a) energy (b) momentum
   (c) velocity (d) angular momentum

14. For a given kinetic energy, which of the following has the smallest de Broglie wavelength?
   (a) electron (b) proton
   (c) neutron (d) α-particle

15. The work function of a metal is 2.31 eV. Its threshold frequency is
   (a) 6.08×10^4 Hz (b) 7.4×10^4 Hz
   (c) 6.5×10^{11} Hz (d) 5.6×10^{14} Hz

16. The kinetic energy of photoelectrons emitted from a metal surface depends upon [DCE]
   (a) the intensity of the incident light
   (b) the frequency of the incident light
   (c) the velocity of the incident light
   (d) both the intensity and the velocity of the incident light

17. The energy of a photon and the kinetic energy of a proton are both equal to E. If λ_1 be the de Broglie wavelength of the proton and λ_2 be the wavelength of the photon, the ratio λ_1/λ_2 is proportional to [IIT Screening]
   (a) E^0 (b) $\sqrt{E}$
   (c) E^{-1} (d) E^{-2}

18. If the frequency of the light incident on a metal surface is doubled, the kinetic energy of the emitted electrons will
   (a) be doubled
   (b) be less than double
   (c) be more than double
   (d) nothing can be said

19. According to Einstein's photoelectric equation, the plot of the kinetic energy of the photoelectrons emitted from a metal versus the frequency of the incident radiation is a straight line whose slope [AIEEE]
   (a) depends on the nature of the metal used
   (b) depends on the intensity of the incident radiation
   (c) depends on the intensity of the incident radiation and the metal used
   (d) is the same for all metals and is independent of the intensity of the incident radiation

20. The time taken by a photoelectron to be emitted after a photon strikes it is approximately [AIEEE]
   (a) 10^{-1} s (b) 10^{-4} s
   (c) 10^{-10} s (d) 10^{-16} s

21. The threshold frequency for a metallic surface corresponds to an energy of 6.2 eV and the stopping potential for a radiation incident on this surface is 5 V. The incident radiation lies in the [AIEEE]
   (a) X-ray region (b) ultraviolet region
   (c) infrared region (d) visible region

22. A photon of frequency ν has a momentum associated with it. If c be the velocity of light, the momentum is [AIEEE]
   (a) $h\nu/c^2$ (b) $h\nu/c$
   (c) ν/c (d) $h\nu c$

23. Electrons are emitted when green light is incident on a certain metal surface, but not when yellow light is incident on it. If red light is incident on the same metal surface,
   (a) more energetic electrons will be emitted
   (b) less energetic electrons will be emitted
   (c) the emission of electrons will depend on the intensity of light

II. Fill in the blanks.

1. The dimensions of the Planck constant are ....
2. The unit of the Planck constant is ....
3. 1 eV = ... J.
4. Photoemission is the phenomenon of emission of electrons from a surface when ...... strikes the surface.
5. Photoemission does not take place if the frequency of the incident light is less than the ....
6. The maximum kinetic energy of photoelectrons is proportional to the ...... of the incident light.
7. The rate of emission of photoelectrons from a surface is proportional to the ...... of the incident light.
8. The minimum energy required to pull out an electron from a metallic surface is known as the ...... of the metal.
9. The de Broglie wavelength associated with a particle of mass m and moving with a velocity v is ....
10. The energy of a photon of wavelength λ is ....
11. The waves associated with moving material particles are called ....
12. The photoelectric effect shows the ...... nature of light.

VERY SHORT QUESTION:

1. What is a photon?
2. What is the velocity of a photon?
3. What is the rest mass of a photon?
4. If the wavelength of electromagnetic radiation were doubled, what would happen to the energy of a photon? [CBSE]
5. If the intensity of the incident radiation on a metal were doubled, what would happen to the kinetic energy of the electrons emitted? [CBSE]
6. Define stopping potential.
7. Write Einstein's photoelectric equation. [CBSE]
8. Name the phenomenon that illustrates the particle nature of light. [CBSE]
9. If the intensity of the incident radiation in a photocell were increased, how would the stopping potential change? [CBSE]
10. Write the expression for the de Broglie wavelength of a photon.
11. Mention one physical process by which electrons are emitted from the surface of a metal. [CBSE]
12. Define photoelectric work function. [CBSE]
13. A beam of red light and a beam of blue light of the same intensity are incident on a metallic surface. Which one will cause the emission of electrons with greater kinetic energy? [CBSE]
14. Electrons are emitted from a sensitive surface when it is illuminated by green light, but not when it is illuminated by yellow light. Will electrons be emitted when the surface is illuminated by (a) red light, and (b) blue light? [CBSE]
15. Ultraviolet light is incident on two photosensitive materials that have the work function ϕ_1 and ϕ_2 ($\phi_1 > \phi_2$). In which will the kinetic energy of the emitted electrons be greater, and why? [CBSE]
16. The de Broglie wavelength associated with an electron accelerated through a potential difference of 1 V is λ. What will be the wavelength when the accelerating potential is increased to 4 V? [CBSE]
17. Ultraviolet radiations of frequencies ν_1 and ν_2 are incident on two photosensitive materials whose work functions are ϕ_1 and ϕ_2 ($\phi_1 > \phi_2$) respectively. The kinetic energy of the emitted electrons is the same in both cases. Which of the radiations will be of higher frequency? [CBSE]
18. Show graphically how the stopping potential for a given photosensitive surface varies with the frequency of the incident radiation. [CBSE[
19. How does the stopping potential of a photocell change, when the distance between the light source and the cathode of the cell is doubled? [CBSE]
20. The work functions of some metals are given below.

    Na: 1.92 eV, K: 2.15 eV, Mo: 4.17 eV, Ni: 5.0 eV

    Which of these metals will not emit photoelectrons when radiation of wavelength 3300 Å is incident on them? [CBSE]

Objective Questions

I. **1.** (c) **2.** (d) **3.** (a) **4.** (a)
5. (d) **6.** (b) **7.** (c) **8.** (a)
9. (d) **10.** (b) **11.** (b) **12.** (b)
13. (b) **14.** (d) **15.** (d) **16.** (b)
17. (b) **18.** (c) **19.** (d) **20.** (c)
21. (b) **22.** (b) **23.** (d)

II. **1.** ML^2T^{-1} **2.** J s **3.** 1.6×10^{-19} C
4. light **5.** threshold value **6.** frequency
7. intensity **8.** work function **9.** h/mv
10. hc/λ **11.** matter waves **12.** particle