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# DUAL NATURE OF RADIATION AND MATTER

You must have seen films in cinema halls. The picture on the screen is produced by passing light through films which have the scenes shot on them. But have you ever thought as to how the sound is reproduced in the cinema? The sound is also recorded on the side of the film as a sound track. The light beam passing through this sound track falls on a photocell, which converts it into electrical pulses. These electrical pulses are converted into sound. In this lesson you will study the effect which governs the working of a photocell. It is called the *photoelectric effect*. It is also used in burglar alarm to detect intruders. Einstein's explanation of photoelectric effect led de Broglie (read as de Broy) to the wave-particle duality, i.e. matter exhibits wave as well as particle properties.

You now know that a particle is characterized by properties such as definite position, size, mass, velocity, momentum, etc. Its motion is described by Newton's laws of motion. On the other hand, a wave is characterized by properties such as periodicity in space-time, wavelength, amplitude, frequency, wavevelocity, etc. It transports energy, but no matter. That is, it extends in space unlike a particle, which is localised. The term wave-particle duality refers to the behaviour where both wave-like and particle-like properties are exhibited under different conditions by the same entity. His arguments were simple: Nature likes simplicity and loves symmetry. So if wave-particle duality can be exhibited by light, it should be exhibited by matter as well. You will learn about his explanation of matter waves in sec. 25.4.

## OBJECTIVES

After studying this lesson, you should be able to:

- *explain photoelectric effect;*
- *describe the experimental arrangement to study photoelectric effect;*

- *state the laws of photoelectric emission;*
- *interpret the graphs between frequency of radiation and retarding potential;*
- *write deBroglie wavelength of matter waves associated with a particle of momentum* **p**; *and*
- *describe the experimental arrangement for the verification of matter waves.*

## 25.1 PHOTOELECTRIC EFFECT

In 1887, while working on propagation of electromagnetic waves, Hertz discovered that air in a spark gap became a better conductor when it was illuminated by ultraviolet rays. Further experiments by him showed that zinc became positively charged on irradiation by ultraviolet rays. In 1900, Leonard showed that electrons were emitted from a metal surface when light of sufficiently high frequency falls on it. This phenomenon is known as *photoelectric effect* and the electrons so emitted are called photoelectrons.

*The emission of electrons from metals irradiated by light of a frequency greater than a certain characteristic frequency is called photoelectric effect.*

> The emission of electrons from metals can also take place when they are heated. This is known as **thermionic emission.** *Note that electrons gain energy from thermal energy in thermionic emission.*

### 25.1.1 Experimental Arrangement to Study Photoelectric Effect

Refer to Fig. 25.1. It shows a schematic diagram of the apparatus that can be used to study this phenomenon.

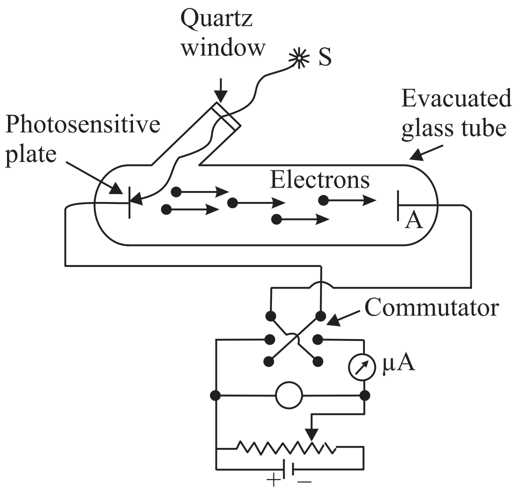



**Fig. 25.1:** Experimental arrangement for observing the photoelectric effect

A metallic cup *C* called photo cathode is sealed inside an evacuated tube along with another metal plate *A,* which is used to collect photoelectrons emitted by *C*.These electrodes are connected to a battery and microammeter circuit, as shown in Fig.25.1. The battery is so connected that the voltage on plate *A* is positive with respect to *C*. If the battery terminals are reversed, the voltage of the plate *A* will become negative relative to *C*.

To study the effect of intensity of incident light on the number of photoelectrons emitted by *C*, the collector plate *A* is kept at positive potential relative to *C*.

Keeping the frequency of incident light and the value of accelerating potential fixed, the photoelectrons emitted per unit area from the emitting surface vary linearly with the intensity of light, as shown in Fig. 25.2 (a).

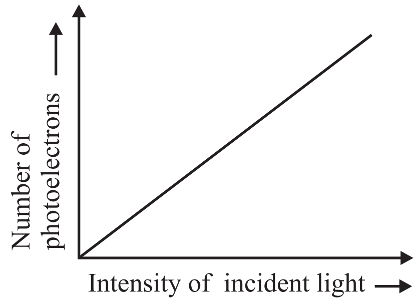



**Fig. 25.2 : (a)** Variation of number of photoelectrons with intensity of incident light

### Case-I: *Plate A positive relative to C*

Let us first consider the case when the plate *A* is at a positive potential relative to *C*. When light of high frequency is incident on the emitter, it starts emitting electrons. Since *A* is at a higher potential relative to *C*, the emitted electrons experience an attractive force. When we increase the voltage on *A*, the kinetic energy of the photoelectrons increases. The current in the outer circuit shown by the microammeter depends on the number of electrons reaching the plate *A*. If we keep on increasing the voltage, a stage comes when all the emitted electrons are collected by the plate. The current is said to have *saturated* at this stage. If the voltage on the plate is increased further, the current remains constant in magnitude. This behaviour of current with respect to plate voltage is shown in Fig. 25.2(b). The voltage $V_s$ is called *saturating voltage*.

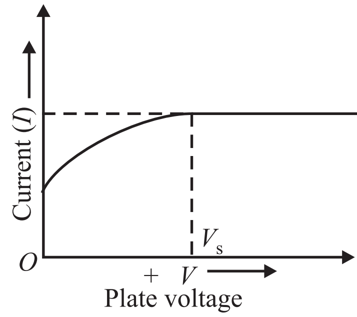



**Fig. 25.2 : (b)** Dependence of photoelectric current on plate voltage.

### Case-II: *Plate A negative relative to C*

If *C* is at a positive potential relative to the plate *A* and light of a proper frequency is incident on the emitter, photoelectrons emitted by *C* will experience retarding potential, which impedes their motion towards *A*. Some of the electrons emitted from *C* may still reach the plate. This gives rise to current, which is registered by the microammeter. What does this mean? If the p.d between *A* and *C* only provides the force which makes the electrons move towards the plate, then none of the electrons should have reached the plate. Since such electrons have overcome the retarding potential while moving against it to reach the plate, they have some initial kinetic energy. This is also confirmed by observed results. For any incident light of particular frequency, if the retarding potential is gradually increased in magnitude, a stage is ultimately reached when none of the electrons reach the plate and the current becomes zero.

*The minimum retarding potential for which the photoelectric current becomes zero for a particular frequency of incident light is called the stopping potential, $V_0$ for that frequency.*

The work done by an electron $W$ against the stopping potential $V_0$ is $eV_0$ where $e$ is electronic charge. This work is done by the electron at the expense of its kinetic energy. So, we can write

$$eV_0 = \frac{1}{2} m v_{max}^2 \qquad (25.1)$$

The stopping potential $V_0$ was found by Millikan to depend on the frequency of the incident light. A plot of the stopping potential ($V_0$) versus the frequency of the incident light ($\nu$) is shown in Fig. 25.3. You will note that there is a minimum cut-off frequency $\nu_0$ below which ejection of electrons is not possible. It is called *threshold frequency.*

To study the effect of frequency of incident light on stopping potential, Millikan adjusted the intensity of light at a fixed value for various frequencies and studied the variation of photoelectric current with anode potential. He obtained different values of stopping potential for different frequencies of incident light. Moreover, the stopping potential is more negative for higher frequencies, as shown in Fig. 25.4. This implies that if the frequency of the incident light increases, the maximum kinetic energy of the photoelectrons also increases. Therefore, with increasing frequency, greater retarding potential is required to completely stop the movement of photoelectrons towards the anode.

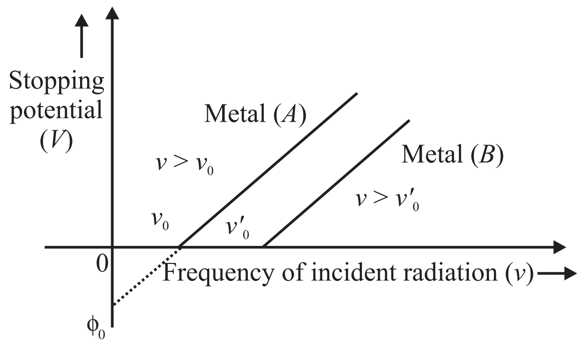



**Fig. 25.3 :** Stopping potential versus frequency of incident light.

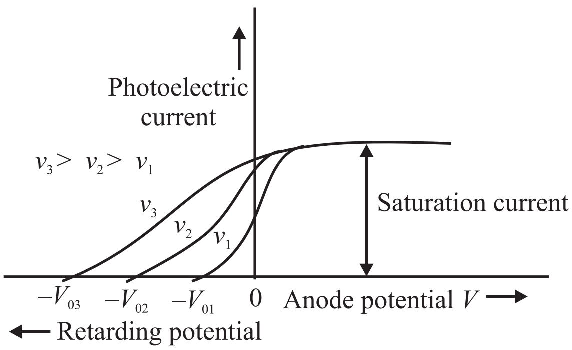



**Fig. 25.4 :** Photo electric current

This experiment also established that there exists a minimum cut-off frequency $\nu_0$ for which stopping potential is zero. Moreover, photo emission begins as soon as light is incident on the material, i.e. photo emission is instantaneous, even if the incident light is dim. Now it is known that time lag between incident light and emission of photoelectrons from the emitter is of the order of $10^{-9}$s.

These observations can be summarised as follows :

- *The maximum velocity of photoelectrons increases with frequency of incident light and depends on the nature of emitter material.*
- *The maximum velocity of photoelectrons does not depend on the intensity of incident light.*
- *For every material, there exists a thereshold frequency below which no photoelectrons are emitted.*
- *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.*
- *There is practically no time lapse* ($\sim 10^{-9}$s) *between the incidence of light on the metal and emission of electrons from it. In other words, photoelectric emission is an instantaneous process.*

### INTEXT QUESTIONS 25.1

1. State whether the following statements are true or false :
   (a) In thermionic emission, electrons gain energy from photons.
   (b) The maximum velocity of photoelectron is independent of the frequency of incident radiation.
   (c) There exists a frequency $v_0$ below which no photoelectric effect takes place.
2. Refer to Fig. 25.3 and interpret the intercepts on $x$ and $y$-axes and calculate the slope.
3. Draw a graph showing the variation of stopping potential ($-V_0$) with the intensity of incident light.

## 25.2 EINSTEIN'S THEORY OF PHOTOELECTRIC EMISSION

In 1905, Einstein proposed a simple but revolutionary explanation for the photoelectric effect. He assumed that light consists of bundles of energy, called photons and viewed photoelectric effect as a collision between a photon and a bound electron.

The energy $E$ of a single photon is given by

$$E = hv \qquad (25.2)$$

## Robert A. Millikan
## (1868-1953)

Robert Andrews Millikan was born on March 22, 1868 in U.S.A. During his undergraduate course, his favourite subjects were Greek and Mathematics. But after his graduation in 1891, he took, for two years, a teaching post in elementary physics. In this period, he developed interest in the subject. He received his Ph.D. (1895) for research on polarization of light emitted by incandescent surfaces.

Millikan spent a year (1895-1896) in Germany, at the Universities of Berlin and Göttingen. He returned at the invitation of A.A. Michelson to take appointment as his assistant at the newly established Ryerson Laboratory at the University of Chicago (1896). He became Professor at that University in 1910, a post which he retained till 1921. As a scientist, Millikan made numerous momentous discoveries in the fields of electricity, optics, and molecular physics. His earliest major success was the accurate determination of the charge carried by an electron, using the elegant "falling-drop method". He also proved that this quantity was a constant for all electrons demonstrating the quantised nature of charge.

He also verified experimentally Einstein's photoelectric equation, and made the first direct photoelectric determination of Planck's constant *h*. Throughout his life, Millikan remained a prolific author, making numerous contributions to scientific journals. He was awarded the Nobel Prize in Physics in 1923.

where $v$ is the frequency of the incident light and $h$ is Planck's constant. Let us now assume that a photon of energy $hv$ is incident on the metal surface. Suppose $\phi_0$ 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 by an electron to come out of the conductor surface.*

The typical values of work function for a few metals are given (in eV.) in Table 25.1, along with the corresponding threshold frequency ($v_0$).

**Table 25.1:** Work function and threshold frequencies of some typical metals

| Metal | $\phi_0$(eV) | $v$ (Hz) |
|---|---|---|
| Sodium | 2.5 | $6.07 \times 10^{14}$ |
| Potassium | 2.3 | $5.58 \times 10^{14}$ |
| Zinc | 3.4 | $8.25 \times 10^{14}$ |
| Iron | 4.8 | $11.65 \times 10^{14}$ |
| Nickel | 5.9 | $14.32 \times 10^{14}$ |

What do you think would happen when a photon of energy $E$ ( $> \phi_0$) strikes the metal surface? We expect that out of the total energy $E$, an amount $\phi_0$ would be used up by the electron to come out of the metal surface. The difference in energy, i.e. $(E - \phi_0)$, would then be imparted to the emitted electron in the form of kinetic energy. (The electron may lose some energy in internal collisions before it escapes from the metal surface.) Mathematically, we can write

$$hv = \phi_0 + K_{max} \qquad (25.3)$$

## Albert Einstein
## (1879-1955)

Albert Einstein was born in Wurttemberg, Germany, on March 14, 1879. In 1901, he acquired Swiss citizenship and, as he was unable to find a teaching post, he accepted a position as technical assistant in the Swiss Patent Office. During his stay at the Patent office, in his spare time, he produced much of his remarkable work, including the theory of photoelectric effect and the special theory of relativity. In 1909 he became Professor Extraordinary at Zurich. In 1911 he accepted the post of Professor of Theoretical Physics at Prague but returned to Zurich in the following year to fill a similar post. In 1914, he was appointed Director of the Kaiser Wilhelm Physical Institute and Professor in the University of Berlin. He became a German citizen in 1914. He was awarded the Nobel Prize in Physics in 1921 for his theory of photoelectric effect, though he is more famous for his theory of relativity. He remained in Berlin until 1933, when he renounced his citizenship for political reasons and immigrated to take the position of Professor of Theoretical Physics at Princeton in USA.

He became a US citizen in 1940 and retired from his post in 1945. He spent the later years of his life working on General Theory of Relativity and Unification of basic Forces. Einstein nurtured scientific humanism. He protested to President Roosevelt against the use of nuclear bombs for destruction of humanity. He is considered the greatest scientist to have ever walked on this planet and named scientist of the millenium.

Let us now see how observed results can be explained on the basis of this theory. Let us take

$$\phi_0 = h\nu_0.$$

Then Eqn. (25.3) takes the form

$$K_{max} = \frac{1}{2}mv^2 = h(\nu - \nu_o) \qquad (25.4)$$

This equation implies that

- For $v_{max}$ to be positive, no emission can take place for $\nu < \nu_o$. That is, the incident light must have frequency above the threshold frequency.
- $K_{max}$ is linearly proportional to $(\nu - \nu_o)$
- An increase in the intensity of incident light of frequency $\nu$ corresponds to an increase in the number of photons. Each and every photon has same

energy; there is no increase in the energy of photoelectrons. However, the no. of emitted electrons and hence photocurrent will increase with increase in intensity.

- Since photoelectric effect is produced by collisions between photons and electrons, the energy transfer from photons is instantaneous, i.e. there is almost no time lag.
- Since work function is a characteristic property of a material, $v_o$ is independent of the intensity of incident light.

We see that Einstein's theory of the photoelectric effect successfully explains its physical origin.

To understand these concepts and get an idea about the values of physical parameters, go through the following examples carefully.

**Example 25.1:** Sodium has a work function of 2.3 eV. Calculate (i) its threshold frequency, (ii) the maximum velocity of photoelectrons produced when sodium is illuminated by light of wavelength $5 \times 10^{-7}$ m, (iii) the stopping potential for light of this wavelength. Given $h = 6.6 \times 10^{-34}$ J s, $c = 3 \times 10^{8}$ m s$^{-1}$, 1eV = $1.6 \times 10^{-19}$ J, and mass of electron $m = 9.1 \times 10^{-31}$ kg.

**Solution:** (i) The threshold frequency is given as $hv_0 = \phi_0$. Here, $h = 6.6 \times 10^{-34}$ Js and $\phi_0 = 2.3 \text{ eV} = 2.3 \times 1.6 \times 10^{-19}$ J.

$$\therefore \qquad v_0 = \frac{\phi_0}{h}$$

$$= \frac{2.3 \times 1.6 \times 10^{-19}\ \text{J}}{6.6 \times 10^{-34}\ \text{J s}} = 5.6 \times 10^{14}\ \text{Hz}$$

(ii) From Einstein's photoelectric equation, we know that

$$hv = \phi_0 + K_{max} = \phi_0 + \frac{1}{2} m v_{max}^2 ,$$

Since $v = \dfrac{c}{\lambda}$, we can write

$$E = h \times \frac{c}{\lambda} = \phi_0 + \frac{1}{2}\left(m v_{max}^2\right)$$

where $c$ is velocity of light and $\lambda$ is its wavelength. On substituting the given values, we get

$$\therefore \qquad E = \frac{(6.6\times10^{-34}\,\mathrm{J}s)(3\times10^{8}\,\mathrm{ms}^{-1})}{5\times10^{-7}\,\mathrm{m}}$$

$$= 3.96 \times 10^{-19}\ \mathrm{J}$$

$$\Rightarrow \qquad 3.96 \times 10^{-19} = 2.3 \times 1.6 \times 10^{-19} + \frac{1}{2}\, m\, v_{\max}^2$$

$$= 3.68 \times 10^{-19} + \frac{1}{2}\, m\, v_{\max}^2$$

$$\therefore \qquad v_{\max}^2 = \frac{2\times0.28\times10^{-19}}{m} = \frac{2\times0.28\times10^{-19}}{9.1\times10^{-31}}$$

$$\therefore \qquad v_{\max} = \sqrt{\frac{0.56\times10^{-19}\,\mathrm{J}}{9.1\times10^{-31}\,\mathrm{kg}}} = 2.5 \times 10^{5}\ \mathrm{m\ s^{-1}}$$

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

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

$$\therefore \qquad V_0 = \frac{0.28\times10^{-19}\,\mathrm{J}}{1.6\times10^{-19}\,\mathrm{JV}^{-1}} = 0.18\ \mathrm{V}$$

You may now like to answer some simple questions

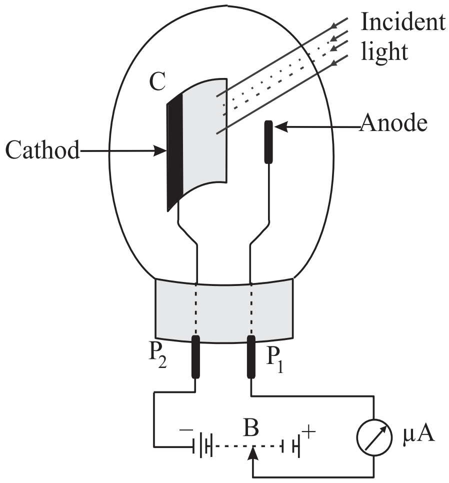
## INTEXT QUESTIONS 25.2

1. Calculate the momentum of a photon of frequency $v$.
2. If the wavelength of an electromagnetic radiation is doubled, how will be the energy of the photons change?
3. The intensity of incident radiation is doubled. How will it affect the kinetic energy of emitted photoelectrons.

## 25.3 PHOTOELECTRIC TUBE

You have studied the photoelectric effect in detail now. We know that when light of a frequency above $v_0$ is incident on a material, electrons are emitted. Their kinetic energies are different. We also know that flow of electrons constitutes current.

The photoelectric tube is based on photoelectric effect.



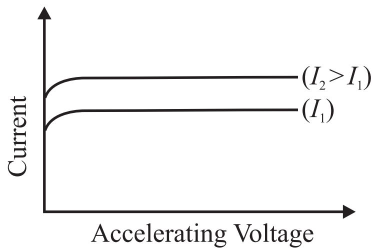




**Fig. 25.5:** Variation of current and accelerating voltage

A photoelectric tube consists of an evacuated glass vessel which contains a semi-cylindrical cathode and an anode in the form of a straight wire. The cathode is coated with a metal of low work function to ensure emission of photoelectrons when light of a pre-decided frequency is incident on it. The threshold frequency above which a phototube responds determines the choice of this coating.

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 microammeter are connected between the anode and the cathode to provide the accelerating voltage. The arrow on the battery indicates that the voltage applied by it can be varied. The microammeter placed in the circuit measures the current passing through it (Fig. 25.5a).

To understand the working of a photoelectric tube, let us suppose that light of frequency higher than the threshold frequency is incident on the cathode. Some photoelectrons will be emitted even when accelerating potential between the cathode and the anode is zero. As you know, these electrons come out of the cathode with definite kinetic energy and reach the anode giving rise to a current, which is indicated by the microammeter. Let us now apply some accelerating voltage and see what happens. Obviously, more electrons will reach the anode and increase the current. This is shown in Fig. 25.5(b).

As we keep on increasing the voltage between the cathode and the anode of the photoelectric tube, current also increases. However, at high voltage, the current saturates to a fixed value as shown in Figure 25.5(b). ***The value of saturation current is determined by the intensity (I) of incident light.*** The magnitude of saturation current is of the order of nano-ampere ($\sim 10^{-9}$ A). It is seen that ***if the intensity of the light is increased, the saturation current also increases, as shown in the*** **Fig. 25.5. (b)**

### 25.3.1 Applications

Photoelectric cells find wide applications in processes wherever light energy has to be transformed into equivalent electric current.

**(i) Reproduction of sound in cinematography (motion pictures):** One of the most important applications of photoelectric cells is in reproduction of sound in films. A sound track is a track on the film of uniform width whose intensity varies in accordance with the audio frequency variations. 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 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 across the resistance is then suitably amplified and fed to a loudspeaker. The loudspeaker reproduces the sound as was originally recorded on the sound track. You will learn more about it on the optional module on photography and video-recording.

**(ii) Transmitting pictures over large distances :** Photo electric tubes are also used in systems that transmit pictures over large distances. The technique of transmission of pictures to large distances is called **photo-telegraphy.**

**(iii) Other Uses :** Many types of systems used for counting articles or living beings are based on photoelectric tubes. These are also used in burglar alarms, fire alarms, detectors used for detection of traffic law defaulters, in television camera for scanning, telecasting scenes and in industry for detecting minor flaws or holes in metal sheets.

## INTEXT QUESTIONS 25.3

1. State whether the following statements are true or false:
   (a) The cathode in a phototube is biased positively with respect to anode.
   (b) The saturation current in a phototube depends on the frequency of incident radiation.
   (c) The saturation current in a photodiode increases with intensity of incident light.
2. State three applications of photoelectric tube.
3. A phototube is illuminated by a small bright source placed 100 cm away. When the same source of light is 50 cm away, what will be the effect on the number of electrons emitted by photo cathode?

In the previous section, you have studied Einstein's theory of photoelectric effect and learnt that light consists of photons. You have also learnt that the phenomena of interference and diffraction can be explained on the basis of wave theory of light. This duality in the nature of light came to be accepted by the physicists in the early 20th century. Thinking about the wave-particle duality of light, de Broglie asked himself the question : If light exhibits dual nature, will particles of matter also not act like waves? Successful resolution of this question led to de Broglie hypothesis.

## 25.4 THE DE BROGLIE HYPOTHESIS

As a young graduate student, de Broglie argued with a great amount of insight that since nature loves symmetry and simplicity in physical phenomena, ordinary "particles" such as electrons, and protons should also exhibit wave characteristics under certain circumstances. His argument runs as follows : Light is an electromagnetic radiation and exhibits wave-particle duality. Therefore, Einstein's mass-energy equivalence relation ($E = mc^2$), which essentially treats light as quantum of photon, a particle, can hold only if matter also exhibits wave character. He therefore proposed that the wavelength and frequency of matter waves should be determined by the momentum and energy of the particle in exactly the same way as for photons : $E = pc$ and the associated wavelength $\lambda$ of a particle having momentum $p$ is given by

$$\lambda = \frac{h}{p} \tag{25.5}$$

Since the momentum of such a particle is gives by $p = mv$, we can write

$$\lambda = \frac{h}{mv} \tag{25.6}$$

$\lambda$ is called deBroglie wavelength. Eqn. (25.5) is a complete statement of wave-particle duality. It implies that a particle with a momentum $p$ can exhibit wave-like properties and the wavelength of the associated matter waves is $h/p$. The converse is also true, i.e., a wave of wavelength $\lambda$ can exhibit particle-like properties and the momentum of the wave-matter is $h/\lambda$

This hypothesis, submitted as Ph.D Thesis was initially rejected by the examiners. However, soon, experimental evidence proved de Broglie's argument. This has a very important inspirational lesson for us : We must keenly analyse every statement and try to seek experimental evidence.

The actual wavelength of anything macroscopic is incomprehensively small, as you can see by calculating it for a cricket ball. The case is quite different for elementary particles such as the electron. An electron has energy $E$ when accelerated through potential difference $V$. Hence, we can write

$$\frac{1}{2}mv^2 = qV \qquad (25.7)$$

or

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

so that

$$mv = p = \sqrt{2qmV} \qquad (25.8)$$

On combining this result with Eqn.(25.5), we find that de-Broglie wavelength is given by

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2qmV}} \qquad (25.9)$$

The constants appearing in Eqn. (25.9) have the values: $h = 6.625 \times 10^{-34}$ Js, $q = 1.602 \times 10^{-19}$ C and $m = 9.11 \times 10^{-31}$ kg. On substituting these values in Eqn.(25.9), we obtain

$$\lambda = \frac{6.625 \times 10^{-34}\,\text{Js}}{\sqrt{2 \times (1.602 \times 10^{-19}\,\text{C}) \times (9.11 \times 10^{-31}\,\text{kg})} \times \sqrt{V}}$$

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

$$= \frac{12.3}{\sqrt{V}}\ \text{Å} \qquad (25.10)$$

It means that if an electron is accelerated through a potential difference of 100V, its wavelength will be given by

$$\lambda = \frac{12.3}{\sqrt{100}}\ \text{Å}$$

$$= 1.23\ \text{Å}$$

This is also the wavelength of an electron of energy 100eV. You can easily verify this using the relation

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

The wavelength of matter waves associated with 100eV electrons lies in the X-ray region and is of the same order as the interatomic seperation in a solid. We therefore expect these to undergo diffraction by a crystal lattice.

The first experimental evidence of matter waves came from the work of Davisson and Germer, who were studying scattering of electrons by crystals. Let us learn about it now.

## Louis Victor de Broglie

## (1892-1987)

Louis de Broglie was born at Dieppe, France on 15th August, 1892. He first studied the arts and took his degree in history in 1910. Then, as his liking for science prevailed, he studied for a science degree, which he gained in 1913. In 1924 at the Faculty of Sciences at Paris University, he submitted a thesis *Recherches sur la Théorie des Quanta* (Researches on the quantum theory), which gained him his doctor's degree. This thesis contained a series of important findings, which he had obtained in the course of about two years. The ideas set out in that work served the basis for developing *wave mechanics,* a theory which has transformed our knowledge of physical phenomena on the atomic scale.

In 1929 he was awarded the Nobel Prize for Physics for his discovery of the wave nature of electrons.

### 25.4.1 Experimental Evidence for Existence of de Broglie Waves

The schematic diagram of Davisson-Germer experiment is shown in Fig.25.6. The set up consists of a filament *F*, which serves as a source of electrons. The electrons emitted from this filament are made to pass through a set of metal diaphragms having a number of slits. The electrons emitted by the filament come out in various directions. The metal diaphragms serve to

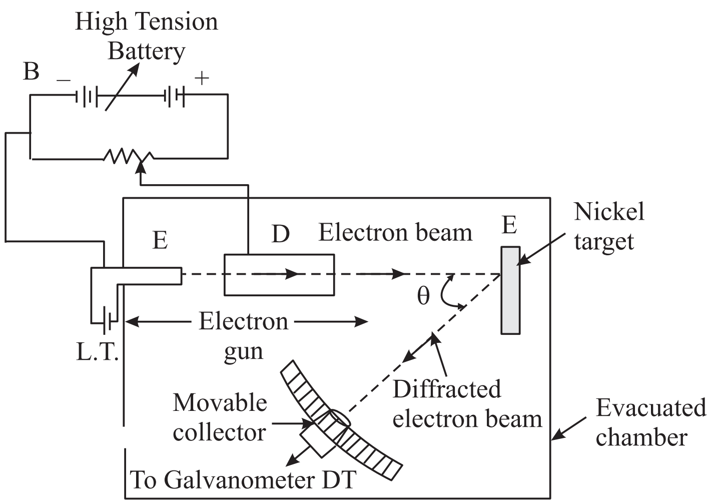



**Fig. 25.6:** Experimental set up to verify the existence of matter waves

collimate these electrons. Only those electrons which are able to pass through the slits in the various diaphragms are able to come out.

Note that the energy of the collimated stream of electrons is controlled by changing the magnitude of the accelerating voltage. The beam of electrons is made to fall perpendicularly 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 target crystal. This detector determines the intensity of the reflected beam. Note that there is nothing special in the choice of nickel.

Fig. 25.7 shows a plot of detector current versus kinetic energy of incident electrons for $\theta = 50°$. As may be noted, the detector current shows a maxima for electrons of kinetic energy 54 eV. If you calculate the wavelength of these electrons, you will get

$$\lambda = \frac{6.62\times10^{-34}\,\text{Js}}{[2\times(9.1\times10^{-31}\,\text{kg})\times54\times1.6\times10^{-19}\,\text{J}]^{1/2}}$$

$$= 1.67\ \text{Å}$$

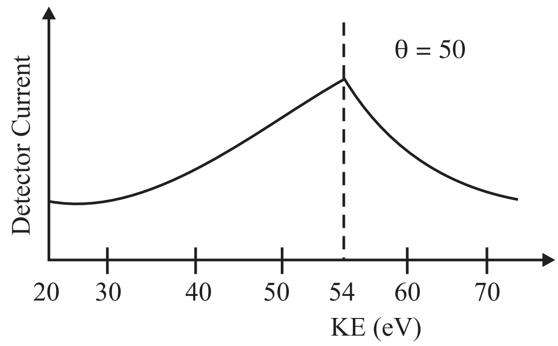



**Fig. 25.7:** Plot of detector current versus kinetic energy of electrons

### 25.4.2 Applications of de Broglie Waves

We now know that very small values of wavelength can be achieved by increasing the kinetic energy of electrons. From Lesson 23 you may recall that resolving power of an optical microscope depends on the wavelength of light used. In fact, the resolution increases with decreasing wavelength. Can you guess as to what would happen if a beam of very energetic electrons is used in a microscope instead of photons? Well, obviously you could obtain very high resolution and magnification by lowering the deBroglie wavelength associated with the electrons. This technique is used in electron microscopes. This is an extremely useful application of deBroglie waves. A comparison of structure and working of electron microscope with optical microscope is shown in Fig. 25.8.

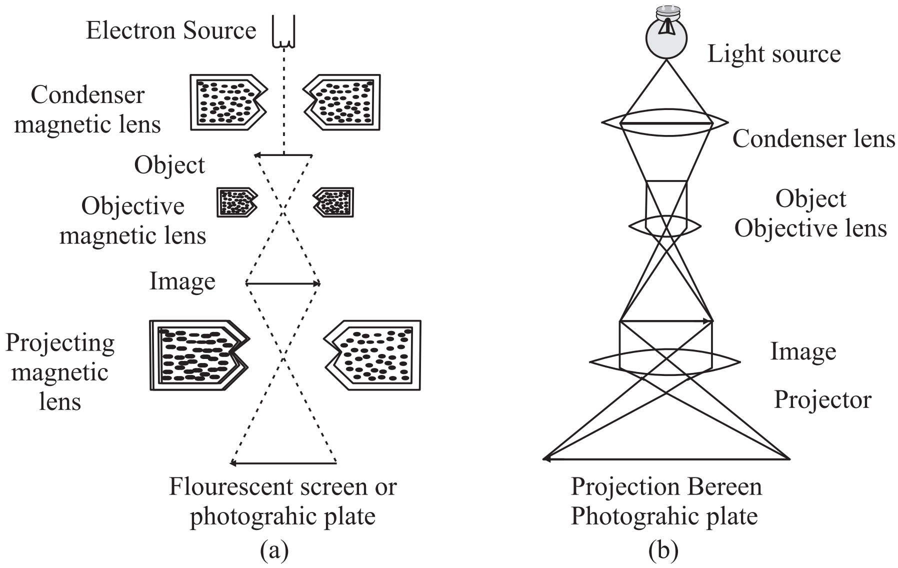
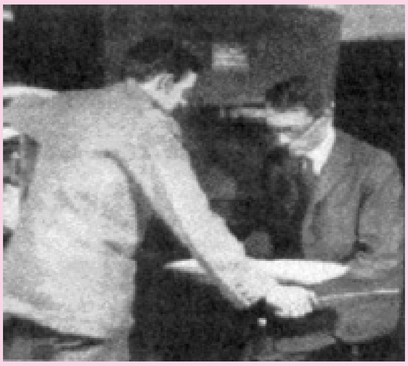



**Fig. 25.8: a)** Electron microscope, and **b)** Optical microscope

## Story of Davisson and Germer's experiment

Germer had recorded in his notebook that he discovered a crack in the vacuum trap in the electron scattering apparatus on Feb. 5, 1925 when he was working with Clinton Davisson at Westren Electric, New York, U.S.A.This was not the first time their equipment had broken, and not the first time they had "resurrected" their precious nickel crystal by **heating it in vacuum and hydrogen.**



This particular break and the subsequent method of repair, however, had a crucial role to play in the later discovery of electron diffraction. By 6 April 1925, the repairs had been completed and the tube put back into operation. During the following weeks, as the tube was run through the usual series of tests, results very similar to those obtained four years earlier were obtained. Then suddenly, in the middle of May, unprecedented results began to appear. This puzzled Davisson and Germer so much that they halted the experiments a few days later, cut open the tube and examined the target (with microscopist F. F. Lucas) to see if they could detect the cause of new observations. What they found was this: the polycrystalline form of nickel target had been changed by the extreme heating until it had formed about ten crystal facets in the area from which the incident electron beam was scattered. Davisson and Germer surmised that the new scattering pattern must have been caused by the new crystal arrangement of the target. In other words, they concluded that it was the arrangement of the atoms in the crystals, not the structure of the atoms that was responsible for the new intensity pattern of scattered electrons.

During the summer of 1926, Davisson and his wife had planned a vacation trip to relax and visit relatives in England. Something was to happen on this particular trip. Theoretical physics was undergoing fundamental changes at this time. In the early months of 1926, Erwin Schrodinger's remarkable series of papers on wave mechanics appeared, following Louis de Broglie's papers of 1923-24 and Albert Einstein's quantum gas paper of 1925. These papers were the subject of lively discussions at the Oxford meeting of the British Association for the Advancement of Science.

Davisson, who generally kept abreast of recent developments in his field but appears to have been largely unaware of these developments in quantum mechanics, attended this meeting. He was surprised when he heard a lecture by Born in which his own and Kunsman's (platinum target) curves of 1923 were cited as confirmatory evidence for de Broglie's electron waves!

Davisson shared the 1937 Nobel Prize for Physics with G.P. Thomson (son of J.J. Thomson).

## Electron Microscope

Electron microscopes are scientific instruments that use a beam of highly energetic electrons to examine objects on a very fine scale. This examination can yield the following information:

The surface features of an object or "how it looks", its texture; direct relation between these features and material properties (hardness, reflectivity, etc.), the shape and size of the particles making up the object; direct relation between these structures and materials properties (ductility, strength, reactivity, etc.), the elements and compounds that the object is composed of and the relative amounts of them; direct relationship between composition and material properties (melting point, reactivity, hardness, etc.). How are the atoms arranged in the object?

Electron microscopes were developed due to the limitations of optical microscopes, which are limited to 500× or 1000× magnification and a resolution of 0.2 micrometers. In the early 1930's, this theoretical limit had been reached and there was a scientific desire to see the finer details of the interior structures of organic cells (nucleus, *mitochondria,*etc.). This required 10,000× plus magnification which was just not possible using the microscopes available at that time.

The Transmission Electron Microscope (TEM) was the first Electron Microscope to be developed and is patterned exactly on the Light Transmission Microscope, except that a focused beam of electrons is used instead of light to image the specimen and gain information about its structure and composition. It was developed by Max Knoll and Ernst Ruska in Germany in 1931.

### Transmission Electron Microscope (TEM)

A TEM works much like a slide projector. A projector throws a beam of light on the slide. As the light passes through the side, it is affected by the structures and objects on the slide. As a result, only certain parts of the light beam are transmitted through certain parts of the slide. This transmitted beam is then projected onto the viewing screen, forming an enlarged image of the slide.

TEMs works in the same way, except that they shine a beam of electrons through the specimen. Whatever part is transmitted is projected onto a phosphor screen for the user to see.

The electron gun, produces a stream of monochromatic electrons. This stream is focused to a small, thin, coherent beam by the use of condenser lenses 1 and 2. The first lens (usually controlled by the "spot size knob") largely determines the "spot size"; the general size range of the fm spot that strikes the sample. The second lens usually controlled by the "intensity or brightness knob" actually changes the size of the spot on the sample; changing it from a wide dispersed spot to a pinpoint beam. The beam is restricted by the condenser **aperture,** knocking out high angle electrons (those far from the optic axis. The beam strikes the **sample specimen** and parts of it are transmitted.

This transmitted portion is focused by the objective lens into an image Optional Objective and Selected Area metal **apertures** can restrict the beam; the Objective aperture enhances contrast by blocking out high-angle diffracted electrons, the Selected Area aperture enables the user to examine the periodic diffraction of electrons by ordered arrangements of atoms in the sample.

The image is passed down the column through the intermediate and projector lenses, being enlarged all the way.

The image strikes the phosphor image screen and light is generated, allowing the user to see the image. The darker areas of the image represent those areas of the sample that fewer electrons were transmitted through (they are thicker or denser). The lighter areas of the image represent those areas of the sample that more electrons were transmitted through (they are thinner or less dense).

**Example 25.2:** An electron is accelerated through a potential difference of 182 V. Calculate its associated wavelength.

**Solutions:** We know that deBroglie wavelength, $\lambda = \frac{h}{p} = \frac{12.3}{\sqrt{V}}$ Å. Here $V = 182$V.

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

**Example 25.3:** Calculate the maximum kinetic energy of the emitted photoelectrons when light of frequency $v = 10^{15}$ Hz is incident on a zinc plate. The work function of zinc is 3.4 eV.

**Solution:** From Einstein's relation, we recall that

$$hv = \phi_0 + K_{max}$$

For this problem, $h = 6.625\times10^{-34}$ Js, $v = 10^{15}$ Hz, $E = hv = 6.625 \times 10^{-34} \times 10^{15}$ $= 6.625\times 10^{-19}$ J and $\phi_0 = 3.4$ eV $= 3.4 \times 1.602 \times 10^{19}$J $= 5.4468 \times 10^{-19}$ J

$$\therefore \qquad K_{max} = E - \phi_0 = (6.625 - 5.447) \times 10^{-19}\text{J} = 1.178 \times 10^{-19}\text{ J}$$

## INTEXT QUESTIONS 25.4

1. State whether the following statement are true or false:
   (a) According to deBroglie, stationary particles exhibit wave-like characteristics.
   (b) Matter waves are the same thing as deBroglie waves.
   (c) Very poor resolution can be obtained in a microscope using energetic electrons by lowering deBroglie wavelengths associated with electrons.
2. A 50 g ball rolls along a table with a speed of 20 cm $s^{-1}$. How large is its associated wavelength? Given $h = 6.625 \times 10^{-34}$ Js.
3. Why can we not observe de Broglie wavelength associated with a cricket ball?

## WHAT YOU HAVE LEARNT

- Emission of electrons from a metal when light of proper frequency incident on its surface is called photoelectric emission.
- In photoelectric emission, electrons gain energy from light.
- The stopping potential increases with increase in frequency of incident light.
- There exists a frequency $v_0$ for every material below which no photoelectric effect takes place.
- The maximum velocity of photoelectrons increases with increasing frequency of incident light but is independent of the intensity of 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 photons, each having energy $h\nu$, where $\nu$ is frequency and $h$ is Planck's constant.
- Photoemissive 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. The wavelength is given by $h/p$, where, $p$ is the momentum.

## TERMINAL EXERCISE

1. In photoelectric emission, what happens to the incident photons?
2. What is the difference between a photon and a matter particle?
3. Why is the wave nature of matter not apparent in daily life?
4. How is velocity of photoelectrons affected if the wavelength of incident light is increased?
5. The threshold frequency of a metal is $5 \times 10^{14}$ Hz. Can a photon of wavelength 6000Å emit an energetic photoelectron?
6. Does the threshold frequency for a metal depend on the incident radiations?
7. What are the various uses of photocell?
8. What was the aim of Davisson and Germer's experiment? On what principle does it depend?
9. Describe the experiment used for studying the photoelectric effect.
10. Explain the terms (a) Saturation voltage and (b)Stopping potential.
11. State the laws of photoelectric emission.
12. Describe the salient features of Einstein's theory of photoelectric effect.
13. Explain Einstein's relation: $h\nu = E_0 + K_{max}$
14. Calculate the wavelength associated with electrons moving with a velocity $\upsilon = 1 \times 10^8$ ms$^{-1}$. Take mass of electron $= 9.1 \times 10^{-31}$ kg and $h = 6.6 \times 10^{-34}$ J.s.
15. Describe an experiment which verifies the existence of deBroglie waves.

16. Show that the deBroglie wavelength associated with electrons accelerated through a potential $V$ is given by the relation;

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

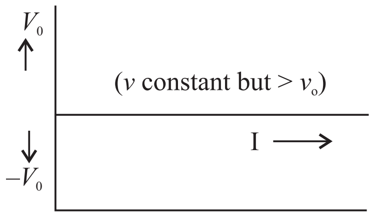
## ANSWERS TO INTEXT QUESTIONS

### 25.1

1. (a) False (b) False (c) True
2. $x$ – intercept gives the threshold frequency

   $y$ – intercept gives $e \times$ work function $(\phi_0)$

   $V_0 = \frac{h}{e}\nu - \frac{h}{e}\nu_0$. slope of graph gives $\frac{h}{e}$

3. 


### 25.2

1. $\lambda = \frac{h}{p} \quad \Rightarrow \quad p = \frac{h}{\lambda} = \frac{h}{c/\nu} = \frac{h\nu}{c}$
2. $E = hc/\lambda$

   If $\lambda$ is doubled, $E$ will become half
3. It is unchanged.

### 25.3

1. (a) False (b) False (c) True
2. (i) Reproduction of sound in films,

   (ii) Transmistting pictures over great distances.

   (iii) Thiefe detecting system.
3. Number of photo electrons will increase by a factor of 4.

## 25.4

1. (a) false, (b) True (c) True

2. $P = mv$ and $\lambda = \dfrac{h}{P}$

   Here $m = 50\text{g} = 0.05\text{kg}$ and $v = 20\ \text{cms}^{-1} = 0.02\text{ms}^{-1}$

   $\therefore\ \lambda = 6.6 \times 10^{-32}\text{m}$

3. From Eqn.(25.14) it is clear that if mass $m$ is large, the value of $\lambda$ will be small. Same is the case with cricket ball.

4. 7.25Å

## Answers to Problems in Terminal Exercise

14. 7.25 Å