De Broglie Waves

Objectives

After going through this module the learner will be able to :

- Appreciate the dual nature of light (particle nature and the wave nature)
- Understand the meaning of wave nature of particles or the concept of matter waves.
- Know de-Broglie relation $\lambda=h/mv$.
- Compare wavelength of material particles with wavelength of electromagnetic waves.
- Recognise the importance of the wave nature of electrons (based on the diffraction of a beam of electrons) in the Davisson-Germer Experiment.

Content Outline

- Unit syllabus
- Module-wise distribution of unit syllabus
- Words you must know
- Introduction
- De Broglie waves
- De Broglie wavelength
- Heisenberg Uncertainty principle
- Davisson Germer Experiment and its importance
- History of wave particle duality
- Summary

Unit Syllabus

Unit 7

Dual Nature of Radiation and matter

Dual nature of radiation, photoelectric effect, Hertz and Lenard's observations. Einstein's photoelectric equation, particle nature of light

Matter waves, wave particle duality, nature of particles de Broglie relation, Davisson -Germer experiment (experimental details should be omitted only conclusion should be explained)

Module Wise Distribution Of Unity Syllabus - 5 Modules

Module 1	• Introduction • Electron emission • Photoelectric effect • Hertz's observations • Hallwachs and Lenard's observation • Dual nature of light
Module 2	• Photocell • Experimental study of photoelectric effect • photocurrent • Effect of intensity of light on photo current • Effect of positive and negative potential on photocurrent • Stopping potential • Effect of frequency of incident radiation on stopping potential • Interpretations from the graphs drawn from above observations • Photoelectric effect and wave theory of light
Module 3	• Einstein's photoelectric equation • Energy quantum of radiation -the photon • Relating Einstein's photoelectric equation and observations from experiments with photocell
Module 4	• Wave nature of matter • de- Broglie's hypothesis • de-Broglie wavelength • Planck's constant • Probability interpretation to matter waves • Davisson and Germer Experiment • Wave nature of electrons
Module 5	• Application of dual nature of radiation and matter • Electron microscope

Module 4

Words You Must Know

- **Atomic structure**: *Atomic structure* is the positively charged nucleus and the negatively charged electrons circling around it, within an *atom.*
- **Electromagnetic waves**: *Electromagnetic waves* are *waves* that are created as a result of vibrations between an electric field and a magnetic field. In other words, *EM waves* are composed of oscillating magnetic and electric fields.
- **Interference and diffraction of waves**: **Interference** is a phenomenon in which two **waves** superimpose to form a resultant **wave** of greater or lower amplitude.
- The **diffraction** phenomenon is described as the apparent bending of **waves** around small obstacles and the spreading out of **waves** past small openings.
- **Electric current**: An *electric current* is a flow of *electric* charge.
- **Ionization of atoms**: is the process by which an **atom** or a molecule acquires a negative or positive charge by gaining or losing electrons to form **ions**, often in conjunction with other chemical changes.
- **Ray and wave optics**: *Ray optics*, describes light propagation in terms of *rays*. The *ray* in *geometric optics* is an abstraction useful for approximating the paths along which light propagates under certain circumstances. Light propagates in straight-line paths as they travel in a homogeneous medium.
- Wave optics is the branch of **optics** that studies interference, diffraction, polarization, and other phenomena for which the **ray** approximation of geometric **optics** is not valid.
- **Plotting and interpreting graphs**: graphs in the scientific world are between any two physical quantities and show the dependence of one on the other.
- **Analysis and deductions from the graphs** show variations and interpretations can give meaning to the study, for example u-v graphs of experimental observations from optics experiments, not only show the variation and dependence of one physical quantity on another under the constraints of the study.
- **Graphs can be linked with a mathematical equation**: All graphs have a mathematical relation. Hence there will always be an equation related to the segment of the graph drawn, the graph could be a straight line, a curve, a parabola, a hyperbola.
- **Photoelectric effect** the emission of electrons from a solid surface when light of suitable frequency is incident on it.

- **Work function**: The minimum amount of energy required by an electron to just escape from the metal surface is known as the work function of the metal. This is generally measured in electron volts (eV) .
- **Electron volt**: It is the energy gained by an electron when it is accelerated through a potential difference of 1 volt ,1 eV = 1.6×10^{-19} joules
- **Electron emission**: The phenomenon of emission of electrons from a metal surface. This occurs in the following ways
    - **Thermionic emission**: electrons are emitted from the surface when the surface is heated
    - **Field emission**: electrons are emitted from a surface when subjected to very high electric field
    - **Photoelectric emission**: electrons are emitted from a metal surface when electromagnetic radiation of suitable frequency is incident on the surface.
    - **Secondary emission**: electrons are emitted from the surface by striking it with high energy electrons.
- **Photosensitive material** It was found that certain metals like **zinc, cadmium, magnesium**, etc., responded only to ultraviolet light, having short wavelength, to cause electron emission from the surface. However, some alkali metals such as **lithium, sodium, potassium, caesium and rubidium were sensitive even to visible light.**
- **Photocell :** Photocell is a device that converts light into electrical energy

Results of Experiments with Photocell

For a given photosensitive material and frequency of incident radiations (above threshold frequency), the photoelectric current is directly proportional to the intensity of incident light.
For a given photosensitive material and frequency of incident radiations, saturation current is observed to be proportional to the intensity of incident radiations, but the stopping potential depends only on incident frequency.
For a given photosensitive material, there exists a certain minimum cut-off frequency of incident radiation, (called the threshold frequency), below which no emission of photoelectrons takes place no matter how intense the incident light is. However, above the threshold frequency, the stopping potential, or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiations but is independent of its intensity.

The photoelectric emission is an instantaneous process without any apparent time lag (10^{-9} s or less), even when the intensity of incident radiations (of frequency greater than the threshold frequency) is very small.

Einstein's photoelectric equation $KE_{max} = h\gamma - \emptyset_0$

Laws of Photoelectric Emission

1. **For a given metal, and a given frequency of incident radiation. (above threshold frequency), the number of photoelectrons emitted per second is proportional to the intensity of incident radiations.**
2. **For a given metal, no photoelectrons are emitted if the incident frequency is less than threshold frequency.**
3. **Above the threshold frequency, the maximum kinetic energy of emitted photoelectrons is directly proportional to the frequency of incident radiations but is independent of the intensity of incident radiations.**
4. **Photoelectric emission is an instantaneous process with a time lag of 10^{-9} s or less.**

Introduction

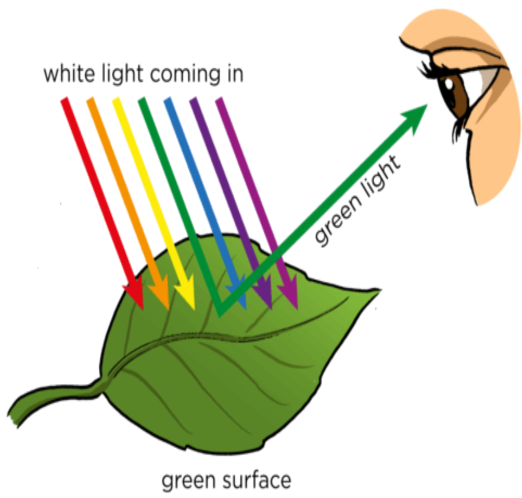
The dual (wave-particle) nature of light (electromagnetic radiation, in general) comes out clearly from what we have learnt in the preceding modules.

The **wave nature** of light shows up in the phenomena of **interference, diffraction and polarisation.**

On the other hand, in **photoelectric effect** and **Compton effect** which involve energy and momentum transfer, radiation behaves as if it is made up of a bunch of particles – the photons.

Whether a particle or wave description is best suited for understanding an experiment depends on the nature of the experiment.

For example, in the familiar phenomenon of seeing an object by our eye, both descriptions are important.



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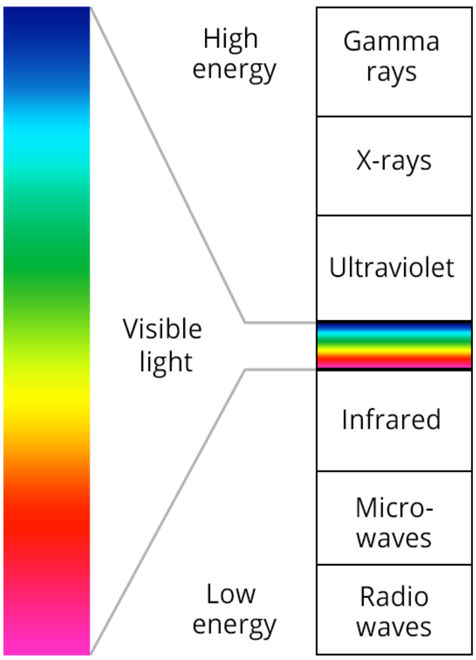
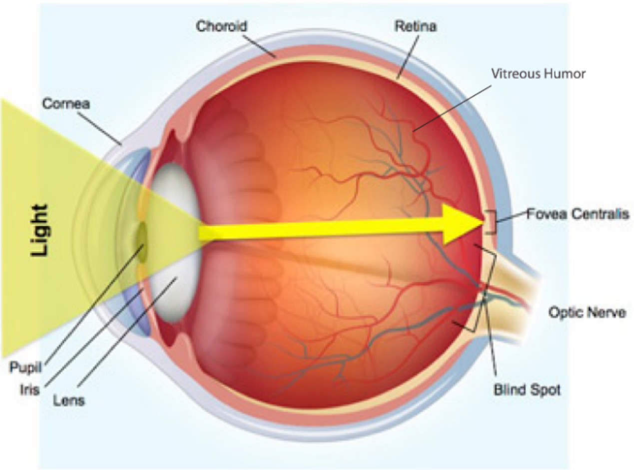
The gathering and focussing mechanism of light by the eye-lens is well described in the wave picture.





http://www.sightscience.com/wp-content/uploads/2017/07/structure-of-the-eye.png

But its absorption by the rods and cones (of the retina) requires the photon picture of light.

A natural question arises: If radiation has a dual (wave-particle) nature, should not the particles of nature (the electrons, protons, etc.) also exhibit wave-like character.why?

De Broglie Waves

In **1924,** the French physicist **Louis Victor de Broglie** (pronounced as de Broygali) (1892-1987) put forward the **bold hypothesis** that **moving particles of matter should display wave-like properties under suitable conditions.**

https://upload.wikimedia.org/wikipedia/commons/e/ed/Louis_de_Broglie.jpg

He reasoned that **nature was symmetrical and that the two basic physical entities – matter and energy, must have symmetrical character.**

a. **The whole universe is composed of matter and electromagnetic radiation. Since both are forms of energy so can be transformed into each other.**
b. **The matter loves symmetry. As the radiation has dual nature, matter should also possess dual character.**

According to the de Broglie concept of matter waves, matter has dual nature.

It means when the matter is moving it shows the wave properties (like interference, diffraction etc.) are associated with it and when it is in the state of rest then it shows particle properties.

Thus the matter has dual nature. The waves associated with moving particles are matter waves or de-Broglie waves.

De Broglie Wavelength

De Broglie proposed that the wavelength λ associated with a particle of momentum p is given as

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

Where m is the mass of the particle and v its speed.

This equation is known as the **de Broglie relation** and the wavelength λ of the matter is called **de Broglie wavelength.**

The dual aspect of matter is evident in the de Broglie relation.

On the left hand side of the equation λ is the attribute of a wave while on the right hand side the momentum p is a typical attribute of a particle.

Planck's constant h relates the two attributes.

Equation for a material particle is basically a hypothesis whose validity can be tested only by experiment. However, it is interesting to see that it is satisfied also by a photon. For a photon, as we have seen

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

Therefore

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

That is, the de Broglie wavelength of a photon given by

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

equals the wavelength of electromagnetic radiation of which the photon is a quantum of energy and momentum.

Clearly, from de Broglie equation λ is smaller for

- a heavier particle (large m) or
- more energetic particle (large v).

Example

Calculate the de Broglie wavelength of a ball of mass 0.12 kg moving with a speed of 20 m s^{-1}

Solution

$$p = mv = 0.12kg \times 20ms^{-1} = 2.40\ kg\ m\ s^{-1}$$

$$\lambda = \frac{h}{p} = \frac{6.63\times10^{-34} Js}{2.40 kgms^{-1}} = 2.76\times10^{-34} m$$

This wavelength is so small that it is beyond any measurement.

This is the reason why macroscopic objects in our daily life do not show wave-like properties.

On the other hand, in the sub-atomic domain, the wave character of particles is significant and measurable.

Consider an electron (mass (m), charge (e)) accelerated from rest through a potential V. The kinetic energy K of the electron equals the work done (eV) on it by the electric field:

$$KE = e\,V$$

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

$$p = \sqrt{2m\,KE} = \sqrt{2m\,e\,V}$$

The de Broglie wavelength λ of the electron is then

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2\,m\,KE}} = \frac{h}{\sqrt{2m\,e\,V}}$$

Substituting the values of h, m and e, we get

$$\lambda = \frac{1.227}{\sqrt{V}}\,nm$$

Where V is the magnitude of accelerating potential in volts.

For a 120 V accelerating potential, we get λ = 0.112 nm.

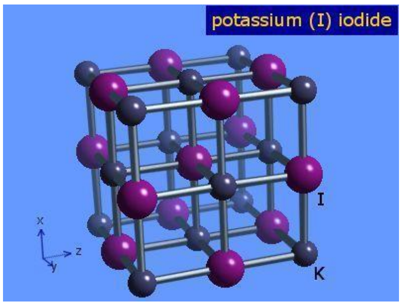
This wavelength is of the same order as the spacing between the atomic planes in crystals.

Think About These

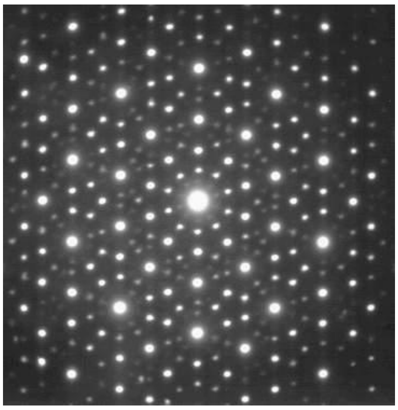
- **The wavelength of a moving particle is inversely proportional to its momentum. If velocity is zero, or the particle is stationary, λ is infinite.**
- **To be associated with a de Broglie wave, particles need not be charged. Hence the waves are called matter waves.**
- **de Broglie waves are not electromagnetic in nature, because em waves are due to accelerated charged particles.**
- **De Broglie waves are not associated with frequency.**
- **The de Broglie wavelength is independent of the material of the particle, so a 50 g tomato will have the same wavelength as a 50 g pebble if the two were to move with the same speed.**
- **Wavelength is inversely proportional to mass. Hence the wavelength is significantly measurable only in the case of subatomic particles, like electrons and protons, as their masses are very small.**
- **The de Broglie wavelength, for large moving masses, would be very small. Hence macroscopic objects, in daily life, do not exhibit wave-like properties of interference and diffraction.**

How was the idea of De Broglie waves proved?

To help you imagine the planar arrangement of atoms in a crystal, a model of potassium iodide is shown.



This suggests that matter waves associated with an electron could be verified by crystal diffraction experiments analogous to X-ray diffraction.



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Diffraction refers to various phenomena that occur when a wave encounters an obstacle or a slit. It is defined as the bending of light around the corners of an obstacle or aperture into the region of geometrical shadow of the obstacle.

In classical physics, **the diffraction phenomenon is described as the interference of waves according to the Huygens principle**.

These characteristic behaviours are exhibited when a wave encounters an obstacle or a slit that is comparable in size to its wavelength.

Similar effects occur when a light wave travels through a medium with a varying refractive index, or when a sound wave travels through a heterogeneous medium.

Diffraction occurs with all waves, **including sound waves, water waves, and electromagnetic waves such as visible light, X-rays and radio waves**.

X-ray crystallography is a technique used for determining the atomic and molecular structure of a crystal, in which the crystalline atoms cause a beam of incident X-rays to diffract into many specific directions.

By measuring the angles and intensities of these diffracted beams a crystallographer can produce a three-dimensional picture of the density of electrons within the crystal.

From this electron density, the mean positions of the atoms in the crystal can be determined, as well as their chemical bonds, their disorder, and various other information.

Since many materials can form crystals—such as salts, metals, minerals, semiconductors, as well as various inorganic, organic, and biological molecules

We describe the **experimental verification** of the de Broglie hypothesis in the next section.

In **1929**, de Broglie was awarded **the Nobel Prize in Physics for his discovery of the wave nature of electrons.**

The matter-wave picture elegantly incorporated Heisenberg's **uncertainty principle**.

Heisenberg's Uncertainty Principle

According to the principle,

It is not possible to measure both the position and momentum of an electron (or any other particle) at the same time exactly. There is always some uncertainty (Δx) in the specification of position and some uncertainty (Δp) in the specification of momentum.

The product of Δx and Δp is h/2π,

$$\Delta x \Delta p \approx \frac{h}{2\pi}$$

allows the possibility that Δx is zero; but then Δp must be infinite in order that the product is non-zero. Similarly, if Δp is zero, Δx must be infinite.

Ordinarily, both Δx and Δp is non-zero such that their product is of the order of ħ (10^{-34})

Now, if an electron has a definite momentum p, (i.e. Δp = 0), by the de Broglie relation, it has a definite wavelength λ.

A wave of definite (single) wavelength extends all over space. Iits position uncertainty is infinite ($\Delta x \rightarrow \infty$), which is consistent with the uncertainty principle.

In general, the matter wave associated with the electron is not extended all over space.

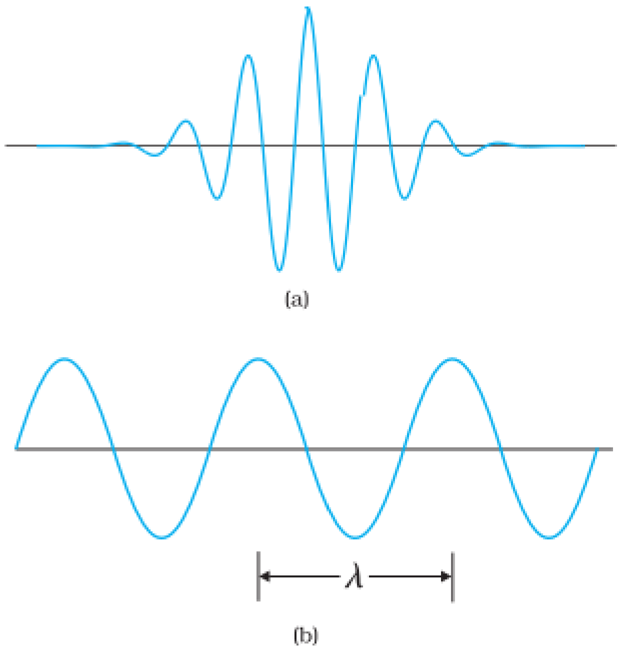
It is a wave packet extending over some finite region of space. In that case Δx is not infinite but has some finite value depending on the extension of the wave packet. Also, you must appreciate that a wave packet of finite extension does not have a single wavelength. It is built up of wavelengths spread around some central wavelength.

By de Broglie's relation, then, the momentum of the electron will also have a spread – an uncertainty Δp. This is as expected from the uncertainty principle.

It can be shown that the wave packet description together with de Broglie relation and probability interpretation reproduce Heisenberg's uncertainty principle exactly.

The figure shows a schematic diagram of

i. **A localised wave packet, and**
ii. **An extended wave with fixed wavelength.**



i. The wave packet description of an electron. The wave packet corresponds to a spread of wavelength around some central wavelength (and hence by de Broglie relation, a spread in momentum). Consequently, it is associated with an uncertainty in position (Δx) and an uncertainty in momentum (Δp).
ii. The matter wave corresponding to a definite momentum of an electron extends all over space. In this case, Δp = 0 and Δ x → ∞.

Example

What is the de Broglie wavelength associated with

a. An electron moving with a speed of 5.4×10^{6} m/s, and

b. A ball of mass 150 g travelling at 30.0 m/s?

Solution

a. For the electron:

Mass $m = 9.11\times10^{-31}$ kg, speed $v = 5.4\times10^{-6}$ m/s. Then the momentum

$p = mv = 9.11\times10^{-31}(kg) \times 5.4\times10^{-6}\ (m/s)$

$p = 4.92\times10^{-24}$ kg m/s

de Broglie wavelength, $\lambda = h/p$

$$= \frac{6.63\times10^{-34} Js}{4.92\times10-24\ kg\ m/s}$$

$$\lambda\ =\ 0.135\ nm$$

b. For the ball:

Mass m'= 0.150 kg, speed v' = 30.0 m/s

The momentum p'= 4.50 kg m/s

de Broglie wavelength $\lambda' = h/p' = \frac{6.63\times10^{-34} Js}{4.50\ kg\ m/s} = \mathbf{1.47\times10^{-34}\ m}$

The de Broglie wavelength of electrons is comparable with X-ray wavelengths. However, for the ball it is about 10 $^{-19}$ times the size of the proton, quite beyond experimental measurement.

Example

An electron, an α-particle, and a proton have the same kinetic energy. Which of these particles has the shortest de Broglie wavelength?

Solution

For a particle, de Broglie wavelength, $\lambda = h/p$

Kinetic energy, $K\ = \frac{p^2}{2m}$

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

For the same kinetic energy K, the de Broglie wavelength associated with the particle is inversely proportional to the square root of their masses.

A proton ${}^{1}_{1}H$ is 1836 times massive than an electron and an α-particle ${}^{4}_{2}He$four times that of a proton.

Hence, α – particle has the shortest de Broglie wavelength.

Example

A particle is moving three times as fast as an electron. The ratio of the de Broglie wavelength of the particle to that of the electron is 1.813×10^{-4}.

Calculate the particle's mass and identify the particle.

Solution

de Broglie wavelength of a moving particle, having mass m and velocity v:

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

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

For an electron , mass $m_e = \frac{h}{\lambda_e v_e}$

Now $\frac{v}{v_e} = 3$ and $\frac{\lambda}{\lambda_e} = 1.813 \times 10^{-4}$

Then, mass of the particle $m = m_e \left(\frac{\lambda_e}{\lambda}\right)\left(\frac{v_e}{v}\right)$

$$m = \left(9.11 \times 10^{-31} kg\right) \times \left(\frac{1}{3}\right) \times \left(\frac{1}{1.813 \times 10^{-4}}\right)$$

m = 1.675 x 10^{-27} kg

Thus the particle with this mass is either a proton or a neutron.

Example

What is the de Broglie wavelength associated with an electron, accelerated through a potential difference of 100 volts?

Solution

Accelerating potential = 100 V

$$\lambda = \frac{h}{p} = \frac{1.227}{\sqrt{V}} nm = \frac{1.227}{\sqrt{100}} nm = 0.1227\ nm$$

The de Broglie wavelength of the electrons is same as that of x rays

Now Try These

i) Calculate

(a) momentum, and

(b) de Broglie wavelength

of the electrons accelerated through a potential difference of 56 V.

ii) **Determine**

(a)momentum,

(b) speed, and

(c) de Broglie wavelength

of an electron with kinetic energy of 120 eV.

iii) **The wavelength of light from the spectral emission line of sodium is 589 nm. Find the kinetic energy at which**

a. **An electron, and**
b. **A neutron would have the same de Broglie wavelength.**

iv) **What is the de Broglie wavelength of**

a. **A bullet of mass 0.040 kg travelling at the speed of 1.0 km/s,**
b. **A ball of mass 0.060 kg moving at a speed of 1.0 m/s, and**
c. **Adust particles of mass 1.0×10^{-9} kg drifting with a speed of 2.2 m/s?**

v) **An electron and a photon each have a wavelength of 1.00 nm. Find**

a. **Their momenta,**
b. **The energy of the photon, and**
c. **The kinetic energy of electrons.**

vi) **(a) For what kinetic energy of a neutron will the associated de Broglie wavelength be 1.40×10^{-10} m?**

(b) Also find the de Broglie wavelength of a neutron, in thermal equilibrium with matter, having an average kinetic energy of (3/2) k T at 300 K.

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

viii) **What is the de Broglie wavelength of a nitrogen molecule in air at 300 K? Assume that the molecule is moving with the root-mean square speed of molecules at this temperature. (Atomic mass of nitrogen = 14.0076 u)**

Hint: mass of nitrogen i.e. N_2 molecule = $2 \times 14.0076 \times 1.66 \times 10^{-27}$kg

$= 46.5 \times 10^{-27}$ kg

Temperature = 300 k

Average kinetic energy

$$\frac{1}{2}mc^2 = \frac{3}{2}kT = \sqrt{\frac{3kT}{m}}$$

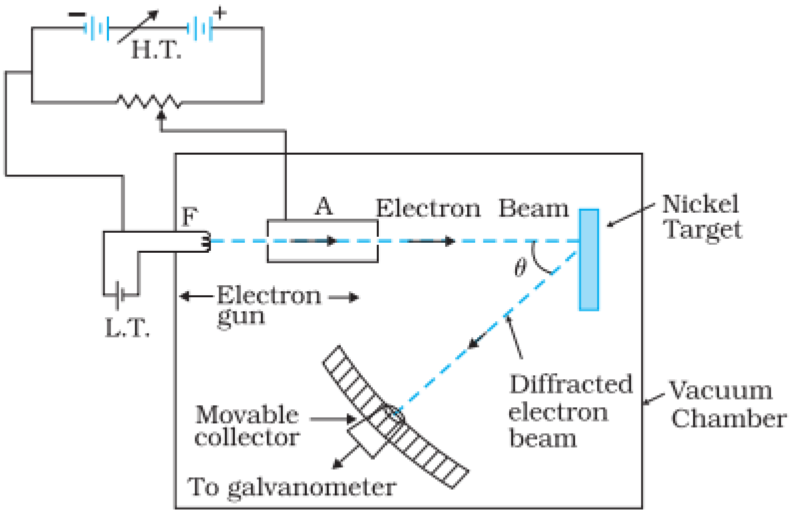
$$\lambda = \frac{h}{mc} = \frac{h}{\sqrt{3mkT}} = \frac{6.63\times10^{-34}}{\sqrt{3\times46.5\times10^{-27}\times12.38\times10^{-23}\times300}} m = 0.0276\times10^{-9} m = 0.028 \ nm$$

Davisson and Germer Experiment and its Importance

The wave nature of electrons was first experimentally verified by C.J. Davisson and L.H. Germer in 1927 and independently by G.P. Thomson, in 1928, who observed diffraction effects with beams of electrons scattered by crystals.

Davisson and Thomson shared the Nobel Prize in 1937 for their **experimental discovery of diffraction of electrons by crystals.**

The experimental arrangement used by Davisson and Germer is schematically shown in Fig. 11.7. It consists of an electron gun which comprises a tungsten filament F coated with barium oxide and heated by a low voltage power supply (L.T. or battery). Electrons emitted by the filament are accelerated to a desired velocity.



by applying suitable potential/voltage from a high voltage power supply (H.T. or battery). They are made to pass through a cylinder with fine holes along its axis, producing a fine collimated beam.

The beam is made to fall on the surface of a nickel crystal. The electrons are scattered in all directions by the atoms of the crystal. The intensity of the electron beam scattered in a given direction is measured by the electron detector (collector). The detector can be moved on a circular scale and is connected to a sensitive galvanometer, which records the current. The deflection of the galvanometer is proportional to the intensity of the electron beam entering the collector.

The apparatus is enclosed in an evacuated chamber. By moving the detector on the circular scale at different positions, the intensity of the scattered electron beam is measured for different values of **angle of scattering** θ which is the angle between the incident and the scattered electron beams.

The variation of the intensity (I) of the scattered electrons with the angle of scattering θ is obtained for different accelerating voltages. The experiment was performed by varying the accelerating voltage from 44 V to 68 V.

It was noticed that a strong peak appeared in the intensity (I) of the scattered electron for an accelerating voltage of 54V at a scattering angle θ = 50º The appearance of the peak in a particular direction is due to the constructive interference of electrons scattered from different layers of the regularly spaced atoms of the crystals. From the electron diffraction measurements, the wavelength of matter waves was found to be 0.165 nm.

The de Broglie wavelength λ associated with electrons, using, for V = 54 V is given by

$$\lambda = \frac{h}{p} = \frac{1.227}{\sqrt{V}} nm$$

$$\lambda = \frac{1.227}{\sqrt{54}} nm = 0.167\, nm$$

Thus, there is an **excellent agreement** between the theoretical value and the experimentally obtained value of de Broglie wavelength.

The Davisson Germer experiment thus strikingly confirms the wave nature of electrons and the de Broglie relation. More recently, in **1989**, the wave nature of a beam of electrons was experimentally demonstrated in a double-slit experiment, similar to that used for the wave nature of light.

Also, in an experiment in **1994**, interference fringes were obtained with the beams of iodine molecules, which are about a million times more massive than electrons.

The de Broglie hypothesis has been basic to the development of modern quantum mechanics. It has also led to the field of electron optics. The wave properties of electrons have been utilised in the design of electron microscope which is a great improvement, with higher resolution, over the optical microscope.

The History of Wave-Particle Flip-Flop

We are now in a position to appreciate the development of explanations of phenomena associated with light.

What is light?

This question has haunted mankind for a long time. But systematic experiments have been done by scientists since the dawn of the scientific and industrial era, about four centuries ago. Around the same time, theoretical models about what light is made of were developed. While building a model in any branch of science, it is essential to see that it is able to explain all the experimental observations existing at that time.

It is therefore appropriate to summarize some observations about light that were known in the seventeenth century.

The properties of light known at that time included

a) rectilinear propagation of light,
b) reflection from plane and curved surfaces,
c) refraction at the boundary of two media,
d) dispersion into various colours,
e) high speed. Appropriate laws were formulated for the first four phenomena.

For example, Snell formulated his laws of refraction in 1621.

Several scientists right from the days of Galileo had tried to measure the speed of light. But they had not been able to do so. They had only concluded that it was higher than the limit of their measurement.

Two models of light were also proposed in the seventeenth century.

Descartes, in the early decades of the seventeenth century, proposed that light consists of particles, while Huygens, around **1650-60**, proposed that light consists of waves.

Descartes′ proposal was merely a philosophical model, devoid of any experiments or scientific arguments. Newton soon after, around 1660-70, extended Descartes′ particle model, known as corpuscular theory, built it up as a scientific theory, and explained various known properties with it.

These models, light as waves and as particles, in a sense, are quite opposite of each other. But both models could explain all the known properties of light. There was nothing to choose between them.

The history of the development of these models over the next few centuries is interesting.

Bartholinus, in **1669**, discovered double refraction of light in some crystals, and Huygens, in **1678,** was quick to explain it on the basis of his wave theory of light.

In spite of this, for over one hundred years, Newton's particle model was firmly believed and preferred over the wave model. This was partly because of its simplicity and partly because of Newton's influence on contemporary physics.

Then in **1801**, Young performed his double-slit experiment and observed interference fringes. This phenomenon could be explained only by wave theory. It was realized that diffraction was also another phenomenon which could be explained only by wave theory. In fact, it was a natural consequence of Huygen's idea of secondary wavelets emanating from every point in the path of light. These experiments could not be explained by assuming that light consists of particles. Another phenomenon of polarisation was discovered around 1810, and this too could be naturally explained by the wave theory. Thus wave theory of Huygens came to the forefront and Newton’s particle theory went into the background.

This situation again continued for almost a century.

Better experiments were performed in the nineteenth century to determine the speed of light. With more accurate experiments, a value of 3×10^{8} m/s for speed of light in vacuum was arrived at.

Around **1860**, Maxwell proposed his equations of electromagnetism and it was realized that all electromagnetic phenomena known at that time could be explained by Maxwell’s four equations. Soon Maxwell showed that electric and magnetic fields could propagate through empty space (vacuum) in the form of electromagnetic waves. He calculated the speed of these waves and arrived at a theoretical value of 2.998×10^{8} m/s. The close agreement of this value with the experimental value suggested that light consists of electromagnetic waves.

In **1887** **H**ertz demonstrated the generation and detection of such waves. This established the wave theory of light on a firm footing.

We might say that while eighteenth century belonged to the particle model, the nineteenth century belonged to the wave model of light

Many experiments were done during the period **1850-1900** on heat and related phenomena, an altogether different area of physics. Theories and models like kinetic theory and thermodynamics were developed which quite successfully explained the various phenomena, except one

Everybody at any temperature emits radiation of all wavelengths. It also absorbs radiation falling on it. A body which absorbs all the radiation falling on it is called a black body. It is an ideal concept in physics, like concepts of a point mass or uniform motion. A graph of the intensity of radiation emitted by a body versus wavelength is called the black body spectrum. No theory in those days could explain the complete black body spectrum! In 1900, Planck hit upon a novel idea. If we assume, he said, that radiation is emitted in packets of energy instead of continuously as in a wave, then we can explain the black body spectrum. Planck himself regarded these quanta, or packets, as a property of emission and absorption, rather than that of light. He derived a formula which agreed with the entire spectrum.

This was a confusing mixture of wave and particle pictures – radiation is emitted as a particle, it travels as a wave, and is again absorbed as a particle! Moreover, this put physicists in a dilemma. Should we again accept the particle picture of light just to explain one phenomenon? Then what happens to the phenomena of interference and diffraction which cannot be explained by the particle model?

But soon in **1905**, **Einstein** explained the photoelectric effect by assuming the particle picture of light. In **1907**, Debye explained the low temperature specific heats of solids by using the particle picture for lattice vibrations in a crystalline solid. Both these phenomena belonging to widely diverse areas of physics could be explained only by the particle model and not by the wave model.

In **1923**, Compton's x-ray scattering experiments from atoms also went in favour of the particle picture. This increased the dilemma further.

Thus by **1923,** physicists faced with the following situation

a) There were some phenomena like rectilinear propagation, reflection, refraction, which could be explained by either particle model or by **wave model.**
b) There were some phenomena such as diffraction and interference which could be explained only by the wave model but not by the **particle model.**
c) There were some phenomena such as black **body radiation, photoelectric effect, and Compton scattering** which could be explained only by the **particle model** but not by the wave model.

In **1924**, de Broglie proposed his theory of **wave-particle duality** in which he said that not only photons of light but also 'particles' of matter such as electrons and atoms possess a dual character, sometimes behaving like a particle and sometimes as a wave. He gave a formula connecting their mass, velocity, momentum (particle characteristics), with their wavelength and frequency (wave characteristics)!

In **1927** Thomson, and Davisson and Germer, in separate experiments, showed that electrons did behave like waves with a wavelength which agreed with that given by de Broglie's formula. Their experiment was **on diffraction of electrons through crystalline solids**, in which the regular arrangement of atoms acted like a grating. Very soon, diffraction experiments with other 'particles' such as neutrons and protons were performed and these too confirmed with de Broglie's formula. This confirmed wave-particle duality as an established principle of Physics. Here was a principle, physicists thought, which explained all the phenomena mentioned above not only for light but also for the so-called particles. But there was no basic theoretical foundation for wave-particle duality. De Broglie's proposal was merely a qualitative argument based on the symmetry of nature. Wave-particle duality was at best a principle, not an outcome of a sound fundamental theory.

It is true that all experiments agree with de Broglie formula.

But physics does not work that way.

On the one hand, it needs experimental confirmation, while on the other hand, it also needs a sound theoretical basis for the models proposed. This was developed over the next two decades.

Dirac developed his theory of radiation in about **1928**, and Heisenberg and Pauli gave it a firm footing by **1930**. Tomonaga, Schwinger, and Feynman, in the late **1940s**, produced further refinements and cleared the theory of inconsistencies which were noticed. All these theories mainly put wave-particle duality on a theoretical footing.

Although the story continues, it grows more and more complex and beyond the scope of this note. But we have here the essential structure of what happened, and let us be satisfied with it at the moment.

Now **it is regarded as a natural consequence of present theories of physics that electromagnetic radiation as well as particles of matter exhibit both wave and particle properties in different experiments, and sometimes even in the different parts of the same experiment.**

Summary

In this module we have learnt:

- Radiation has a dual nature: wave and particle. The nature of experiment determines whether a wave or particle description is best suited for understanding the experimental result. Reasoning that radiation and matter should be symmetrical in nature, Louis Victor de Broglie attributed a wave-like character to matter (material particles). The waves associated with the moving material particles are called matter waves or de Broglie waves.
- The de Broglie wavelength (λ) associated with a moving particle is related to its momentum p as: $\lambda = h/p$. The dualism of matter is inherent in the de Broglie relation which contains a wave concept (λ) and a particle concept (p). The de Broglie wavelength is independent of the charge and nature of the material particle. It is significantly measurable (of the order of the atomic-planes spacing in crystals) only in

case of sub-atomic particles like electrons, protons, etc. (due to smallness of their masses and hence, momenta). However, it is indeed very small, quite beyond measurement, in the case of macroscopic objects, commonly encountered in everyday life.

- Electron diffraction experiments by Davisson and Germer, and by G. P. Thomson, as well as many later experiments, have verified and confirmed the wave-nature of electrons. The de Broglie hypothesis of matter waves supports the Bohr 's concept of stationary orbits.

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