Chapter - 13

Photo-Electric Effect and Matter Waves

In the previous chapter you have studied about wave nature of light. Optical phenomena like reflection, refraction, interference, diffraction and polarization can be explained using wave theory of light. Maxwell propounded electromagnetic waves theory in 1887 and then experimental demonstration of the existence of electromagnetic waves by Hertz very well established wave nature of light. You will read more about electromagnetic waves in chapter 17.

By nineteenth century the wave nature of light was well established, but at the same time some observations like photoelectric effect, Compton effect and later Raman effect could not be explained on the basis of wave theory. To explain them quantum (photon) theory was used which was related to corpuscular theory of light. In this chapter we will mention about photoelectric effect, its experimental results and Einstein's photo-electric equation for their explanation. You will learn more about Compton effect and Raman effect in higher classes. After that we will study about dual nature of light. After knowing about dual nature of light the question arises that if light beam which is supposed to have wave nature generally behaves like a particle in some cases then does a beam of particles or a beam of electrons in certain circumstances behave like waves? Later in this chapter we will be able to answer this question when we study about matter wave hypothesis of de Broglie (pronounced as de Broy in French) and its experimental confirmation. Towards the end of this chapter we will learn about Heisenberg's Uncertainly Principle.

13.1 Photo-electric effect and matter waves

In 1887 while doing experimental study on electromagnetic waves Hertz observed that when ultraviolet light from an Arch lamp falls an cathode the discharge between electrodes becomes easier. These observations led Hertz to propose that when ultraviolet light falls on cathode charged particles are emitted which makes discharge easier. In 1888 scientist Hallwachs connected a negatively charged zinc plate to an electroscope and observed that when ultraviolet light falls on negatively charged plate it loses its negative charge. When an uncharged plate is used and when it is illuminated by ultraviolet light it becomes positively charged. If a positively charged plate is used it gains more positive charge or it remain unaffected. From these experiments it was concluded that when a negatively charged or an uncharged plate is illuminated with ultraviolet light it emits negatively charged particles which makes the negatively charged plate neutral or uncharged plate becomes positively charged. In 1897 after the discovery of electron and on measuring the e/m of particles it was established that these particles are electrons which are emitted when light falls on the plate. Hallwachs and another scientist Leonard observed that when light of frequency lower than a fixed frequency falls on the plate no electrons are emitted. This lowest fixed frequency is known as threshold frequency and its value depends upon the nature of the material of the plate or any photosensitive surface.

We know that why a metal is good conductor is that it has large number of free electrons. These electrons move freely inside the metal but cannot come out of the surface. If they could come out of the surface the surface would have become positively charged and would have attracted electrons back inside. Obviously the elctrons near the surface face resistance. Hence they need some additional energy to come out of the surface and this can be given only by an external source. The minimum amount of energy needed by electrons to just come out of the surface (with zero kinetic energy) is called work function of the metal. The work function is generally denoted by ϕ_0 and is generally measured in eV (electron volt) ($1 eV = 1.602 \times 10^{-19} J$). Different metals have different work functions and this depends on the nature of their surface. When the free electrons of the metal get energy equal to or more than the work-functioon from the incident light, electrons are emitted. Because of their generation by light such electrons are called photoelectrons. Due to these emitted electrons the current flowing in a closed circuit is called photoelectric current. Hence (to summarise) "When light of a specific frequency or more than that frequency falls on a metal surface or optically sensitive surface the electrons are emitted. This phenomenon is called photoelectric effect."

Table 12.1 shows work functions of a few metals. The presence of impurities in the surface changes these values.

Table 13.1 : Work functions of some metals

Metal	Work function eV	Metal	Work function eV
Cesium Cs	2.14	Aluminium Al	4.28
Potassium K	2.30	Mercury Hg	4.49
Sodium Na	2.75	Copper Cu	4.65
Calcium Ca	3.20	Silver Ag	4.70
Molybdenum Mo	4.17	Nickel N	5.15
Lead Pb	4.25	Platenum Pt	5.65
Fe	4.7	Au	5.1
Ir	5.27	Os	4.38
Ta	4.25	W	4.55
Rh	4.98	Ru	4.7

It is observed from experiments that Alkali metals (like Lithium Sodium, Potassium etc.) show photo-electric effect for visible light also while Zinc, cadmium, Magnisium and other similar metals show this effect only for high frequency ultraiolet waves. For emission of electrons from metals there are other methods also. When metals are heated adequately electrons come out because they get extra heat energy. This method is known as thermionic emission. Electrons can also be emitted by applying strong electric field (of the order of 10^8 V/m). This method is known as field emission. Besides this if electrons having high kinetic energy are incident on the metal it is possible that electrons may be ejected. This method is called secondary emission.

13.2 Experimental results of photoelectric effect and their interpretations

To study photo-electric effect in the laboratory a simple experimental arrangement is shown in figure 13.1. It has a glass or quartz tube which has vacuum inside. This tube has two electrodes C and A. C is called cathode (or emitter), is a light sensitive metallic plate. Plate A is called Anode (or collector). Light from source S crosses a window and falls on plate C. The potential difference between C and A is maintained by a battery and it can be varied by means of a current controller in the circuit. The potential of A relative to C can be kept positive or negative through a commutator in the circuit. Photo-electrons emitted by C when light is incident on it are attracted towards A if A is positive with respect to C. The electrons collected by A flow through the microammeter, battery etc. in the external circuit and reach C and thus current flows in the circuit which is called photo-electriccurrent. The voltmeter V in the circuit measures potential difference between A and C and photo-electric current is measured by microammeter. For observing the effect of intensity of light on photo-electric current the intensity can be changed by changing the distance between source S and emitter C. Different sources of light with different frequencies can be used to see the effect of frequency on photoelectric current. Alternatively filters can be kept between source S and plate C to get light of requiredfrequency.

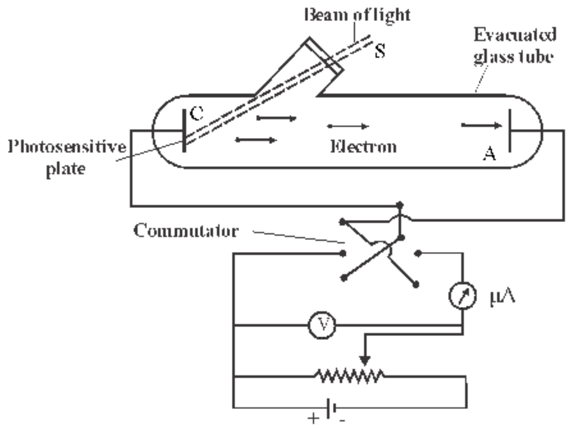

Fig. 13. 1 : Experimental arrangement for studying photoelectric effect.

The following results are obtained through the study of the photoelectric current.

13.2.1 Effect of potential on photoelectric current.

First of all the frequency of light and Intensity I are kept constant and light is incident on C. suppose A is at zero potential relative to C. In this condition all the electrons emitted by C cannot reach A. At any given time electrons emitted by C remain near it and form space charge. This negatively charged space charge repels electrons emitted by C. Even then some electrons reach A and thus photo-electriccurrent begins to flow. When

Anode A is given some positive potential relative to C some more electrons are attracted towards A and space charge is decreased and photoelectric current increases. Thus current depends upon the potential of Anode. Figure 13.2 shows variation in the current with variation in potential of A. If potential of A is gradually increased a stage comes when the effect of space charge becomes negligible and all the electrons emitted by Cathode are able to reach Anode. Then current becomes constant. This current is known as saturated current. This is shown by part bc in fig. 13.2. If potential of A is still increased no change in photo-electric current takes place.

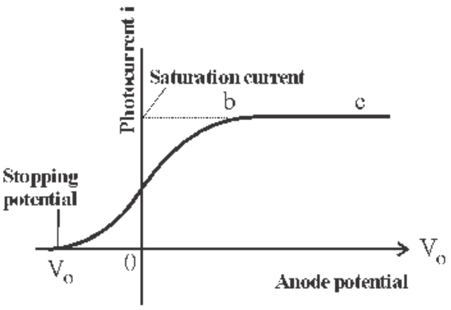

Fig. 13.2 : Graph between photocurrent and Anode potential at constant potential and intensity

If potential of Anode becomes negative relative to Cathode some electrons return to cathode due to repulsion by Anode and current is decreased. If negative potential on A is increased current decreases rapidly. Negative potential is also known as retarding potential. On a certain value V_0 of negative potential the current becomes zero. For a definite frequency of incident light the negative potential V_0 on Anode for which photo-electriccurrent becomes zero is known as cut off potential or stopping potential. This depends upon frequency of incident light.

Stopping potential has direct relation to maximum kinetic energy of emitted electrons. The kinetic energies of all the electrons emitted by cathode are not equal. For current to be zero we have to ensure that an electron with maximum kinetic energy (or fastest moving electron) is not able to reach the Anode. In this situation the maximum kinetic energy of the emitted electron K_{max} is equal to work done against the repelling force of stopping potential V_0 or

$$K_{max} = \frac{1}{2} m v_{max}^2 = eV_0 \qquad \ldots (13.1)$$

where m = mass of electron, e = charge of electron v_{max} = maximum speed of an emitted electron

13.2.2 Effect of intensity of light on photo-electriccurrent

If we repeat the above experiment with a definite frequency but different intensities we will find that with increase in intensity the value of saturated current also increases. (If frequency of light is constant).

In fig 13.3 graphs between photoelectric current versus Anode potential for 3 different intensities have been displayed. Here $I_3 > I_2 > I_1$ It is evident that saturated current increases with increasing intensity. It means that on increasing intensity the electrons emitted by cathode per second and electrons reaching anode per second increase and current is also increased. It is to be kept in mind that stopping potential does not depend upon intensity. If the stopping pointical for a certain metal and for a certain frequency of light from a 1W source is -1.0 then for the same metal and same frequency of light from 5W source the stopping potential will remain - 1.0V.

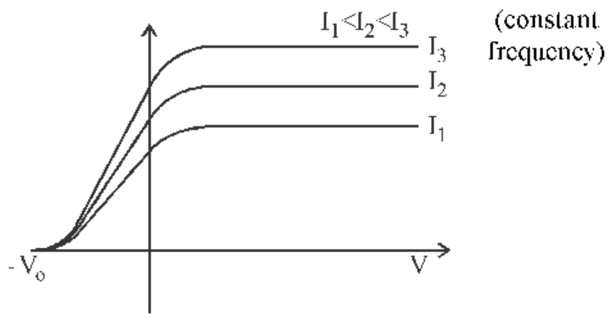

Fig. 13.3 : Graph between photo electric-current and Anode Potential for incident light of different intensities

When intensity of incident light is increased the saturated photo-electriccurrent increases linearly as shown in fig 13.4. Because photo-electric current is directly proportional to emitted electrons per second therefore the number of electrons emitted per second is also directly proportional to intensity of incident light. If the source of light is a point source then intensity of light I will be inversely proportional to distance (d) between cathode & source. Hence photo-electric current will also follow the same principle i.e.

$$i \propto \frac{1}{d^2}$$

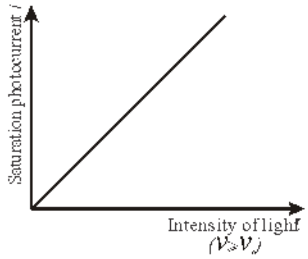

Fig. 13.4 : Graph b/w and intensity

13.2.3 Effect of Frequency on Photo-Electric Current

For a given photo sensitive plate and keeping the intensity of radiation constant if frequency of incident light is changed and for each frequency the corresponding stopping potential is measured, it can be observed that as the frequency is increased the stopping potential will be increased proportionately.

But saturated current will remain the same. In fig 13.5 graph between Anode Potential V and corresponding photo-electric current for three frequencies ν_1, ν_2 and ν_3 is displayed (where $\nu_3>\nu_2>\nu_1$) Here it can be seen that $V_{03} > V_{02} > V_{01}$. Because stopping potential is an indicator of maximum kinetic energy of electrons it can be said that as the frequency of incident light is increased the maximum kinetic energy of electrons will increase proportionaly.

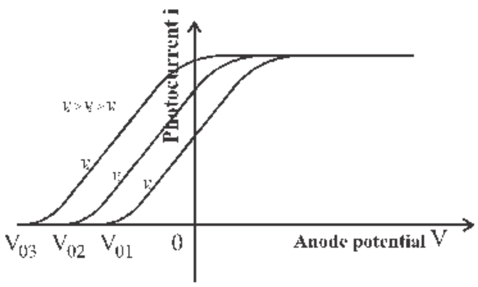

Fig. 13.5 : Graph between Anode Potential V and photoelectric current for different frequencies of incident light of a definite Intensity

If a graph is plotted between the frequency of incident light and corresponding stopping potential for different metals it will be a straight line as shown in fig 13.6 for two metals A and B. From this figure it is clear that for frequeney ν_{0A} for metal A and for frequency ν_{0B} for melal B the stopping potential for emitted electrons (i.e. maximum kinetic energy of electrons) is zero. Hence for every metal there is a definite cut off or threshold frequency ν_o for which the corresponding stopping potential is zero. If the frequency of the incident light is less than cut off value ν_o no photo electrons will be emitted whatever be the intensity. The wavelength λo corresponding to ν_o is called threshold wavelength $(\lambda_0 = c/\nu_0)$.

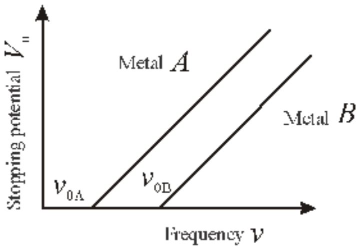

Fig. 13.6 : Graph between stopping potential or frequency for different metals

It should be borne in mind that if the frequency of incident light is more than the threshold frequency then there is no time lag between incidence of light and emission of electrons. Immediately after the incidence of light emission of electrons starts (within 10^{-9} s or less than that time).

The results of the above mentioned experiments can be summarised as follows :

1. When light of high frequency (or adequately short wavelength) falls on any metallic surface the metal emits electrons. This emission takes place immediately without any time lag.
2. For a given metal there is a definite threshold frequency ν_o . If incident light is of less frequency photo-electriceffect will not be observed how so high the intensity may be.
3. Photo electrons may have any Kinetic energy starting from zero to a maximum value K_{max}.
4. By keeping Anode at a negative potential relative to cathode emission of photo-electrons can be stopped. The minimum nagative potential of Anode for which photo-electric current becomes zero is called stopping potenial. The stopping potential v_o and maximum kinetic energy of emitted electrons are related by the equation, $K_{max} = e\,v_o$.

5. Stopping potential does not depend upon intensity of light. That means the maximum kinetic energy of electrons is independent of the intensity. But stopping potential has a linear relationship with frequency of incident light.

6. The saturated photo-electric current increases when intensity of light is increased.

13.2 4 Failure of wave theory to explain Photo-Electric Effect.

According to electromagnetic wave theory of light the distribution of energy takes place wherever the waves are present. Because waves have energy it seems that by absorbing energy from waves the electrons of the metal can come out. But on this basis photo-electriceffect can not be explained adequately.

1. Dependence of kinetic energy of photo-electrons on intensity of light. According to electromagnetic nature of light when light is incident on a metal a periodic force due to oscillatory electric field of the wave should act. If electric field of electromagnetic wave has an amplitude E_0, its intensity $I \propto E_0^2$ and effective force acting on the electron $F=eE_0$. When Intensity increases the force on the electron increases and therefore its acceleration and kinetic energy should increase. In ther words according to wave theory the continuous absorption of energy by electrons goes on and hence electrons will absorb more energy from high intensity beam of ligh and they should come but with greater energy. But according to experimental observations the maximum kinetic energy of electrons does not depend upon intensity of light.

2. Dependence of emission of electrons on frequency of light waves :

   According to wave theory photo-electric effect should be observed for all frequencies of light subject to intensity being adequately high so that electrons get needed energy to come out of the metal

   This is not observed in experiments as light of less frequency than the threshold frequency does not show photo-electric effect how so high the intensity may be.

(iii) Time Lag: In any wave energy distribution takes place at the wave front and hence all the electrons in the illuminated area should absorb energy. If the intensity is low the electron should take finite time to gain energy to come out of the metal. It means there should be measurable time lag between incidence of light and emission of electrons. According to wave theory this time could be even a few hours. But the experimental observation is that emission of electrons takes place immediately after incidence of light (within 10^{-9}s or even less time).

(iv) Dependence of kinetic energy of photo-electrons on frequency of light.

According to wave theory the frequency of light and kinetic energy of photo-electrons should have no relation while the experimental fact is that maximum kinetic energy of emitted electrons increases with increasing frequency of light.

Thus we conclude that wave theory of light cannot explain experimental results.

13.3 Concept of Photons:

To explain energy distribution in Black body spectrum Planck in 1900 proposed that emission of radiation by a body or absorption of the same does not take place continuously. But it happens by means of discrete bundles (called quanta). Agreeing to views of Planck, Einstein in 1905, proposed that light energy (universally known as electromagnetic radiation) is quantised. It means radiation energy is made of discrete units which are called quanta of radiation energy. We now call them photons. During mutual interaction with matter radiation behaves as if it is made of particles known as photons. Some important characteristics of Photons are given below :-

1. In vacuum every photon always travels with the velocity of light (3 x 108 m/s)

2. Every photon has a definite energy and a definite momentum. A photon of radiation (light) of frequency v has energy equal to $hv = hc/\lambda$ and a momentum equal to $p = hv/c = h/\lambda$. Here λ is the wave length of electro magnetic radiation (light). h is a universal constant which is known as Plank's constant. Its value is $h = 6.63 \times 10^{34}$ Js = 4.1 x 10^{-15} eVs.

3. Photon can collide with a particle (like electron). In such a collision the total energy and total

momentum are conserved. Photon can be absorbed also during a collision and /or new photons can be formed. It is not necessary that the number of photons remains unchanged.

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

5. If the intensity of light of a given frequency is increased the number of photons passing through a given area in a given time also increases. Energy of every photon remains the same.

6. Rest mass of a photon is zero.

Example 13.1 : For a photon of wavelength 4000Å find (a) Frequency (in Hz) (b) energy in eV and (c) momentum [h = 6.63 × 10^{-34} J.S and c = 3×10^{8} m/s]

Solution : (a) For light, $c = \nu\lambda$

$$\therefore \quad \nu = \frac{c}{\lambda} = \frac{3\times10^{8} m/s}{4000\times10^{-10} m}$$

$= 7.5 \times 10^{14}$ Hz

(b) energy of Photon $E = h\nu$

$= (6.63 \times 10^{-34}$ Js) $(7.5 \times 10^{14}$ s$^{-1})$

$= 4.97 \times 10^{-19}$ J

$$= \frac{4.97\times10^{-19}}{1.6\times10^{-19}} = 3.10 eV$$

(c) Momentum of photon

$$p = \frac{h}{\lambda} = \frac{6.63\times10^{-34}}{4000\times10^{-10}}$$

$= 1.66 \times 10^{-27}$ N.s

Example 13.2 : A monochromatic source of light operating on 100W emits 4x10^{20} photons per second find the frequency of light [h = 6.63 × 10^{-34} J.s and c = 3 × 10^{8} m/s]

Solution : If number of photons emitted by source per second is n and every photon has energy E and Power of source is P

Then $P = nE$

$$\therefore \quad E = \frac{P}{n} = \frac{(100 Js^{-1})}{4\times10^{20}}$$

$= 2.5 \times 10^{-19} J$

Hence wavelength of Photon $\lambda = \frac{hc}{E}$

$$= \frac{(6.63\times10^{-34} Js)(3\times10^{8} m/s)}{2.5\times10^{-19}}$$

$= 8.0 \times 10^{-7} m = 8000$Å

13.4 Einstein's Photo-electric equation and explanation of experimental results of photoelectric effect on the basis of this equation

As mentioned in the previous section in order to give theoretical explanation of photoelectric effect Einstein in 1905 considered light (Electromagnetic radiation) as made up of quanta. In that research paper Einstein used the word Quanta but we are using the word Photon.

Through this revolutionary theory proper explanation of experimental results about Photoelectric effect was given for which Einstein got Nobel Prize in 1921.

After striking the metallic surface photons collide with the free electrons of the metal. In a certain collision Photon can transfer all its energy E to free electron. If this energy is more than the work function of the metal the electron can come out of the metal. It is not necessary that if the energy given to electron is more than ϕ_0 it must be emitted. Deep inside the metal the electrons that have gained energy collide with the ions and may loose their energy. Near the surface of the metal the electron after getting additional energy may move towards the surface and come out. If such electrons after getting energy E from photon come towards the surface without further collision and come out their Kinetic energy will be $E - \phi_0$. If before coming out the electrons have further collisions their kinetic energy may be less than $E - \phi_0$. Thus the photoelectrons emitted by the metal may have any energy between zero and maximum value $E - \phi_0$. If this maximum value is denoted by K_{max} we have

$$K_{max} = E - \phi_0 \qquad ...(13.2)$$

But energy of a photon having frequency is given by $E = h\nu$, hence

$$K_{max} = h\nu - \phi_0 \qquad ...(13.3a)$$

or $$h\nu = K_{max} + \phi_0 \qquad ...(13.3b)$$

Equation 13.3 is known as photoelectric equation of Einstein. In reality this is the statement of law of conservation of energy about work function ϕ_0 and absorption of a single photon. If the mass of the ejected electron is m and maximum velocity is v_{max} we have

$$h\nu = \frac{1}{2}mv_{max}^2 + \phi_0 \qquad \ldots (13.4)$$

If stopping potential is V_0 then $K_{max} = eV_0$

Hence $h\nu = eV_0 + \phi$ $\ldots (13.5)$

Equation 13.4 and 13.5 are alternative forms of Photo-electric equation

Now we will explain experimental results of photoelectric effect using photoelectric equation.

(i) According to equation 13.3 the maximum energy of photoelectrons K_{max} varies linearly with the frequency of incident light and does not depend upon intensity. It tallies with the experimental observations.

(ii) By definition kinetic energy can never be negative. Hence in equation 13.3 it is provided that photoelectric effect can be observed only when

$h\nu > \phi_0$.

or $h\nu > h\nu_0$

where $$\nu_0 = \frac{\phi_0}{h} \qquad \ldots (13.6)$$

Thus threshold frequency comes into existence Light having a frequency less than threshold cannot eject electrons whatever be its intensity. It also tallies with the observations.

It is also evident from eq. 13.6 that threshold frequency must be more in case of metals having more work function ϕ_0 .

(iii) Experimental observations regarding dependence of photoelectric current on intensity in case of frequency of light being more than threshold can be explained using the concept of photons. Intensity of light is proportional to the number of photons per unit area per unit time. If more photons are incident they will eject more photoelectrons i. e. photoelectric current will also be more. Hence for $\nu > \nu_0$ the photoelectric current will be proportional to intensity.

(iv) In propounding the photoelectric equation the basic consideration was absorption of a photon by an electron which can be considered as a collision. Time taken in collision is negligible hence absorption process is almost instantaneous. Hence in photoelectric effect there is no time lag between incidence of light and emission of electrons. This also is in agreement with experimental observations. Decreasing the intensity of light does not delay the emission of electrons because basic process is absorption of a photon by an electron. As given in (iii) intensity affects the magnitude of current only. In addition the rate of emission of electrons does not depend upon frequency of incident light because according photoelectric equation increasing results in increase of maximum kinetic energy of electrons but not the number of electrons emitted.

Using the relation $\nu = c/\lambda$ the photoelectric equation can be written in terms of wavelength also.

Equation 13.5 can also be written as :-

$$V_0 = \left(\frac{h}{e}\right)\nu - \frac{\phi_0}{e} \qquad \ldots (13.7)$$

which is similar to linear equation $y - mx \quad c$. It means graph between stopping potential V_o and frequency should be a straight line whose slope is h/e which does not depend upon the nature of the matter. such a graph has been depicted in fig 13.6 Since e is a known constant and slope h/e can be measured. Hence the value of h can be determined.

During 1906 to 1916 Millikan studied photoelectric effect using sodium metal and by measuring the slope of the straight line determined the value of Planck Constant h which agreed with the values determined through other methods. Thus Millikan established photoelectric equation of Einstein experimentally.

Example 13.3 : For a certain metal the work function is 2.2eV. Determine the maximum wavelength of light that can show photoelectric effect for this metal.

[$h = 4.14 \times 10^{-15}$ eV. s, $c = 3 \times 10^8 ms^{-1}$]

Solution :

Threshold frequency $\nu_0 = \frac{h}{\phi_0}$

But $\nu_0 = \dfrac{c}{\lambda_0}$ where λ_0 is corresponding threshold frequency.

$$\therefore \quad \lambda_0 = \frac{hc}{\phi_0}$$

$$= \frac{(4.14\times10^{-15}\,eVs)\times(3\times10^{8}\,m/s)}{2.2\,eV}$$

$$= \frac{12.42\times10^{-7}\,eV.m}{2.2\,eV}$$

$$= \frac{1242\,eV\,nm}{2.2\,eV} = 564.5\,nm = 5645\ \text{Å}$$

Note : In this example it can be seen that hc = 1242 eVnm If we can remember this result it will help us in the solution, of those questions (specially objective type questions) where the values of h and c are not given or in the question energy is given in eV and wavelength λ is to be determined or vice-versa.

Example 13.4 : In an experiment on photo-electriceffect light of 200 nm is incident on lithium metal 0 = 2.5eV determine (a) maximum kinetic energy of photoelectrons in eV and (b) stopping potential

Solution : The maximum kinetic energy is given by

$$K_{max} = h\nu - \phi = \frac{hc}{\lambda} - \phi$$

$$\therefore \quad K_{max} = \left(\frac{1242\,eV.nm}{200\,nm}\right) - 2.5\,eV$$

= 6.21 eV – 2.5 eV = 3.71 eV

For practice get this result using h = 6.63 × 10^{-34} J.S and c = 3 × 10^{8} ms^{-1}. You will get in joules which you will have to convert in eV.

(b) Stopping potential is given this way -

$$V_0 = \frac{K_{max}}{e}$$

$$= \frac{3.71\,eV}{e} = 3.71\,V$$

Example 13.5 : Certain metal surface is illuminated first by light 2000Å wave length and then by light of 6000 Å wave length. It was observed that the ratio of maximum velocities of photo-elecrons emitted in these two cases is 3 : 1. Find out the work function of the metal.

Soloution: According to Einstein's photo-electric equation

$$\frac{hc}{\lambda} = \phi_0 + \frac{1}{2}mv_{max}^2$$

For $\lambda_1 = 3000\mathring{A} = 300\,nm$

$$\frac{hc}{300\,nm} = \phi_0 + \frac{1}{2}m(3v)^2 \qquad \ldots(i)$$

For $\lambda_2 = 6000\mathring{A} = 600\,nm$

$$\frac{hc}{600\,nm} = \phi_0 + \frac{1}{2}mv^2 \qquad \ldots(ii)$$

Multiplying eq (ii) by 9 and then subtracting eq (i) from it we get

$$8\phi_0 = hc\left\{\frac{9}{600\,nm} - \frac{1}{300\,nm}\right\}$$

$$= \frac{1242\,eV.nm\times7}{600\,nm}$$

$$\therefore \quad \phi_0 = \frac{1242\times7}{8\times600} = 1.81\,eV$$

= 2.89 J

13.5 Dual Nature of Light

What is the nature of light? Is it a wave or has a particle nature. Searching answers to these questions has an interesting background history. In the process of discovery there was very important advancement is knowledge and understanding in the area of Physics which became the basis of Quantum mechanics, upto 17th century some of the known properties of light were: 1 Motion along a straight line path, 2 Reflection of light from plane and curved surfaces, 3 Refraction at interface of two medium and 4 Colour dispersion of light about which you have read earlier.

Great Scientist Newton in his Corpuscular theory of light treated light to be composed of little corpuscles. Corpuscles emitted by a source travelled in straight lines in the absence of external forces. Not going into details of this theory we will mention that corpuscular theory successfully explained linear propagation of light, formation of shadow behind an obstacle and reflection of light. Refraction of light could also be partially explained but the conclusion of this theory that if the ray of light bends towards the normal in the second medium its speed in this medium should be more than the speed of light is against the experimental evidence.

Contemporary of Newton scientist Huygens proposed wave theory of light in 1678. You have learnt about it in detail in the previous chapter. After the successful explanation of reflection of light, refraction etc. the wave theory of light could also successfully explain other phenomena of light e.g. interference, diffraction and polarization which could not be explained by corpuscular theory. Wave theory gained more support when Maxwell in 1860 established mathematically the existence of electromagnetic waves by using electromagnetic equations. These waves move with the speed of light in vacuum and their transverse nature was in agreement with polarisation which is exclusive properly of transverse waves. In 1887 the experimental work done by Hertz regarding origin and detection of electromagnetic waves paved the way for universal acceptance of wave theory of light.

It is ironical that during discoveries done by Hertz the photo-electriceffect was discovered which put a question mark on completeness of wave theory. Compton effect and Raman effect observed later could be explained by photon, (quanta) model like photo-electric effect. In order to explain specific heat of solids. Debye put forward a hypothesis that lattice vibrations are quantised.

Thus we find that in some optical phenomena like reflection, refraction, diffraction, polarisation etc light has a wave nature and they cannot be explained on corpuscular theory of light. On the other side the phenomena like photo-electriceffect, Compton effect and Raman effect can be explained only on the basis of quantum (photon model) theory and not on wave theory. Hence it is an open question even now whether light is a wave or a particle. At present there is a general agreement that light has a dual nature. It has characteristics of waves as well as particles. In some event it behaves like a wave and in another behaves like a particle. You can note that a beam of light behaves like a particle in some event and the same beam behaves like a wave in another event. It can be said that particle model and wave model of light are complementary. It may be mentioned that in any single experiment light does not behave as a wave and as a particle simultaneously.

13.6 De-Broglie Hypothesis and wavelength of matter wave

As has been mentioned earlier in this chapter that usually behaving like a wave, light in some circumstance behaves as a particle (photon). Naturally the question arises whether particles of matter like electron, proton and Neutron can behave like a wave. In view of the similarities of different kinds in nature a French Physicist de-Broglie in 1924 put forward a hypothesis that as light (electromagnetic radiation) energy exhibits dual nature, matter should also show dual nature i.e. in some circumstances matter should behave like waves de-Broglie suggested that the formula $p = h/\lambda$ for photon should also be applicable on a particle. A particle of momentum p can be associated with a wave length as given below-

$$\lambda = \frac{h}{p} = \frac{h}{mv} \qquad \text{...(13.8)}$$

Where m is the mass and v the speed of the particle λ is called the wavelength of matter wave or de-Broglie wave length. Equation 13.8 which is called de-Broglie eq also specifies dual nature of matter. On the left the wave length λ is a characteristic of wave and on the right side momentum p is characteristic of a matter particle. To estimate the order of λ we consider a ping pong ball of mass 10gm (10^{-2} kg) moving with a speed of 2 m/s. Then-

$$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}\,Js}{(10^{-2}\,kg)(2\,m/s)} = 3.31\times10^{\;34}\,m$$

Obviously the measurement of such a short length is not possible with the present apparatus. This is why the matter waves associated with bulky bodies cannot be observed. We will later see that wavelengths associated with subatomic particles like electrons and protons having sufficient energy are of the order of wavelengths for x-rays can be measured.

If the kinetic energy of a particle of mass m is K we have

$$K = p^2/2\text{ m} \;;\quad p = \sqrt{2mK}$$

Using this relation in 13.8 we have

$$\lambda = \frac{h}{\sqrt{2mK}} \qquad \ldots(13.9)$$

If kinetic energy of a particle is known we can determine the de-Broglie wavelength associated with it.

13.7 Now we will find wavelengths associated with different kinds of particles

(a) Wavelength of charged particle accelerated by potential difference of V volts :

If a particles of mass m and charge q is accelerated by potential difference V its kinetic energy will be $K-qV$. Hence from eq (13.9)

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

For electron $m = m_e = 9.1 \times 10^{31}$ kg and $q = e = 1.6 \times 10^{19}$ C

$$\lambda_e = \frac{6.63 \times 10^{-34}\ J.s}{\sqrt{2 \times 9.1 \times 10^{-31} kg \times 1.6 \times 10^{-19}\ CV}}$$

$$= \frac{12.27}{\sqrt{V}} \times 10^{-10} m = \frac{12.27}{\sqrt{V}} \mathring{A} \qquad \ldots.(13.9)$$

For proton $m_p = 1.67 \times 10^{-27}$ kg and $q = e = 1.6 \times 10^{19}$ C

$$\lambda_p = \frac{6.63 \times 10^{\ 34}}{\sqrt{2 \times 1.67 \times 10^{\ 27} \times 1.6 \times 10^{\ 19} V}}$$

$$= \frac{0.286}{\sqrt{V}} \qquad \ldots(13.10)$$

similarly for dutron $m_d = 2\, m_p$ and $q = e$

$$\lambda_d = \frac{0.0202}{\sqrt{V}} \mathring{A} \qquad \ldots(13.11)$$

And for α – particle $m_\alpha = 4m_p$ and $q = 2e$ के लिए

$$\lambda_\alpha = \frac{0.101}{\sqrt{V}} \mathring{A} \qquad \ldots(13.12)$$

(b) For in charged particles, Neutrons and gas molecules :

If particles of mass m e.g. neutron or gas molecules are in thermal equilibrium at Absolute temperature T, Then by equipartition of energy their average kinetic energy k=3/2 KT, where k=1.38x10^{-23} J, K is Boltzman constt and from eq. (13.9)

$$\lambda = \frac{h}{\sqrt{2mK}} = \frac{h}{\sqrt{3\,mkT}} \qquad \ldots(13.13)$$

Putting the values of m, k and T in the above equation the wavelength of the concerned particle can be determined

Hence for one neutron or proton $m_n = m_p = 1.67 \times 10^{-27}\ kg$

$$\lambda = \frac{25.2}{\sqrt{T}} \text{Å}$$

Sometimes thermal energy is of the order of kT

$$\lambda = \frac{h}{\sqrt{2mkT}} \qquad \ldots(13.14)$$

which is the maximum possible energy. Hence K=kT

In this situation wavelength of Neutron is

$$\lambda = \frac{30.8}{\sqrt{T}} \text{Å}$$

Example 13.6

Find out the ratio of wavelengths of proton and λ particles which are accelerated by the same potential difference.

Solution : From formula for de-Broglie wavelength of charged particles

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

For same V

$$\frac{\lambda_p}{\lambda_\alpha} = \frac{h}{\sqrt{2m_p q_p V}} \frac{\sqrt{2m_\alpha q_\alpha V}}{h}$$

$$= \sqrt{\frac{m_\alpha q_\alpha}{m_p q_p}}$$

because $m_\alpha = 4m_p$ and $q_\alpha = 2q_p$

$$\therefore \quad \frac{\lambda_p}{\lambda_\alpha} = \sqrt{4\times 2} = 2\sqrt{2}$$

Example 13.7

Find out the wavelength of an electron accelerated by a potential difference of 100V.

Solution : The formula for de-Broglie wavelength of an electron accelerate by a potential difference of V is

$$\lambda_e = \frac{12.27}{\sqrt{V}} \mathring{A}$$

$$\lambda_e = \frac{12.27}{\sqrt{100}} \text{Å} = 1.227\text{Å} \simeq 1.23\ \text{Å}$$

Here we can see that this wavelength is of the order of wavelength of x-ray.

Example 13.8

An ∝ particle and a proton enter an equal magnetic field such that their velocity vectors are perpendicular to the field. α–particles and proton travel in a way such that their radius of curvature are equal. Determine the ratio of their de-Broglie wavelengths.

Solution : We know that when a particles of mass m and charge q enters a magnetic field B such that B and v are perpendicular then it moves in a circular path. If the radius of the path is r we have

$$Bqv = \frac{mv^2}{r}$$

or $\quad mv = qBr$

$$\therefore \quad \lambda = \frac{h}{mv} = \frac{h}{qBr}$$

hence $\quad \frac{\lambda_\alpha}{\lambda_p} = \frac{q_p}{q_\alpha}$ (given B = r)

$$= \frac{1}{2} \quad \{ \text{ because } q_\alpha = 2q_p \}$$

13.8 Davisson and Germer Experiment and its conclusion

This experiment verified wave nature of electrons for the first time. We know that diffraction is a characteristic of a wave. This experiment showed that diffraction in electron beam is possible. We know that for clear diffraction it is essential that the size of the diffractor is of the order of the wavelength of wave. The wavelength of matter waves associated with moving electrons is of the order of wavelength of x-rays.

To see the diffraction of X-rays a crystal is used as a diffractor. Davisson and Germer thought if particles like electrons have wave property then they should also be diffracted by the crystal like x-rays.

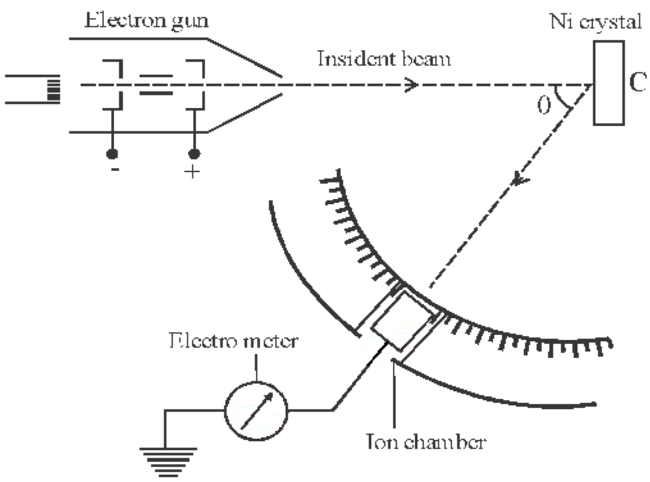

Fig 13.7 : Experimental setup of Davisson and Germer Experiment

Fig13.7 shows the experimental arrangement of Davisson and Germer. A beam of high energy electrons is obtained from an electron gun. In this current flows through a tungsten filament which emits electrons due to thermionic emission. These electrons pass through holes in linear diaphrams. Diaphrams are kept at a high positive potential relative to filament. This accelerates electrons. Thus a narrow beam of accelerated electrons is produced. By changing the potential difference between the filament and the Diaphrams the energy of the electron beam can be changed.

The electron beam obtained from the electron gun is incident on the Nickel crystal normally. Electrons scattered from the crystal are collected in a detector. The detector is a device for identifying the particles and in measuring their energies. In this experiment an ionization chamber was used as a detector. When electrons diffracted from the crystal enter the ionization chamber the gas is ionized The number of ions depends upon the energy of diffracted electron beam. A current flows in the galvanometer because of ions. By moving the detector in a circular path the angle between incident electron beam and scattered beam can be changed. If electrons are treated as particles then according age-old theory of scattering the intensity of scattered electron beam should have very little change due to variation of θ but the results of this experiment are different.

In the experiment polar graphs are drawn between intensity of diffracted beam and angle of diffraction from various values of accelerating voltage, In fig 13.8 graphs are shown for accelerating voltages 44*v*, 54*v* & 64*v*. For definite values of θ the length of the radius vector is a measure of the intensity of the diffracted electron beam. From these graphs it is clear that when accelerating voltage is 54v the intensity in the detector is maximum at 50°. For voltage more than or less than this value the peak disappears. The formation of sharp peak at 54 Volts indicates that the electrons are being diffracted.

Fig 13.8 shows the diffraction of electrons by the Nickel Crystal. In this experiment such lattice surfaces are chosen where the distance between two atoms is less than 2.15A. If diffraction of electrons beam and X-rays is compared we have for diffraction of X-rays the path difference is given by Bragg's law

d sin u = nλ

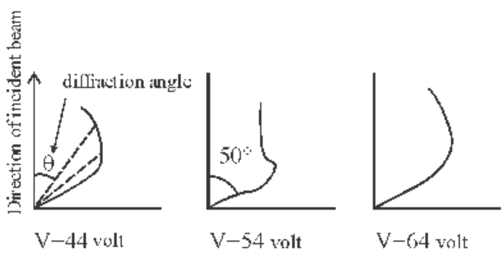

Fig 13.8 : Polar diagram for diffrent voltages

where, n is the order of diffraction Hence for d= 2.15, θ=50 ° and n= 1 the value of wave length is given by

$$\lambda = 2.15 \times \sin 50^\circ$$
$$= 2.15 \times 0.766$$
$$= 1.65\,\mathring{A}$$

For accelerating voltage 54 volts the theoretical value of de Broglie wave length of electron is given by

$$\lambda = \frac{12.27}{\sqrt{V}}\mathring{A} = \frac{12.27}{\sqrt{54}}\mathring{A} = \frac{12.27}{7.348}\mathring{A} = 1.67\mathring{A}$$

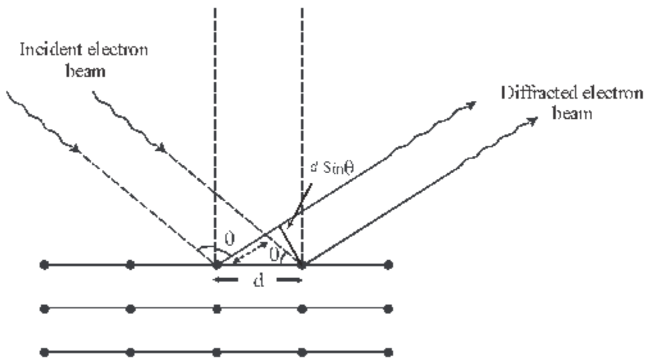

Fig 13.9 : Diffraction of electrons
by lattice surfaces of the crystal

In this way the experimental and theoretical value of wave lengths from Davissan and Germen experiment are very near to each other. Hence it is concluded from Davisson and Germen experiment that diffraction of electrons is possible. Because diffraction is a property of waves it is proved that waves are associated with electrons or the hypothesis of de Broglie regarding matter waves is verified. Apart from this the experiment of G.P Thomson also confirms matter waves. Like light the interfrence for electrons also has been observed by two slit experiment. An important theoretical application of de Broglie hypothesis is that it explains the second postulate of Bohr's Atomic Model about which you will learn later. Diffraction of electrons and Neutrons gives information regarding crystal structure. In addition to it the electron microscope was developed on the basis of wave properties of electrons.

13.9 Heisenberg's Uncertainty Principle

In 1923 Heisenberg's propounded the uncertainly Principle. According to it "At any instant (time) the position of a particle and its momentum cannot be determined completely and accurately at the same time and in the same direction. The product of uncertainty in the position of the particle, Δx and uncertainty in the x component of the momentum Δp_x can never be less than $\hbar/2$

Mathematically, according to this theory

$$\Delta x \Delta p_x \geq \frac{\hbar}{2} \qquad \ldots (13.15)$$

Here $\hbar = \frac{h}{2\pi} = 1.054 \times 10^{34} J \cdot s$

It should be borne in mind that Δx and ΔPx are not the errors due to measurement by instruments. These errors will not end even if we use very sensitive instruments. In reality Δx and ΔPx are such inherent errors which follow Heisenberg's uncertainly principle because of the matter waves associated with particles of matter.

Position in the x direction, x and momentaum in the same direction Px are cannonically conjugate quantities. Like 13.15 the uncertainly principles can also be written:

$$\Delta y \Delta p_y \geq \frac{h}{2} \qquad \ldots (13.16)$$

$$\Delta z \Delta p_z \geq \frac{h}{2} \qquad \ldots (13.17)$$

Similarly energy and time are also cannonical conjugate quantities, hence for them the uncertainly principle is

$$\Delta E \Delta t \geq \frac{h}{2} \qquad \ldots (13.18)$$

This means energy of a particle and its time coordinate can not measured with unlimited accuracy. All measurements of energy will have inherent uncertainty unless you have infinite time for measurement. For example the energy of the atom in its original stationary condition is well defined because the atom remains in this condition for infinite time, while the excited conditions of atoms are not well defined as it remains in this condition only for $\Delta t = 10^{-8}$s. After that it reverts back to lower energy level. Hence there is uncertainty in the energy in the excited condition or the energy level is not sharply defined. It should have some breadth given by equation

$$\Delta E \sim \frac{h}{\Delta t}$$

Heisenberg's Uncertainty principle is for both micro as well as macro particles. The size of macro particles is too big so that uncertainty in its position is negligible and since mass is more therefore uncertainty in macro objects is not observed.

Example 13.9 : If the uncertainty in the position of a particle is 0.1 nm calculate the uncertainty in its momentum

Solution : According to Uncertainty principle of Heisenberg

$$\Delta x.\Delta p_x \geq \frac{\hbar}{2}$$

If minimum value of the product of uncertainties is taken we have

$$\Delta x.\Delta p_x \simeq \frac{h}{2}$$

Therefore uncertainty in momentum

$$\Delta p_x \simeq \frac{h}{2\Delta x} = \frac{1.054\times10^{-34}}{2\times0.1\times10^{9}}$$

$$= 0.53\times10^{-24}\ kg\cdot m/s$$

Example 13.10 : In an atom the time period for excited energy level is 1.0×10^{-8}s. Find the minimum uncertainty in the frequency of emitted photon in transition.

In the question $\Delta t = 1.0 \times 10^{-8}{}_{s}$

Hence according to uncertainty principle of Heisenberg

$$\Delta E = \frac{h}{4\pi\Delta t}$$

$$= \frac{6.63\times10^{34}}{4\times3.14\times10^{-8}} = 0.53\times10^{26}\ J$$

$\therefore$ Uncertainty in frequency

$$\Delta v = \frac{\Delta E}{h}$$

$$= \frac{0.53\times10^{-26}}{6.63\times10^{34}} = 8\times10^{6}\ Hz$$

Important Points

1. **Work Function** The minimum energy required by free electrons with maximum Kinetic energy on the surface of a metal to come out of the surface of the metal is called work function of the metal. The value of work function for different metals is different and depends upon the impurities present on the surface of the metal.

2. **Photoelectric Effect** When light of a specific frequency or more than that frequency falls on a metalic surface it emits electrons. This phenomenon is called photoelectric effect.

3. **Threshold Frequency** The threshold frequency for a metal is that minimum frequency of light below which the light cannot eject photons from the metal.

4. **Threshold Wavelength** The wavelength corresponding to threshold frequency is called Threshold wavelength.

5. Threshold frequency and threshold wavelength for a light sensitive substance (metal) depends upon the metal and nature of its surface.

6. The number of electrons emitted per second depends upon the intensity of light and not its energy.

7. The maximum kinetic energy of photoelectrons depends upon the frequency of incident light and not on its intensity

8. **Stopping Potential** The negative potential of the collector (Anode) plate which makes photoelectric current zero is called stopping potential. Its value depends upon the frequency of incident light.

9. **Photon** It is a quanta of electromagnetic energy such that its energy is proportional to frequency of light and can be calculated by the formula $E = h\nu$. The rest mass of Photon is zero.

10. It is not possible to explain photoelectric effect on the basis of electromagnetic wave theory. Einstein explained it on the basis of quantum theory (photon).

11. Einstein's photoelectric equation is $K_{max} = h\nu - \phi_0$ or $K_{max} = h\nu - h\nu_0$

12. de Broglie Hypothes is every moving particle has a wave associated with it which is called matter wave. Like light matter also has dual nature.

    The wavelength of matter wave is inversely proportional to the momentum of the particle and can be calculated by the following formula

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

13. Formula for de-Broglie wavelengths for different particles :

$$\lambda_e = \frac{12.27}{\sqrt{V}} \mathring{A} \quad ; \quad \lambda_p = \frac{0.286}{\sqrt{V}} \mathring{A}$$

$$\lambda_\alpha = \frac{0.101}{\sqrt{V}} \mathring{A} \quad ;$$

Wave length of a particle in thermal equilibrium at absolute temp T, $\lambda = \frac{h}{\sqrt{3mkT}}$

14. De Broglie Hypothesis is verified by Davisson and Germer experiment. This experiment also proves that diffraction of matter particles is possible

15. Heisenberg's Uncertainty Principle

    $\Delta x \Delta p_x \geq \hbar / 2$

    At any instant the position of a particle and its momentum in the same direction can not be determined with cent percent accuracy simultaneously. According to it,

    $\Delta x \,.\, \Delta Px \geq \hbar /2$

    Time Energy uncertainty relation is $\Delta E \Delta t \geq \hbar / 2$

Questions For practice

Multiple Choice Questions

1. A Photon of ernergy 40ev is incident on a metal surface. Due to this an electron having kinetic energy 37.5eV is emitted. The work function of metal surface is

   (a) 2.5eV (b) 57.5eV

   (c) 5.0eV (d) zero

2. For light having frequency more than threshhold frequency the number of electrons emitted in photo-electric effect experiment is proportional to

   (a) Their Kinetic energy

   (b) Their potential energy

   (c) Frequency of incident light

   (d) The number of photons incident on the metal

3. The energy of a photon of light beam A is twice that of photon of onother light beam B. Then ratio of their momenta P_A/P_B is

   a) ½ (b) ¼

   (c) 4 (d) 2

4. The emission of electrons from a metal begins when green light is incident on it The emission of electrons will be possible for which of the folio wing group of colours ?

   (a) yellow, blue, red, (b) violet, red , yellow

   (c) violet , blue, yellow (d)violet, blue, indigo

5. The de-Broglie wavelength associated with an electron emerging from an electron-gun is 0.1227 A^0. The value of the accelerating Voltage applied on the gun is

   (a) 20 kV (b) 10 kV

   (c) 30kV (d) 40 kV

6. If the energy of a non-relativistic free electron is doubled the frequency of the matter wave associated with it will be changed by which factor?

   (a) $1/\sqrt{2}$ (b) ½ (c) $\sqrt{2}$ (d) 2

7. If the position of a particle is determined with cent percent accuracy the uncertainty in its momentum according to uncertainty principle will be

   (a) zero (b) ∞

   (c) -h (d) nothing can be said

8. Which property of electrons asssoeiated with waves was demonstrated by Davisson and Germer experiment

   (a) Refraction (b) polarisation

   (c) Interference (d) diffraction

9. The de-Broglie wavelength associated with an electron having kinetic energy 10 eV is

   (a) 10Å (b) 12.27Å

   (c) 0.10 Å (d) 3.9 Å

10. An electron and a proton are contrained to remain in a linear box of dimension 10 Å . The ratio of uneertainties in their momenta is

    (a)1:1 (b) 1:1836

    (c) 1836:1 (d) insufficient information

Very Short Type Questions

1. Write Einstein"s photo-electric equation.
2. The stopping potential depends upon what ?
3. To observe photo-electric effect the frequency of incident light should be more than which Frequency ?
4. What is the name given to a quanta of electronagnetic energy ?

5. Write the formula for wavlength of a matter wave according to de-Broglie hypolheies

6. Write down the relation betweeen the uncertainties in the position of a particle and its associated momentum accerding to Heisenberg.

7. Write the name of an experiment that establishes matter wave theory of de- Broglie.

Short Answer type questions

1. What is photo-electric effect?
2. What do you mean by Threshhold frequency?
3. Write down the definition of work function?
4. State the objective of Davissone Germer experiment.
5. Write down the hypothesis of de-Broglie about the dual nature of matter waves.
6. Define Uncertainty Principle.

Essay Type questions

1. Explaining photo-electriceffect describe experimental obervation associated with it.
2. Why it is not possible to explain photo-electriceffect on the age old wave theory? Explain.
3. Explain the explanation given by Einstein about photo-electric effect. What is meant by threshhold frequency?
4. Explaining the concept of photon describe its various properties.
5. Mention de-Broglie hypothesis and describe in detail the experiment of Davisson and Germer for its experimental verification.
6. Extablish the formulae for finding de-Broglie wavelengths of electrons, proton and ∝ particles.

Answers

Multiple Choice Questions.

1. (a) 2. (d) 3. (d) 4. (d) 5. (b)

6. (d) 7. (b) 8. (d) 9. (d) 10. (a)

Very Short Answer Questions

1. $h\nu = \frac{1}{2}mv^2_{max} + \phi$
2. On the frequency of incident light.
3. Greater than the threshhold frequency of the material.
4. Photon
5. $\lambda = \frac{h}{mv}$
6. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$
7. Davission and Germer Experiment.

Numerical Questions

1. The thresh hold frequncy for copper is 1.12×10^{15} Hz. Light of wavelength 2537Å falls on its surface. Find the work function and stopping prtential $h = 6.63 \times 10^{-34}$ Js (Ans. 4.64 ev, 0.24v)
2. For a certain metal threshhold frequency is 5675 Å Calulate the work function of the metal $h = 6.63 \times 10^{-34}$Js (Ans. 2.20 eV)
3. Calculate the difference between kinetic energies of photo-electrons emitted by radiations of wavelengths 3000 Å and 6000 Å.

   (Ans. 2.07 eV)
4. Calculated the de-Broglie wavelengths associated with an electron and an ∝ particale accelerated by equal potential difference of 100v. (Ans. 1.227 Å, 0.010 Å)
5. A 20 watt bulb is emitting light of frequency 5×10^{14} Hz. Find the number of photons emitted by the bulb in one second. (Ans. 6×10^{19})
6. First order diffraction is observed in Davisson and Gemer experiment, Accelerating voltage in 54 volt. If the distance between reflecting surfaces of the used Ni crystal is 0.92 Å find out the angle of diffraction. (Ans. 65°)
7. If the uncertainty in the x component of the momentum of a moving electron is 13.18×10^{-30}

Kg m/s. find out the uncertainties in the x component of positon and velocity. (Ans. $0.40x10^{-5}$ m, 14.48 m/s)

8. Find out the ratio of de-Broglie wavelengths of a proton and an $\propto$- particle having equal energies. (Ans. 2:1)

9. The period of electromagnetic vibration is 0.30 ms. Find out the uncertainly in the energy of photon. (Ans. $1.76x10^{-31}$J)

10. The work function for sodium is 2.3ev. Find out the maximum wavelength of light that can emit photo electrons from sodium. (Ans. 539nm)

11. When a metallic surface is illuminated with light of frequency $8.5x10^{14}$ Hz the maximum kinetic energy of emitted electrons is 0.52ev. When the same surface is illuminated by light of frequency $12.0x10^{14}$ Hz the maximum kinetic energy of emitted electrons is 1.97 ev. Find out work function of the metal. (Ans. -3eV)

12. At room temperature T=300K Neutrons are in thermal equilibrium. Find out their de-Broglie wavelengths. (Ans. 1.45 Å)