

# 30

## PHOTOELECTRIC EFFECT AND MATTER WAVES

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### 30.1 INTRODUCTION

All of you must have seen films in cinema halls. The picture on the screen is produced by light passing through films which have the scenes shot on them. But, have you ever wondered how the sounds are reproduced in the cinema? On the film in the cinema halls the sound is also recorded on one side of the screen as a sound track. The light beam passing through this sound track falls on a device known as photocell which convert it into electrical pulses. These electrical pulses are converted to produce actual sound. In this lesson you will study the effect on which the working of a photocell is based. The same effect is used in burglar alarm to detect thieves and in many other areas. In the same lesson you will also study about the wave properties of matter.

### 30.2 OBJECTIVES

After studying this lesson, you should be able to :

- *explain photoelectric effect and distinguish between thermionic emission and photoemission;*
- *describe the experimental arrangement to study the photo electric effect;*
- *draw with labels a diagram of a photoelectric tube;*
- *explain the graph between photocurrent and the voltage between the electrodes of a photo-tube;*
- *state the laws of photoelectric emission;*
- *interpret the graph between frequency of radiation and retarding potential;*
- *explain Einstein's theory for photoelectric effect and cite some uses of photoelectric cells.*
- *explain the dual nature of matter;*
- *explain de-Broglie waves and state the relation between the wave length of matter waves and the momentum of matter;*
- *describe the experimental arrangement for the verification of de-Broglie waves; and*
- *give some applications of de-Broglie waves.*

### 30.3 PHOTOELECTRIC EFFECT AND THERMIONIC EMISSION

Suppose we have a source of light which emits radiation over a wide frequency range. Let us further assume that we have means of selecting light of one fixed frequency. Let us now allow this monochromatic light to fall on a sheet of metal. It is observed that above a certain frequency, the metal plate starts emitting electrons. This phenomenon is called photoelectric effect and the electrons so emitted are called photoelectrons.

*The emission of electrons from metals when light of a frequency greater than a certain characteristic frequency falls on it, is called photoelectric effect or photoemission.*

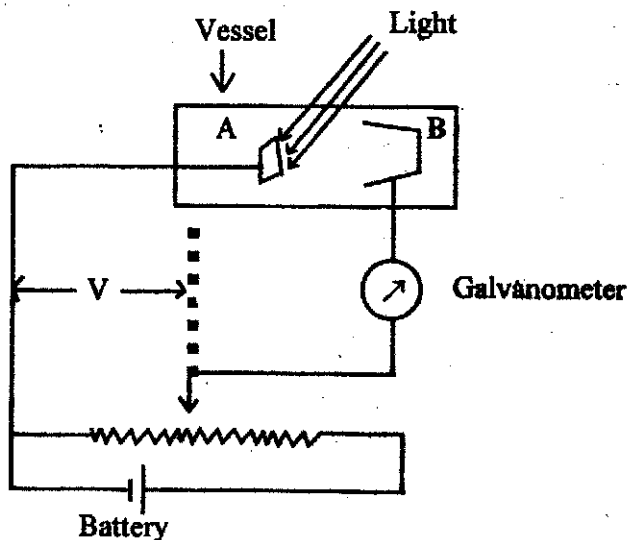
This phenomenon was first established experimentally in 1900 by Lenard and Sir J.J. Thomson. Electrons can come out of a conductor by absorbing sufficient energy. In the photoelectric effect this energy is obtained from the incident light.

**Thermionic emission:** Suppose we take a sheet of conductor and start heating it. The temperature of conductor would then start rising and therefore the kinetic energy of the electrons inside the conductor would also start increasing. A stage would come when the electrons would have sufficient energy to come out of the conductor. This type of emission of electrons is, therefore, called thermionic emission. Thus,

*Electrons gain energy from light in photoelectric emission and from heat in thermionic emission.*

#### 30.3.1 Experimental Study of Photoelectric Effect

Let us now learn the essential part of an experimental arrangement which demonstrates the photoelectric effect and also allows us to study this phenomenon. Such an experimental set up is shown in Figure 30.1.



*Fig. 30.1: Experimental set up for observing the photoelectric effect*

The set up consists of metal plate  $A$  called photo cathode inside a sealed vessel along with a metal cup  $B$  which is used to collect the photoelectrons emitted by  $A$ . These elements are connected to a battery and galvanometer circuit as shown in Fig.30.1. The battery has been so connected that the voltage on cup  $B$  is of positive polarity with respect to the plate  $A$ . If the battery terminals are reversed then the metal voltage become positive relative to the cup  $B$ .

#### Case-I : Plate $A$ -ve relative to $B$

Let us now consider the case when the plate  $A$  is at a negative potential relative to the cup  $B$ . If light of proper frequency falls on the metal plate, then the metal plate starts emitting electrons. Because the cup is at a positive potential relative to the plate therefore the electrons emitted by the plate experience an attractive force which drive them towards the cup. Electrons trapped by the cup give rise to a current in the external circuit and this current is detected by the galvanometer placed in the circuit. When we increase the voltage, the attractive force experienced by the electrons increases. This in turn increases the kinetic

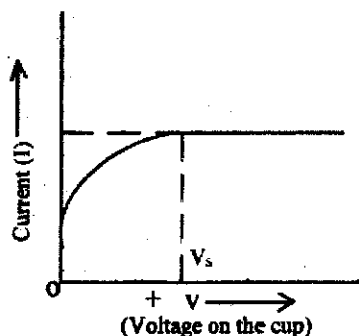


Fig. 30.2 : Dependence of current on voltage

energy of the photoelectrons. The chance of an electron reaching the cup  $B$  also increases with increasing kinetic energy. Furthermore, the current shown by the galvanometer depends upon the number of electrons collected by the cup. Therefore, the current shown by the galvanometer increases with increasing voltage. As we keep on increasing the voltage, a stage comes when all the electrons emitted by the plate get collected by the cup. The current is said to have saturated at this stage. If the voltage on the cup is increased further, the current remains constant in magnitude. The above mentioned dependence of current on voltage is shown graphically in Figure 30.2.  $V_s$  is called the saturating voltage.

#### Case-II : Plate $A$ +ve relative to $B$

Let us study, what would happen if the plate  $A$  is at a positive potential relative to the cup  $B$ . If light of a proper frequency falls on the plate  $A$ , photoelectrons are emitted. These electrons then find a retarding potential which impedes their movement towards the cup  $B$ . Some of the electrons emitted from the plate are able to reach the cup giving rise to a current which is registered by the galvanometer. What does this mean? If the only force which moved the electrons towards the cup was due to the potential difference between the plate and the cup, then none of the electrons would be able to reach the cup. After all electrons have to move against a retarding potential in order to reach the cup, the electrons would have some chance of reaching the cup only if they are initially emitted with some kinetic energy. Experimentally also, a current is observed if the cup is at a negative potential with respect to the plate. If for any particular incident light frequency, the retarding potential is gradually increased in magnitude, a stage would ultimately be reached when none of the electrons would be able to reach the cup because their kinetic energy would not be sufficient to enable them to overcome the retarding force.

*This retarding potential where the photocurrent becomes zero for a particular incident light frequency is called the stopping potential,  $V_s$  for that frequency.*

Against the stopping potential  $V_0$ , the work done by an electron =  $eV_0$  where  $e$  is the charge of electron. This work is done at the expense of the KE of the electron i.e.

$$eV_0 = \frac{1}{2} m v_{\max}^2 \quad (30.1)$$

This experiment was performed by R.A. Millikan. Millikan also did a lot of other experimental and the theoretical work on the photoelectric effect. For this work he was awarded the Nobel prize in 1923. The stopping potential  $V_0$  was found by him to be dependent upon the frequency of the incident light. A plot of the stopping potential versus the frequency of the incident light is shown in Figure 30.3.

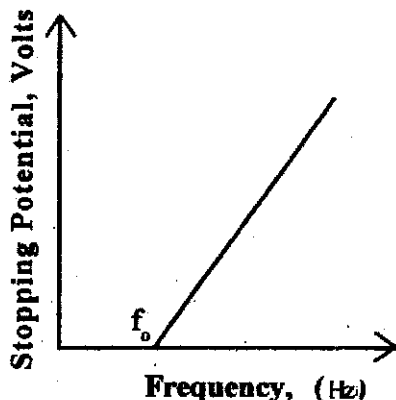


Fig.30.3: Stopping potential versus frequency

From the figure you should note the following two observations:

1. *The stopping potential increases with increasing frequency of the incident light. Further more, the dependence is linear.*
2. *There is a frequency,  $f_0$  below which no photoelectric effect takes place i.e no current is observed. It is called the threshold frequency.*

These two observations are important for understanding the physical laws governing the photoelectric effect.

### 30.4 LAWS OF PHOTOELECTRIC EMISSION

In the last section, you have learnt about the results of the experimental study of photoelectric emission. These results can be summarized in the following law of photoelectric emission:

- (i) *The maximum velocity of the photoelectrons increases with increasing frequency of the incident light and depends upon the nature of the substance emitting the photoelectrons.*
- (ii) *The maximum velocity of the photoelectrons is independent of the intensity of the incident light.*
- (iii) *For every substance, a threshold frequency,  $f_0$  exists below which no photoelectrons are emitted.*
- (iv) *For a particular frequency, the number of photoelectrons emitted per unit area of the emitting surface is proportional to the intensity of the incident light.*

### 30.4.1 Einstein's Theory

Many of you must have read about Albert Einstein's life and work. He provided us deep insights into many scientific phenomena and photoelectric effect was one of them. For his theory of photoelectric effect he was awarded the Noble prize in 1905. Many scientists believed at that time that light consisted of waves moving in space. This approach was called the wave theory of light. Suppose we increase the intensity of the light incident upon a metal plate and we start expecting the result on the basis of the wave theory: What should happen? Increasing the intensity would imply more energy being imparted to the electrons of the metal plate and hence should increase the energy of the emitted photoelectric electrons. But does this happen? You have already learnt the laws of photoelectric emission and you know that this does not happen. *Einstein assumed light to consist of energetic bundles called photons.*

Einstein's assumption, therefore, imparted a particle like characteristic to light. The energy  $E$  of a single photon is given by

$$E = hf \tag{30.2}$$

where,  $f$  is the frequency of the light and  $h$  is the Planck's constant. Let us now assume that a photon of energy  $E$  is incident upon the metal surface. Suppose  $E_0$  is the energy needed for an electron to come out of the metal surface. As you have studied earlier, this energy is also called the work function of the conductor. *The work function of a conductor is the minimum energy required for an electron to come out of the conductor surface.*

You are aware that energy is measured in units of joule and denoted by the symbol 'J' Joule is however a very large unit for specifying the work function of a conductor. Suppose we take an electron and accelerate it through potential difference of 1 volt. Obviously the kinetic energy of the electrons increases.

*What is the amount of energy gained by an electron on being accelerated through 1 volt called?* Well it is called one electron volt (eV). Therefore, write down the value of 1 eV in joules.

1 eV = (charge of an electron) x a volt = .....joules

Very often, the work function of conductors is given in units of eV. Table 30.1 shows  $E_0$  of some metals along with the corresponding frequency of light which can impart an energy, equal to the work function, to the electrons in the metal.

**Table 30.1: Work function of some metals**

Metal	Sodium	Potassium	Zinc	Iron	Nickel
$E_0$ (eV)	2.5	2.3	3.4	4.8	5.9
$f$ (Hz)	$6.07 \times 10^{14}$	$5.58 \times 10^{14}$	$8.25 \times 10^{14}$	$11.65 \times 10^{14}$	$14.32 \times 10^{14}$

Looking at table 30.1 what do you think would happen when such a photon strikes the metal surface? Out of the total energy  $E$ , an amount  $E_0$  would be needed to force an electron to come out of the metal surface. The difference amount, i.e.  $(E - E_0)$  would then be imparted to the emitted electron in the form of kinetic energy. Of course, not all of the energy difference would be imparted to the electron as kinetic energy because the electron would lose some energy by internal collisions before it escapes from the metal surface. But,  $(E - E_0)$  would definitely give the maximum kinetic energy,  $K_{max}$  which the photoelectrons can have. This physical idea can be written down in the following mathematical form:

$$hf = E_0 + K_{max} \quad (30.3)$$

Increasing the intensity would increase the number of photons per unit area but would not increase the energy of each photon. Therefore the  $K_{max}$  and hence in general the velocity of the photoelectrons would not increase with increasing intensity. Thus you can see that the second law of photoelectric emission can be explained on the basis of Einstein's theory of photoelectric effect.

Let us now see whether all the other laws are also explainable on the basis of this theory. What do you think would happen if the frequency of the incident radiation is increased?  $E_0$  would remain constant because it is a property of the material emitting the photoelectrons. Therefore increasing  $f$  in equation (30.3) would result in an increased value of  $K_{max}$  and hence to a higher maximum velocity. This is exactly what the law (i) states. Suppose we put  $K_{max} = 0$  then equation (30.3) reduces to

$$hf_0 = E_0 \quad (30.4)$$

Where  $f_0$  denotes the particular frequency at which the product of the Planck's constant and frequency becomes exactly equal to  $E_0$ . It is the *threshold frequency*. What happens when light of a frequency  $f_0$  is incident upon a metal plate? The metal does emit electrons but these electrons would have no kinetic energy. Suppose we reduce the frequency of the light below  $f_0$  and let it fall on the same metal plate. Obviously, the electrons inside the plate would not receive enough energy to come out of it. Hence there would be no photoelectric effect. You should now note that law (ii) states this precisely.

Now let us keep the frequency of the light fixed and increase its intensity. What will happen? Increasing the intensity increases the number of photons striking any particular area of the plate. All these photons have energy equal to  $hf$  where  $f$  is the constant frequency. For each photon, an equation identical to (30.2) is valid. Thus each photon results in one emitted electron. Therefore, when the number of photons striking any particular area increases, the number of photoelectrons emitted from this area also increases proportionally. We have now seen that law (iv) can also thus be explained on the basis of Einstein's theory. Einstein's photoelectric effect can be seen to be a great success for explaining the physical origin of photoelectric effect.

**Example 30.1:** Sodium has a work function of 2.3eV. Calculate (i) its threshold frequency (ii) the maximum velocity of the photoelectrons produced when the sodium is illuminated by light of wavelength  $5 \times 10^{-7}m$  (iii) the stopping potential with light of this wavelength.

(Given  $h = 6.6 \times 10^{-34} Js$ ,  $c = 3 \times 10^8 ms^{-1}$ ,  $1eV = 1.6 \times 10^{-19} J$ ; mass of electron  $m = 9.1 \times 10^{-31} kg$ ).

**Solution :** (i) The threshold frequency is given as  $hf_0 = E_0$

Here,  $h = 6.6 \times 10^{-34}$  Js,  $E_0 = 2.3\text{eV} = 2.3 \times 1.6 \times 10^{-19}$  J

$$\therefore f_0 = \frac{E_0}{h} = \frac{2.3 \times 1.6 \times 10^{-19}\text{J}}{6.6 \times 10^{-34}\text{Js}} = 5.6 \times 10^{14} \text{ Hz}$$

(ii) By Einstein's photoelectric equation

$$hf = E_0 + K_{\max} = E_0 + \frac{1}{2}mv_{\max}^2, \quad \text{Since } f = \frac{c}{\lambda}$$

$$\text{Or } h = \frac{c}{\lambda} = E_0 + \frac{1}{2}m(v_{\max}^2)$$

where  $c$  = velocity of light,  $\lambda$  = wavelength of light

$$\text{or } = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{5 \times 10^{-7}} = 2.3 \times 1.6 \times 10^{-19} + \frac{1}{2}mv_{\max}^2$$

$$\text{or } 3.96 \times 10^{-19} = 3.68 \times 10^{-19} + \frac{1}{2}mv_{\max}^2$$

$$\therefore v_{\max}^2 = \frac{2 \times 0.28 \times 10^{-19}}{m} = \frac{2 \times 0.28 \times 10^{-19}}{9.1 \times 10^{-31}}$$

$$\therefore v_{\max} = \sqrt{\frac{0.56 \times 10^{-19}}{9.1 \times 10^{-31}}} = 2.5 \times 10^5 \text{ ms}^{-1}$$

(iii) The stopping potential  $V_0$  is given as

$$eV_0 = \frac{1}{2}mv_{\max}^2$$

$$\therefore V_0 = \frac{0.28 \times 10^{-19}}{1.6 \times 10^{-19}} = 0.18 \text{ V.}$$

### INTEXT QUESTIONS 30.1

1. State whether the following statements are true or false:
  - (a) In thermionic emission, electrons gain energy from photons.
  - (b) The maximum velocity of the photoelectron is independent of the frequency of the incident radiation.
  - (c) There exists a frequency,  $f_0$  above which no photoelectric effect takes place.
2. Light of frequency  $6.0 \times 10^{14}$  Hz incident on a metal surface ejects photoelectrons having a kinetic energy  $2.0 \times 10^{-19}$  J. Calculate the energy needed to remove an electron from the metal.

### 30.4 PHOTOELECTRIC TUBE

We have studied the photoelectric effect in detail in the last section. By now, we know that when light of a frequency above  $f_0$  is incident upon a material, electrons are emitted. We also know from earlier studies that the flow of electrons constitutes a current. Furthermore, we have also seen that the photoelectrons are emitted with certain kinetic energies. The effect of changing accelerating voltage on the magnitude of the current was also studied by us. In fact, Fig. (30.2) depicted this dependence schematically. Photoelectric tube is one such arrangement which converts light energy into electrical energy. They are of various types.

The photoemissive type of phototube is based on the phenomenon of *photoelectric effect*.

#### Construction

Let us understand the essential parts of the photoelectric tube. It consists of a glass vessel which has been evacuated. This glass vessel contains a semi-cylindrical cathode and an anode in the form of a straight wire. The cathode is coated with a suitable metal to ensure the emission of photoelectrons when light of a pre-decided frequency falls on it. The threshold frequency above which a phototube responds determines the choice of this coating

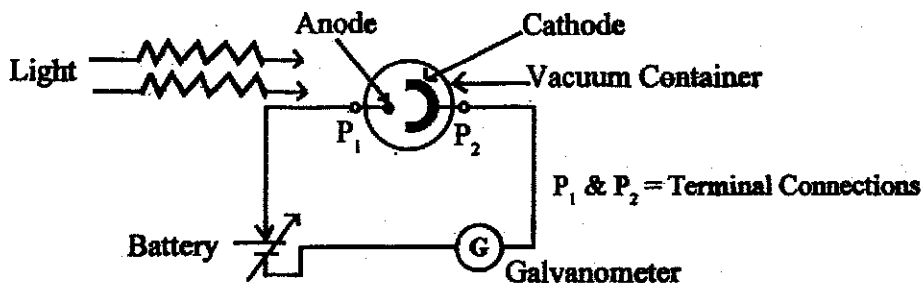
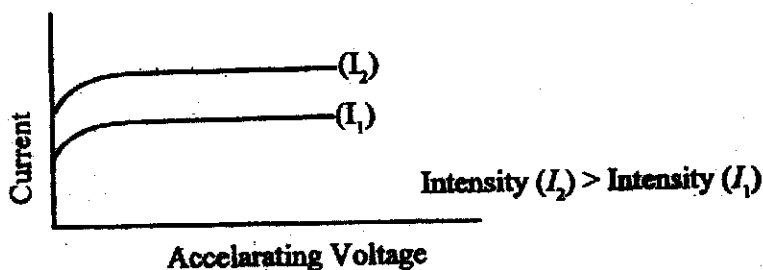


Fig. 30.A : Photoelectric tube

The anode is usually made of nickel or platinum. Electrical connections  $P_1$  and  $P_2$  are brought out on to the surface of the glass vessel. A battery and a galvanometer are connected between the anode and the cathode to provide the accelerating voltage. The arrow on the battery indicates the fact that the voltage applied by it can be varied. You must have seen this symbol being used with resistances also. A variable resistance is shown by an arrow cutting across the normal resistance symbol. The galvanometer placed in the circuit measures the current passing through it.

#### Working

Now suppose light of frequency higher than the threshold frequency  $f_0$ , is incident upon the cathode. Some photoelectrons are emitted. Let us further assume that the accelerating potential between the cathode and the anode is zero. As you know the electrons come out of the cathode with certain velocities and hence reach the anode. These electrons give rise to a current as indicated by the galvanometer. Let us now apply some accelerating voltage and see what happens. Obviously more electrons would now be able to reach the anode and hence the current would increase. This is shown in Figure 30.5



**Fig.30.5 : Variation of current and acceleration voltage**

As we keep on increasing the voltage between the cathode and the anode of the photoelectric tube current also increases. Finally at very high voltages the current saturates to a fixed value as shown in Figure 30.5 *The saturation current is determined by the intensity ( $I$ ) of the incident light.* The magnitude of saturation current is the order of nano amperes. It is seen that *if the intensity of the light is increased then the saturation current also increases as shown in the Fig. 30.5.*

### 30.4.1 Application

Let us now try to understand some important applications of photoelectric cells. You can appreciate that where ever light energy has to be transformed into equivalent electric current, photoelectric cells would find use.

(i) **Reproduction of sound in films:** One of the important application of photoelectric cells is in the reproduction of sound in films. A sound crack is a track on the film of uniform width whose capacity varies in accordance with the audio frequency variations of the sound waves. Light is made to pass through this film and is then made to fall on the cathode of a photoelectric cell. The current developed in the circuit of the photoelectric cell is then proportional to the audio frequency and the variations in current are also in accordance with the variations in the audio frequency. This current is then made to pass through a resistance. The voltage developed across the resistance is then suitably amplified and then fed to a loudspeaker. The loudspeaker reproduces the sound as was originally recorded on the sound track.

(ii) **Transmitting pictures over great distances :** Photoelectric tubes are also used in systems that transmit pictures over great distances. You must be aware that the transmission of information from one place to another place is called telegraphy. Likewise the transmission of picture is called photo telegraphy.

(iii) **Other Uses :** Many types of system used for counting articles or living being are based on photoelectric tubes. Photoelectric tubes are also used in burglar alarms and other thief detecting systems. These are also used in fire alarms.

### INTEXT QUESTIONS 30.2

- State whether the following statements are true or false.
    - The cathode in a phototube is biased positively with respect to the anode.
    - The saturation current in a phototube is dependent upon the frequency of the incident radiation.
    - The saturation current in a photodiode increases with the intensity of the incident light.
  - Mention three applications of photo electric tube.
- .....

### 30.5 de - BROGLIE WAVES

In the last section, you studied the Einstein's theory of photoelectric effect. In that theory light was considered to consist of particles. But light is also known to be a kind of energy. Therefore Einstein's assumption also means another important thing, i.e. radiant energy can be associated with material particles. You will recollect that light consists of particles called photons. Each of these photons contain an energy  $E$  given by equation  $E = hf$ . Therefore, as the frequency of the light increases, the energy content of each of the photon particles increases. But light also has a wave like behaviour because the concept of frequency is applicable to waves only. What does the above mean? The above discussion finally means that energy transmitting in the form of waves also exhibits particle like behaviour. What about the opposite situation, would moving particles also exhibit wave like behaviour?

The answer to the very interesting question was provided by de-Broglie in 1924. He *postulated that the particles in motion do exhibit wave like characteristics.*

The theory of de-Broglie is often termed wave-particle dualism. The waves associated with moving matter are called by different names such as matter waves, de-Braglie waves. Many of you would be wondering why de-Broglie's assumption is being projected as a theory. Actually, de Broglie started with this assumption and then went on to derive a relation between the momentum of the moving particles and the wavelength of the associated waves. His theory has since been tested experimentally also. Let us study about this in this section.

The wave particle dualism can be understood in another way. Particles constitute matter and radiant energy travel as waves, therefore the relationship between matter and energy is dual in nature. This means that matter can be thought in terms of energy and vice versa. The matter-energy duality is a very important concept in physics.

#### 30.5.1 Wave-length and Momentum

We have learnt that waves can be associated with particles in motion. Two quantities that characterize a particle in motion are (i) its velocity and (ii) its mass. Can you think of a parameter that depends on both and therefore can alone be used to characterize the particle in motion?

One such parameter is momentum,  $p$ . Let us now think of a quantity that best characterizes a wave. One of the best examples is the wavelength of the wave. Let this be denoted by the symbol  $\lambda$ . If matter has waves associated with it then there must be a relationship between the momentum of the material particles and the wavelength of the associated waves. Such a relationship was indeed derived by de-Broglie and is given in the following equation,

$$\lambda = \frac{h}{p} \quad (30.5)$$

where  $h$  is the Planck's constant =  $6.62 \times 10^{-34}$  joule sec.

Let us get familiar with the above equation without deriving it. What does the above equation imply? If we increase the momentum of a particle then the wavelength of the associated matter waves decreases. Therefore, a faster particle would have shorter waves associated with it. Also we note that for the same speed, a heavier particle will have a shorter wavelength.

Earlier, in this lesson you have learnt that the energy gained by an electron on being accelerated through 1 volt is 1 eV

where,  $1 \text{ eV} = q \text{ Joules}$ .

where,  $q$  is the magnitude of the charge of an electron.

### de-Broglie Wavelength

Let us derive a relation for the de-Broglie wavelength associated with an electron that has been accelerated through a voltage ' $V$ '. If the velocity of the electron after acceleration is denoted by ' $v$ ' and the mass of the electron is denoted by ' $m$ ' then the kinetic energy of the electron must be equal to  $qV$  Joules Therefore,

$$\frac{1}{2} mv^2 = qV \quad (30.6)$$

$$\text{or } v = \sqrt{\frac{2qV}{m}}$$

$$\text{or } mv = p = \sqrt{2qmV} \quad (30.7)$$

The de-Broglie wavelength,  $\lambda$ , from equation (30.5) is therefore given by

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2qmV}} \quad (30.8)$$

The various constants in equation (30.8) have the following values:

$$h = 6.625 \times 10^{-34} \text{ Joule-second}$$

$$q = 1.602 \times 10^{-19} \text{ Coulombs}$$

$$m = 9.11 \times 10^{-31} \text{ kg.}$$

Putting these values in (30.8) we obtain

$$\lambda = \frac{6.625 \times 10^{-34}}{2 \times 1.602 \times 10^{-19} \times 9.11 \times 10^{-31} \times \sqrt{V}}$$

$$\text{or, } \lambda = \frac{12.3}{\sqrt{V}} \times 10^{-10} \text{ m}$$

$$\text{or, } \lambda = \frac{12.3}{\sqrt{V}} \times \text{\AA} \quad (30.9)$$

### 30.5.2 Experimental Verification of Existence of de-Broglie Waves:

Earlier in this section, it was mentioned that the existence of de-Broglie waves can be verified experimentally. Let us understand one such experimental arrangement. This experimental set up is shown in Fig.30.6 where

$B$  = Battery,  $V$  = Variable potential difference  $F$  = Filament,  $D$  = Metallic Diaphragm,  $N$  = Nickel Single Crystal, and  $DT$  = Detector.

The set up consists of a filament  $F$ , which serves as a source of electrons. The electrons emitted from this filament are then made to pass through a set of metal diaphragms. The electrons emitted by the filament come out in various directions. The metal diaphragms serve the purpose of collimating the stream of electrons. Only the electrons which are able to pass through the slits in the various diaphragms are able to come out of the metallic diaphragms. But this is not the only purpose being served by the diaphragms.

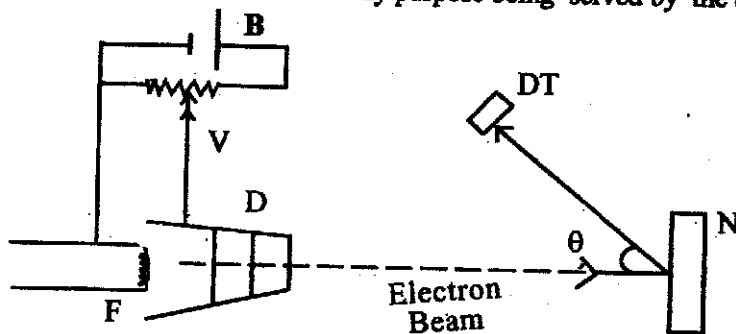


Fig. 30.6: Experimental set up to verify the existence of de-Broglie waves

You would notice in Figure 30.6 that an arrangement exists which allows the application of different voltages between the filament and the diaphragms. Furthermore, the polarity of the voltage is such as to accelerate the emitted electrons. The energy of the collimated stream of electrons can therefore be controlled by controlling the magnitude of the accelerating voltage. The beam of electrons then falls perpendicular to the face on a single crystal of nickel. The set-up also contains a detector  $DT$  which can be placed at any particular angle with respect to the normal to the nickel single crystal. This detector can determine the intensity of the reflected beam. The set-up described above was used by Davisson and Germer. You must understand that there is nothing special in the choice of nickel. In fact, Davisson and Germer used this particular crystal. Figure 30.7 shows the plot of detector current versus the kinetic energy of incident electrons for  $\theta = 50^\circ$ , as obtained by Davisson and Germer.

You should note that the detector current shows a maxima for electron kinetic energy of 54 eV. Suppose the electrons of K.E. = 54 eV can be thought of as waves with a wavelength given by equation (30.5). Let us try and calculate this wavelength. We need to first calculate the momentum of these electrons. You know that the K.E. of any particle is given by

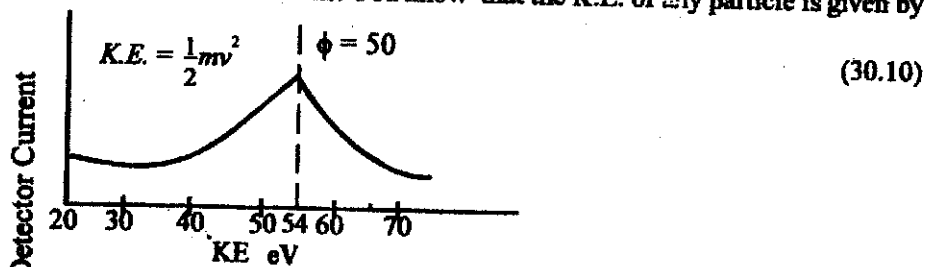


Fig 30.7: Plot of detector current versus the kinetic energy.

We know that K.E. value of 54 eV is equal to  $(54 \times q)$  joules where,  $q$  is the charge carried by an electron.

The magnitude of  $q$  is  $1.6 \times 10^{-19}$  coulombs.

Therefore,  $54 \text{ eV} = 54 \times 1.6 \times 10^{-19}$  joules.

The mass,  $m$ , of an electron is  $9.1 \times 10^{-31}$  kg.

The velocity of the electrons according to equation (30.10) is then given by

$$v = \sqrt{\frac{2(\text{KE})}{m}} \quad (30.11)$$

Putting the values of the various parameters we get,

$$v = \sqrt{\frac{2 \times 54 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}} = 4.4 \times 10^6 \text{ ms}^{-1}$$

The momentum of the electrons is therefore,

$$\begin{aligned} p &= mv = 9.1 \times 10^{-31} \times 4.4 \times 10^6 \\ &= 4 \times 10^{-24} \text{ kgms}^{-1} \end{aligned}$$

The wavelength of the associated de-Broglie waves is therefore,

$$\begin{aligned} \lambda &= \frac{h}{p} = \frac{6.6 \times 10^{-34} \text{ Js}}{4 \times 10^{-24} \text{ kgms}^{-1}} \\ &= 1.65 \times 10^{-10} \text{ m} = 1.65 \text{ \AA} \end{aligned}$$

where,  $1 \text{ \AA} = 1 \times 10^{-10} \text{ m}$ .

This wavelength lies in the range of X-rays wavelength. If  $d$  is the inter atomic plane 'spacing' then the intensity of the reflected ray should exhibit maximas according to the Bragg's rule, viz.

$$m\lambda = 2d \sin \theta \quad ; \quad m = 1, 2, 3, \quad (30.12)$$

Where,  $\theta$  is angle between the reflected ray and the interatomic planes Figure 30.8 shows the X-rays getting reflected from the atomic planes of the single nickel crystal. This figure should be used to determine the value of  $\theta$  for  $\phi = 50^\circ$ .

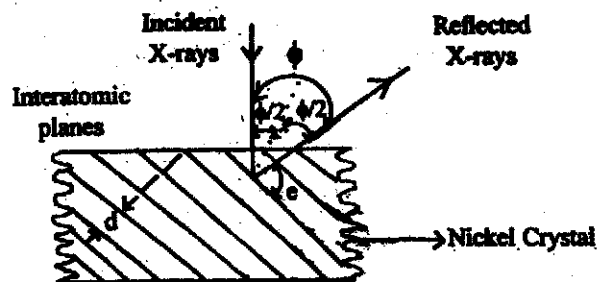


Fig.30.8: Reflection of X-rays from atomic plants of nickel crystal

You should note that according to figure 30.8

$$\theta = 90 - \frac{\phi}{2} \quad (30.13)$$

Therefore,

$$\theta = 90^\circ - 25^\circ = 65^\circ$$

For  $m = 1$ , equation (30.12) takes the form

$$\lambda = 2d \sin \theta$$

Now, we have already seen that  $\lambda = 1.65 \text{ \AA}$  and  $\theta = 65^\circ$  therefore

$$\lambda = \frac{1.6}{2 \times \sin 65^\circ} = 0.91 \text{ \AA}$$

Therefore, if electrons of energy equal to 54 eV are indeed behaving like waves then the inter-atomic plane spacing in single nickel crystal must be 0.91 Å. From independent studies it is well documented that the interatomic spacing,  $d$ , is indeed 0.91 Å for nickel single crystal. Therefore, Davisson and Germer concluded that de-Broglie waves are a reality and are not mere theoretical identities.

### 30.5.3 Applications of de-Broglie Waves

In the above section we studied about the reflected beam from a single crystal of nickel when energetic electrons are incident on it. We saw that the stream of energetic electrons have wave like properties and these waves exhibit Bragg reflections at the crystal planes.

(i) **Crystal Structure** : In our example one experiment was described to prove the validity of de-Broglie relation [i.e. equation (30.5)]. However, this experiment can be used to determine the crystal structure of any material replacing the nickel crystal. This is an important application of de-Broglie waves.

(ii) **Neutron Spectroscopy** : You would agree that not only electrons but all other particles would also show wave-like behavior. Another application of de-Broglie waves lies in the use of slow neutrons obtained from nuclear reactors, to investigate the atomic structure of solid. This kind of study is very useful at places where nuclear reactors have been installed because this allows us to use the facility for some novel spectrometry. In fact, this technique is now called neutron spectrometry. About the nuclear reactor you will study in the coming lessons.

(iii) **Electron Microscop**: From equation (30.11) we can see that the velocity of electrons with a particular kinetic energy is given by

$$v = \sqrt{\frac{2(KE)}{m}}$$

The momentum of these electrons is therefore,

$$p = mv = \sqrt{2m(KE)} \quad (30.14)$$

The wavelength of the associated de -Broglie waves is given by,

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m(KE)}} \quad (30.15)$$

From equation (30.14) we find that very small values of wavelength can be achieved by increasing the kinetic energy of the electrons. We know that the resolving power of an optical microscope depends upon the wavelength of light used. In fact, the resolution increases with decreasing wavelength. Can you guess what would happen if a stream of very energetic electrons are used in a microscope instead of photons? Well, obviously you could obtain very high resolution and magnification by lowering the de-Broglie wavelength associated with the electrons. This technique is used in electron microscopes. This is yet another useful application of de-Broglie waves.

**Example 30.2 :** An electron is accelerated through a potential difference of 182 V. How large is its associated wavelength?

**Solution:**

We know,  $\lambda = \frac{12.3}{\sqrt{V}} \text{ \AA}$  which is the expression for de-Broglie wavelength.

Here  $V = 182 \text{ V}$

$$\therefore \lambda = \frac{12.3}{\sqrt{182}} \text{ \AA} = \frac{12.3}{13.5} = 0.91 \text{ \AA}$$

**Note :** This is of the same order of magnitude as X-ray wavelengths. It is therefore clear why electrons show diffraction effects similar to X-rays.

### INTEXT QUESTIONS 30.3

- State whether the following statements are true or false.
  - According to de-Broglie, stationary particles exhibit wave-like characteristics.
  - Matter waves are the same thing as de-Broglie waves.
  - Very poor resolution can be obtained in a microscope using energetic electrons by lowering the de-Broglie wavelengths associated with the electrons.
- A 50 g ball rolls along a table with a speed of 20  $\text{cm s}^{-1}$ . How large is its associated wavelength?

Given  $h = 6.625 \times 10^{-34} \text{ Joule Second}$

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

- Why can't we observe de-Broglie wavelengths of a big ball of size of a cricket ball?

**Example 30.3 :** Calculate the maximum kinetic energy of the emitted photoelectrons when light of frequency  $f = 10^{15} \text{ Hz}$  is incident on a Zinc plate. The work function of zinc is 3.4 eV.

**Solution :** The above numerical is a direct application of Einstein's relation

$$hf = E_0 + K_{\text{max}}$$

In, this problem the various parameters like  $h$ ,  $f$ ,  $E_0$  have the following values :

$$\begin{aligned} h &= 6.625 \times 10^{-34} \text{ joule -sec} \\ f &= 10^{13} \text{ Hz} \\ E_0 &= 3.4 \text{ eV} = 3.4 \times 1.602 \times 10^{-19} \text{ joules} \end{aligned}$$

From (30.17) we get,

$$\begin{aligned} K_{\text{max}} &= hf - E_{0,34} \\ &= (6.625 \times 10^{-34} \times 10^{13}) - (3.4 \times 1.602 \times 10^{-19}) \\ &= 6.625 \times 10^{-19} - 5.447 \times 10^{-19} \\ &= 1.178 \times 10^{-19} \text{ Joules} \end{aligned}$$

**Example 30.4 :** Calculate the de-Broglie wavelength associated with electrons that have been accelerated through 10 kV.

**Solution:** We know,

$$\lambda = \frac{12.3}{\sqrt{V}} \text{ \AA}$$

Putting the value of  $V$  to be equal to 10 kV or  $10^4$  V we get,

$$\begin{aligned} &= \frac{12.3}{\sqrt{10^4}} = \frac{12.3}{100} = 0.123 \text{ \AA} \end{aligned}$$

### 30.6 WHAT YOU HAVE LEARNT

- Emission of electrons from a metal when light of proper frequency falls on it is called photoemission.
- In photoemission, electrons gain energy from light where as they gain energy from heat in thermionic emission.
- The stopping potential increases with increasing incident light frequency.
- There exists a frequency  $f_0$  for every material, below which no photoelectric effect takes place.
- The maximum velocity of the photoelectrons increases with increasing frequency of the incident light but is independent of the intensity of the incident light.
- The number of photoelectrons emitted from each square centimeter of the emitting surface for any particular frequency, is proportional to the intensity of incident light.
- Einstein assumed light to consist of bundles of energy called photons, each of them having an energy of  $hf$ , where  $f$  is the frequency and  $h$  is the Planck's constant.
- Photomissive type of phototube is based on the photoelectric effect.
- The saturation current of a phototube increases with increasing intensity of the incident light.
- Particles in motion have waves associated with them with a wavelength given by  $h/p$ , where,  $p$  is the momentum and  $h$  is the Planck's constant.

### 30.7 TERMINAL QUESTIONS

- In photo electric emission what happens to the incident photons ?
- What is difference between a photon particle and a matter particle ?
- Why is the wave nature of matter not apparent to our daily observations ?
- What is the effect on the velocity of photo-electrons, if the wavelength of incident light is increased ?
- The threshold frequency of a metal is  $5 \times 10^{14}$  Hz . Can a photon of wavelength  $6000 \text{ \AA}$  emit on energetic photo-electron ?
- What is work function of a metal ? Does it depend upon the temperature ?
- How does the stopping potential help in determining the work function of the metal ?
- Does the threshold frequency for a metal depend on the incident radiations ?
- What are the various uses of photocell ?
- What was the aim of Davisson and Germer's experiment ? Or, what principle does it depend ?
- Explain why the photo electrons are not ejected out of a photo-sensitive metal surface, by all photons what ever may be their energy ?
- What is the difference between photoelectric emission and thermionic emission.
- Describe an experimental setup for studying the photoelectric effect.
- Explain the following terms:  
(a) Saturating voltage ; (b) Stopping potential
- State the laws of photoelectric emission.
- Describe the salient features of Einstein's theory of photoelectric effect.
- Explain Einstein's relation:  
 $hf = E_p + K_{max}$
- Describe the construction of a photoelectric tube and outline its working.
- Calculate the wavelength associated with electrons moving with a velocity  $v = 1 \times 10^8 \text{ m/s}$ .  
(mass of electron =  $9.1 \times 10^{-31} \text{ kg}$ ,  $h = 6.6 \times 10^{-34} \text{ J. s}$ ).
- Describe an experiment which verifies the existence of de-Broglie waves.
- State some application of de-Broglie Waves.
- Show that the de-Broglie wavelength associated with electrons accelerated through a potential  $V$  is given by the relation:

$$\lambda = \frac{12.3}{\sqrt{V}} \text{ \AA}$$

### CHECK YOUR ANSWERS

#### Intex Questions 30.1

- (a) False (b) False (c) False

2. We know  $hf = E_0 + KE$  where  $E_0$  is the energy required to remove an electron from the metal.

$$\text{Here } h = 6.625 \times 10^{-34} \text{ Js, } f = 6 \times 10^{14} \text{ Hz}$$

$$KE = 2 \times 10^{-19} \text{ J}$$

$$E_0 = 6.625 \times 10^{-34} \text{ Js} \times 6 \times 10^{14} - 2 \times 10^{-19} \text{ J}$$

$$= 39.756 \times 10^{-20} \text{ J} - 2 \times 10^{-19} \text{ J}$$

$$= 10^{-19} (3.9756 - 2) \text{ J}$$

$$= 1.9756 \times 10^{-19} \text{ J} = 1.98 \times 10^{-19} \text{ J}$$

### Intex Question 30.2

- (1) (a) False (b) False (c) True  
 (2) (i) Reproduction of sound in films,  
 (ii) Transmisting pictures over great distances.  
 (iii) Thieve detecting systems.

### Intex Question 30.3

1. (a) False (b) True (c) True  
 2.  $p = mv$  and  $\lambda = \frac{h}{p}$   
 Here  $m = 50\text{g} = .05\text{kg}$ ,  $v = 20 \text{ cms}^{-1} = 0.02 \text{ ms}^{-1}$   
 $\lambda = 6.6 \times 10^{-32} \text{ m}$ .  
 3. From equation 30.15 it is clear if mass  $m$  is large, the value of  $\lambda$  will be very small. Same is the case with cricket ball.

### Terminal Questions

8. 7.25 A