G.C.E. (Advanced Level)

Physics

Grade 13
Resource Book
Unit 11

Matter and Radiation

Department of Science
Faculty of Science and Technology
National Institute of Education
Maharagama
www.nie.lk

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Message from the Director General

The National Institute of Education takes opportune steps from time to time for the development of quality in education. Preparation of supplementary resource books for respective subjects is one such initiative.

Supplementary resource books have been composed by a team of curriculum developers of the National Institute of Education, subject experts from the national universities and experienced teachers from the school system. These resource books have been written in line with the G. C. E. (A/L) new syllabus implemented in 2017, so that students can broaden their understanding of the subject matter by referring to these books and teachers can refer to them in order to plan more effective learning teaching activities.

I wish to express my sincere gratitude to the staff members of the National Institute of Education and external subject experts who made their academic contribution to make this material available to you.

Dr. Sunil Jayantha Nawarathna
Director General
National Institute of Education
Maharagama.

Message from the Director

Since 2017, a rationalized curriculum, which is an updated version of the previous curriculum has been in effect for the G.C.E (A/L) in the general education system of Sri Lanka. In this new curriculum cycle, revisions were made in the subject content, mode of delivery and curricular materials of the G.C.E. (A/L) Physics, Chemistry and Biology. Several alterations in the learning teaching sequence were also made. A new Teachers' Guide was introduced in place of the previous Teacher's Instruction Manual. In concurrence with that, certain changes in the learning teaching methodology, evaluation and assessment are expected. The newly introduced Teachers' Guide provides the expected learning outcomes, a guideline for teachers to mould the learning events, assessment and evaluation.

When implementing the previous curricula, the use of internationally recognized standard textbooks published in English was imperative for the Advanced Level science subjects. Due to the contradictions of facts related to the subject matter among different textbooks and inclusion of the content beyond the limits of the local curriculum, the usage of those books was not convenient for both teachers and students. This book comes to you as an attempt to overcome that issue.

As this book is available in Sinhala, Tamil, and English, the book offers students an opportunity to refer to the relevant subject content in their mother tongue as well as in English within the limits of the local curriculum. It also provides both students and teachers a source of reliable information expected by the curriculum instead of varied information gathered from the other sources.

This book authored by subject experts from the universities and experienced subject teachers is presented to you followed by the approval of the Academic Affairs Board and the Council of the National Institute of Education. Thus, it can be recommended as material of a high standard.

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Content

Chapter one

Quantum nature of radiation

1.1 Thermal radiation

As we know, the transfer of heat by conduction and convection requires a material medium or substance acting as a propulsive medium. However, an enormous amount of heat reaches the earth after travelling a distance of about $1 \cdot 49 \times 10^{11}\,\text{m}$ through empty space without any matter. This process of transfer of energy without involving any material medium is known as thermal radiation.

All objects radiate heat. When the temperature of an object increases, the amount of energy flown out from that object per second, also increases. When we get closer to a fire, we sense the warmth of it due to the transfer of heat by radiation. There the temperature of heat due to conduction is negligible as air is a bad conductor. Convection does not transfer heat downwards or sideways.

Visible light and heat emitted by a filament lamp, transfer mainly by the process of radiation. When the tungsten filament in the lamp gets heated and becomes white-hot, it emits visible light and heat, which then come out passing through the vacuum inside the bulb. The radiation we get from the sun consists of visible light (about 47%), infra-red radiation (about 45%), and ultraviolet radiation (about 8%).

In 1862, James Clark Maxwell showed that visible light, infra-red radiation and ultraviolet radiation are components of the electromagnetic spectrum. Another important matter he discovered was that, when an electric current flowing through a wire is changing through the electromagnetic waves radiate out from that wire. It means that electromagnetic waves can be produced by accelerating or decelerating charged particles.

Figure 1.1 James Clark Maxwell

1.2 Basic properties of thermal radiation

The emission of electromagnetic radiation due to the temperature of a hot body is known as thermal (heat) radiation.

- No material medium is necessary for the propagation of thermal radiation.
- It travels in free space with a velocity which is equal to the velocity of light.
- It gets reflected by shiny surfaces and obeys the laws of reflection.
- It undergoes refraction when passing through different media.
- The intensity of radiation is inversely proportional to the square of the distance from the source.
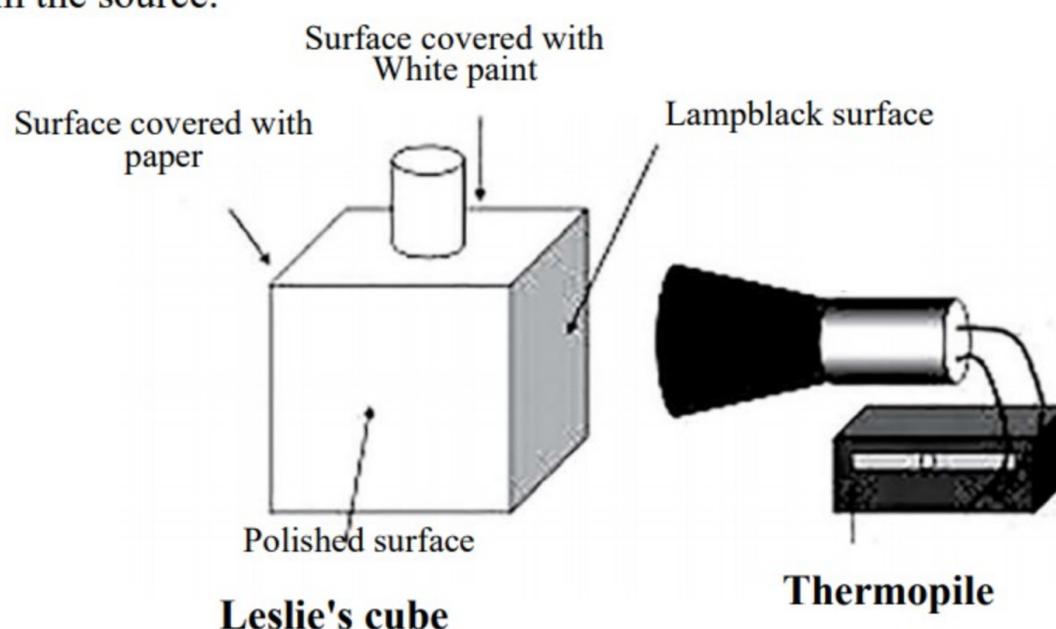

Figure 1.2 Leslie's cube and thermopile

The rate of emission of heat from a hot body depends mainly on the following factors.

- Temperature of the body
- Nature of the surface of the body
- Surface area of the body

These factors can be demonstrated using the Leslie's cube and the thermopile as shown in Figure 1.2. The Leslie's cube is a hollow cube made of metal and is used to compare emissivities of heat of different material. The thermopile is used to measure the rate of heat radiation emitted by each surface of the Leslie's cube. The thermopile is made by connecting a number of thermocouples in series.

Suppose that three vertical faces of the Leslie's cube are covered with lampblack, white paint and paper separately, and the remaining vertical surface is made highly polished and the Leslie's cube is now filled with boiling water and the thermopile is placed at the same distance from each surface in turn. In each case, the relevant galvonometer reading of it is recorded and from those readings it is observed that out of the four surfaces at the same temperature, the surface covered with lampblack radiates heat the most and the surface which is polished radiates heat the least.

The above experiment is repeated with several Leslie's cubes of different size, all having the same nature of surface and all filled with boiling water. It is clear from the observations that the rate of radiation depends on the surface area. By repeating this experiment, with the Leslie's cube filling with hot water at different temperatures, one at a time, the observations show that the rate of emission of radiation also depends on the temperature.

Crooke's radiometer

This is an apparatus used to demonstrate thermal radiation. A small windmill with four vertical vanes of mica is mounted inside a glass bulb so that it can spin about a vertical axis. One face of each vane is blackened and the other surface is made shiny. Inside the bulb there is air at a low pressure. The blackened faces absorb more radiation than the polished faces, and therefore the black faces are always hotter than the polished faces. Hence, air molecules colliding with the black faces rebound at a higher average velocity than that with the polished faces. As a result, there is a reaction causing the mill to spin with the polished faces at the lead.

Figure 1.3

Crooke's radiometer

1.3   Thermal equilibrium

Our usual experience is that, hot bodies radiate heat. We can realize it when going near a fire or bringing hands closer to a highly heated piece of metal. The theory of heat exchange, which was introduced by Prevost in 1791, says that thermal radiation occurs from an object at any temperature. According to that theory, the rate of radiation increases when the temperature increases.

Figure 1.4 shows a box (B) which has been evacuated by connecting to a vacuum pump. A small body A, at temperature T_A is suspended by a non-conducting thread inside the box B of which the walls are at a different **constant** temperature T_B.

The energy exchange between A and B can occur only by radiation because the box B has been evacuated. If $T_A > T_B$ temperature of A fall down to T_B and if $T_A < T_B$ temperature of A rise upto T_B. In both cases, it seems that heat exchange stops after reaching a condition where the temperatures of both A and B are equal.

According to Prevost's theory of heat exchanges, on both these occasions, both objects radiate heat. In the case where $T_A < T_B$, B radiates more than A radiates.
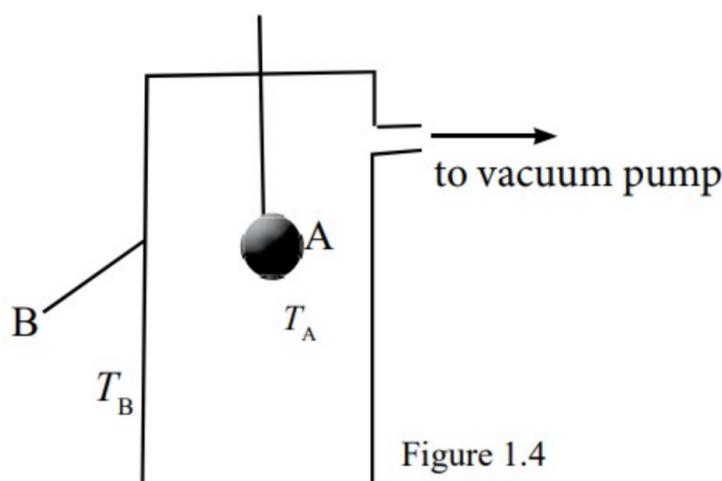
to vacuum pump

T_A

B

T_B

Figure 1.4

Therefore, the resultant radiation occurs from B to A. Due to this, the temperature of A gradually increases and therefore the radiation emitted by A also increases. When the temperature of A reaches the temperature of B, the resultant exchange of heat becomes zero, as the amounts of radiation emitted by A and B are now equal, and therefore the rising of temperature of A stops.

In the case where $T_A > T_B$, A radiates more than B radiates. Therefore, the resultant radiation occurs from A to B. So the temperature of A and the radiation emitted by A decrease gradually. When the temperature of A reaches the temperature of B the amounts of radiation emitted by A and B become equal, and therefore the decreasing of temperature of A stops.

According to this, when the temperature of an object is equal to the temperature of its surroundings, a dynamic equilibrium state is reached as the rate of radiation emitted by the object to the surroundings becomes equal to the rate of radiation absorbed by the object from the surroundings. The heat exchange still takes place and its rate depends on the temperature.

1.4   Black body radiation

An object appears to be black as it absorbs almost totally the various radiation of various wavelengths (of various colours) falling on it. A body having surfaces which totally absorb all the radiation of all the wavelengths falling on it, is defined as a black body.

A black body can be made practically as shown by Figure 1.5. There it shows a shell with a spherical cavity and a tiny hole. The inner surface of the shell has been blackened by applying soot. Any radiation entering the cavity through the hole undergoes several reflections. In each reflection some part of the radiation is absorbed and after several reflections the radiation is absorbed totally. There is a small conical part embossed facing the hole,   so as to prevent backward reflection and escape of the ray which enters perpendicular to the hole. Since all the rays entering in are absorbed by the inner surface of the cavity, the hole can be considered as a black body. In this manner, if a radiation of any wavelength entering through the hole is totally absorbed by the inner surface then that hole acts as a black body.

Figure 1.5
Model of a black body

A surface which absorbs thermal radiation well also radiates them out well. If a black body is heated to a very high temperature then it emits all types of radiation which it was able to absorb.

The intensity of radiation emitted by a black body depends only on its temperature. The energy carried by the radiation does not distribute equally in the range of wavelengths. When the temperature of the radiating source changes this distribution also changes. When the temperature increases the energy radiated by short waves, also increases. The

following experience will clarify it. When a piece of steel is heated, initially it begins to glow a gloomy red and when heated furthermore it glows an orange-red. Figure 1.6 shows how the intensity of radiation emitted per unit time (E_λ) vary with the wavelength (λ). It also shows that the peak values of the distribution curves corresponding to individual temperatures, get shifted towards shorter wavelengths as temperature increases.

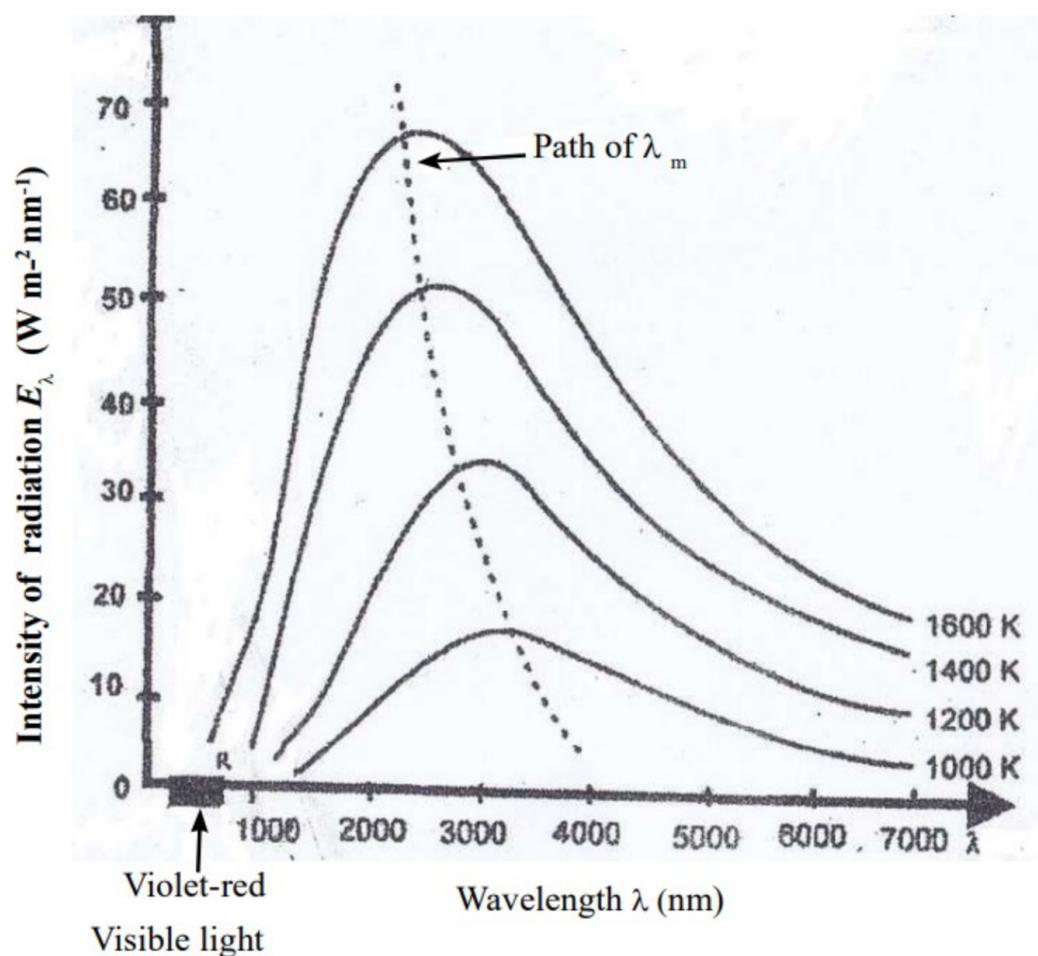**Intensity distribution of black body radiation**

Figure 1.6 Variation of E_λ with λ in black body radiation

According to the above graphs,

- When the wavelength increases starting from a shorter value, initially E_λ increases and comes to a maximum at a particular wavelength (λ_m). When the wavelength increases furthermore E_λ decreases gradually.

- When the temperature of the body (T) increases, E_λ also increases at all wavelengths.

- At high temperatures a certain amount of visible light is also emitted by the black bodies.

- At each temperature (T), the intensity at which radiation is emitted (E_λ) comes to a maximum at a particular wavelength (λ_m)

The dotted line in Figure 1.6 shows how the peak values of E_λ that is ($E_{\lambda\,m}$) vary with temperature. The area under the curve relevant to each temperature, represents the total radiant power (of all wavelengths emitted) from the black body at that temperature.

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1.5 Wien's displacement law

In the spectral distribution of black body radiation, the product of the wavelength relevant to the maximum intensity and the relevant absolute temperature is constant.

$$\lambda_m T = C \ (C \text{ is a constant})$$

The value of this constant is 2.898×10^{-3} m K

This law could not be explained until Einstein came up with his photon theory of radiation. This law is used by the astronomers to determine the temperature of stars. Using Wien's law, the temperature of the sun and other stars can be estimated.

If the wavelength value $\lambda_m = 475$ nm corresponding to the maximum intensity of the sun's radiation, let us calculate the surface temperature of the sun.

According to Wien's displacement law,

$$\lambda_m T = C$$ Substituting the value 2.898×10^{-3} m K of Wien's constant,

$$T = \frac{2 \cdot 898 \times 10^{-3} \text{ m K}}{475 \times 10^{-9} \text{ m}} = 6101.053 \text{ K}$$

Accordingly, the temperature of the surface of the sun should be about 6101 K.

Stars and filament lamps, both behave as black body radiators. Colours of the stars are related to their temperatures. A red colour star which has a wavelength of about 700 nm corresponding to the maximum intensity, has a temperature of about 4100 K.

1.6 Stefan's law

The total power radiated from a unit area of a hot black body is directly proportional to the fourth power of the absolute temperature of the body.

$E = \sigma T^4$ (σ is the proportionality constant. It is known as Stefan's constant)

$$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

The measuring unit of E is Joule per second per square meter (J s^{-1} m^{-2}) or Watt per square meter (W m^{-2}).

The total radiant energy emitted per second by a surface area A of a black body with temperature T is given by,

$P = A \ \sigma \ T^4$ Here, unit of the P is Watt (W).

1.7 Emissivity of a surface

The emissivity (*e*) of a surface indicates how good it is at radiating heat. The value of *e* is expressed as a value relative to a black body.

$$e = \frac{\text{the radiant energy emitted by a unit surface area per second}}{\begin{array}{l}\text{the radiant energy emitted per second by a unit surface area of a black body under}\\ \text{the same temperature}\end{array}}$$

According to this definition, the value of *e* for a black body is 1.

A black body cannot be found in nature. It is only a concept. The rate of emission of radiation by the surface of any real (practical) object at a given temperature is less than that by a black body at the same temperature. Therefore, the emissivity of a real object is always less than 1. The emissivity of a black rough surface is much closer to 1 and that of a heavily polished surface is much less than 1.

1.8 Absorptivity of a surface

The absorptivity (*a*) of a surface indicates what amount of energy out of the radiant energy falling on it, is absorbed by the surface.

$$a = \frac{\text{radiant energy absorbed by a surface within a given length of time}}{\text{radiant energy falling on that surface within the same length of time}}$$

Modification of Stefan's law for non-black bodies

The total radiant energy emitted per second by a unit surface area of a non-black body at temperature *T* and having emissivity of the surface *e*, is given by,

$$E = e\,\sigma T^4$$

The total radiant energy emitted per second by a surface area A of a non-black body at temperature *T* and having emissivity of the surface *e*, is given by,

$$P = e\,A\sigma T^4$$

When a normal filament lamp is in operation its (filament) temperature is about 3000 K. If the surface area of the filament is 0.3 cm² and its emissivity is 0.4, the energy radiated per second can be calculated as follows.

According to Stefan's law, the total power (*E*) radiated by a unit area of a black body is given by $E = \sigma T^4$. If the area of the filament is *A*, under the assumption that the filament is a black body, the total radiant power,

$$P = \sigma A T^4$$

by substituting the values given above,

$$P = (5 \cdot 67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4}) \times (0.3 \times 10^{-4} \text{ m}^2) \times (3000 \text{ K})^4$$

$$= 137.78 \text{ W}$$

Since the emissivity of the filament is 0.4 the rate at which it radiates energy is,

$$P = \sigma A T^4$$

$$= 0.4 \times 137 \cdot 78 \text{ W}$$

$$= \underline{55 \text{ W}}$$

Now consider a situation where a black body at a constant absolute temperature T, is hung in an enclosure at a constant absolute temperature T_0. Let us assume that $T > T_0$ and the surface area of the body is A. Then the rate of energy radiation of the body is $\sigma A T^4$. While radiating heat, the body also absorbs heat radiated by the wall of the enclosure. If the wall of the enclosure too behaves as a black body, then the radiating power per unit area of it is $\sigma A T_0^4$ and the power absorbed by the body is $\sigma A T_0^4$. The rate at which heat is lost from the body is the difference between $\sigma A T^4$ and $\sigma A T_0^4$. Therefore,

$$P_{net} = \sigma A T^4 - \sigma A T_0^4$$

$$= \sigma A (T^4 - T_0^4)$$

The rate of loss of energy from the back body is given by the above equation. For an object which is not a black body,

$$P_{net} = e\sigma A (T^4 - T_0^4) \text{ where } e \text{ is the emissivity of that object.}$$

Worked example

1. A thin rectangular sheet having sides 15.0 cm and 12.0 cm is heated to a temperature of 600 °C and then the heating source is removed. Calculate the electrical power required to maintain this sheet exactly at the above temperature. Emissivity of the surface of the sheet is 0.25. Disregard the heat loss due to convection.

    The energy radiated per second
    $$P = \sigma A e T^4$$
    $$T = (600 + 273) = 873 \text{ K}$$
    $$A = 3 \cdot 6 \times 10^{-2} \text{ m}^2$$

    The rate of loss of heat from the sheet,

    $$= (5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}) \times (3.6 \times 10^{-2} \text{ m}^2) \times 0.25 \times (873 \text{ K})^4$$

    $$= \underline{296 \text{ W}}$$

To maintain the sheet at 600 °C an amount of energy equal to this energy loss, should be

supplied by an apparatus like an electric heater. As there is a heat loss from the electric heater by radiation, a quantity of heat greater than the above value should be supplied.

1.9 Explanation of intensity distribution for the black body radiation

1.9.1 Rayleigh – Jean's theory and Wien's theory

Although the physicists at that time took various attempts to explain theoretically, the experimental curve showing the intensity distribution of black body radiation, all failed. In all those attempts, it was considered that the black body radiation was a continuous process according to the concepts such as Newtonian mechanics, thermodynamics and electromagnetic theory which were recognized at that time. Using the concepts in classical physics, the two theories which were able to explain the black body radiation to some extent were Rayleigh-Jean's theory and Wien's theory. It is clear from the graphs given in Figure 1.7 that Wien's theory presented in 1896, was in accordance with the experimental curve for shorter wavelengths, while Rayleigh-Jean's theory agrees with the experimental data only for the radiations with longer wavelengths.

Rayleigh – Jean's formula

$$E_\lambda = \frac{2\pi ck.T}{\lambda^4} \quad \text{--------(1)*}$$

c = velocity of light

k = Boltzmann constant

Wien's formula

$$E_\lambda = \frac{c_1}{\lambda^5}\frac{1}{e^{c_2/\lambda T}} \quad \text{--------(2)*}$$

c_1 and c_2 are constants

T is the absolute temperature of the black body

According to their theory, heat radiation starts from thermal vibrations of atoms/molecules on the surface of the black body. Also they emit heat radiation with all the frequencies at a large continuous range. According to Rayleigh – Jean's formula, when λ tends to zero the intensity (E_λ) tends to infinity, but according to experimental data, when $\lambda \to 0$, E_λ is also tends to zero. Because of the inability to explain the experimental results obtained in the black body radiation using both the above mentioned theories, the concepts in classical physics had been at a big crisis.

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* Formulae (1) and (2) above are not included in the syllabus implemented from 2017.
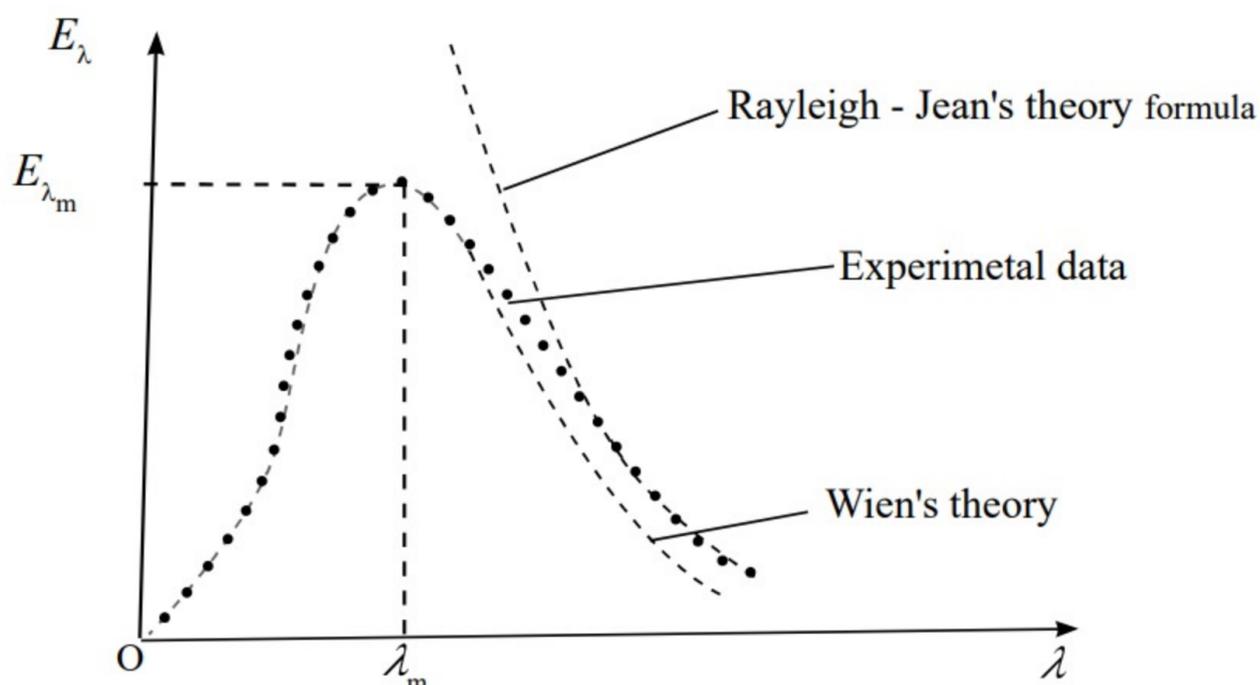
Figure 1.7 - Comparison of Rayleigh - Jean's theory and Wien's theory with experimental data

1.9.2 Planck's Theory

During that period a particular revolutionary concept was produced by a German physicist Max Planck. The hypothesis he presented then, is known as Planck's hypothesis.

According to Planck's hypothesis,

1. Atomic (or molecular) oscillators in thermal equilibrium with black body radiation cannot have any amount of energy. They can have only those energy values given by the equation,

   $E=nhf$ where h is Planck's constant. Its value is $h = 6 \cdot 634 \times 10^{-34}$ J s.

   f is the vibrating frequency of atomic oscillators and n is a quantum

   number ($n = 1, 2, 3, ….$)

   This postulate says that the energy of atomic oscillators is quantized. That is, the energy E of an oscillator vibrating with a frequency f can have only discrete values such as $hf, 2hf, 3hf, ….$ etc. It cannot have an energy value in between two adjacent energy values as mentioned above.

   As stated earlier, according to classical theory the energy that an oscillator can have is continuous. That is, it can have any E value within a particular range. Therefore, Planck's idea that " The energy of an oscillator is quantized " was a revolutionary concept.

2. As long as an atomic oscillator is in an allowed energy level, there is no emission or absorption of radiation, but such emission or absorption occurs when an oscillator transfers from one energy level to another. Atomic oscillators emit or absorb energy in a quantum manner (as energy "packets" or "granules") and not in a continuous

manner. According to this, when an oscillator transfers from one energy level to another adjacent energy level, the amount of energy emitted (or absorbed); that is the "quantum", is $\Delta E = \Delta nhf = hf$, as $\Delta n = 1$. This radiant energy quantum is known as a **Photon.**

For example, when an oscillator transfers from one energy level *E = 4hf* to another *E = 0*, the amount of energy that an emitting quantum contains is *4hf*. The allowed energy levels that an oscillator of vibrating frequency *f* can have, and the way the oscillator emits or absorbs photons, are shown by Figure 1.8.

An atomic oscillator, as an example, can jump from an energy level such as *n=5* to another energy level such as *n = 1*. In that case also the amount of energy that a quantum contains is, *E = 5hf - 1hf*
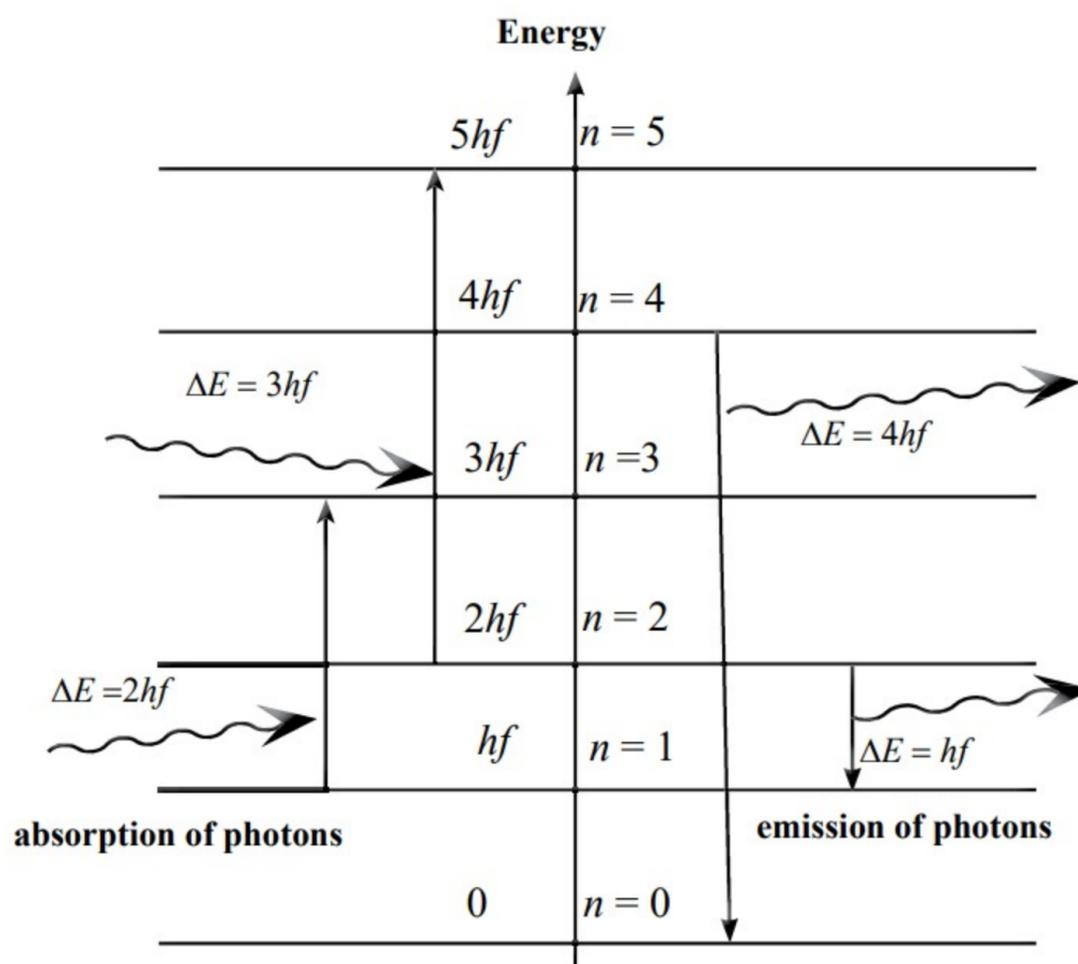
$$= 4hf$$

Figure 1.8 Absorption and emission of photons

According to the above, the absorption or emission of energy occurs in integral multiples of *hf*. The formula derived by Planck using the above assumptions is given below.

$$E_\lambda = \frac{2\pi hc^2}{\lambda^5 \left(e_s^{hc/\lambda kT} - T \right)} \ \text{------(3)}*$$

where, c is the velocity of light
h is the Planck's constant
k is the Boltzmann constant
T is the absolute temperature of the object

* Formulae (3) above is not included in the syllabus implemented from 2017.

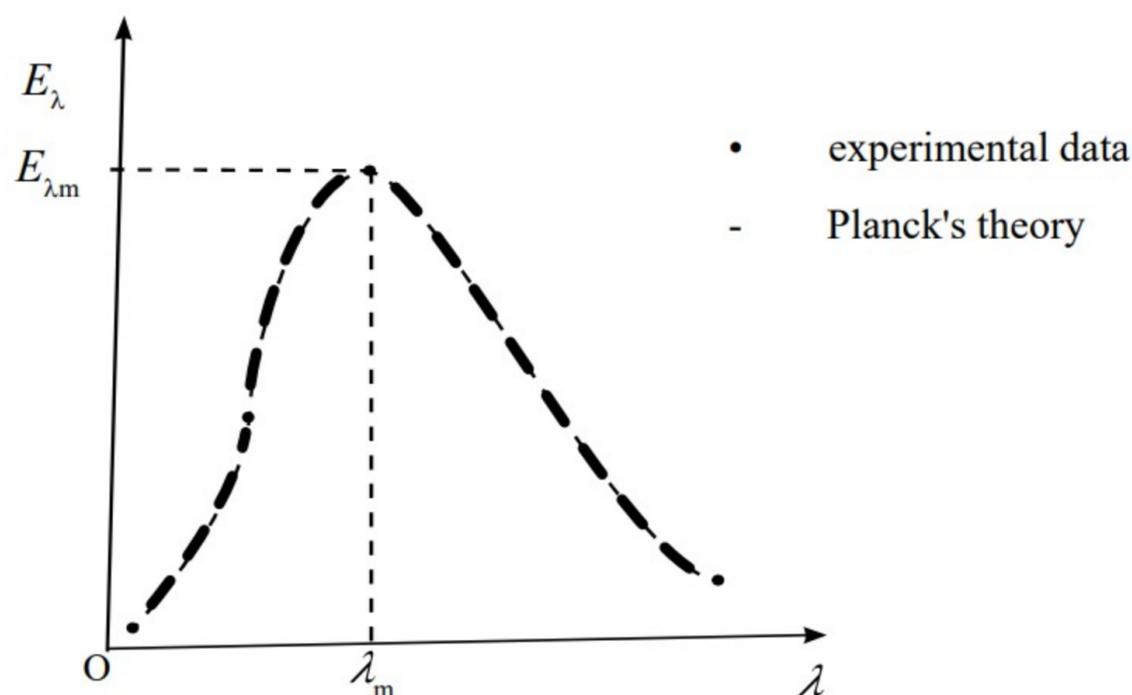This equation is in accordance with the experimental graph obtained for the black body radiation (Figure 1.9).

Figure 1.9 Experimental data and Planck's theory

Worked examples

1. Using Wien's displacement law calculate the temperature which is needed to obtain a distribution of black body radiation of which the wavelength corresponding to the maximum intensity is 1 μm (microwaves).

    $$\lambda_m T = C$$

    $$\lambda_m = 1 \ \mu m = 10^{-6} \ cm$$

    $$T = \frac{2.9 \times 10^{-3} \, mK}{10^{-6} \, m} = 2.9 \times 10^{3} \ K$$

2. About 5% of the power of a 100 W lamp is converted into visible radiation. Find the intensity of visible radiation at a point 1 m away from the lamp.

    $$\text{Intensity } I \ = \ \frac{\text{Power of the visible light}}{\text{area}}$$

    $$\frac{P}{4\pi r^2} = \frac{100}{4\pi 1^2} \times \frac{5}{100}$$

    $$= 0.398 \ W \, m^{-2}$$

3. An amount of energy 11 eV is required to dissociate a carbon monoxide molecule into carbon and oxygen atoms. If energy is supplied to do this in the form of light

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what should be the frequency of that light wave?

$$11 \text{ eV} = 11 \times 1.6 \times 10^{-19} \text{ J}$$

Applying $E = hf$ $\therefore f = \dfrac{11 \times 1.6 \times 10^{-19} \text{ J}}{6.62 \times 10^{-34} \text{ J s}}$

$$= 2.65 \times 10^{15} \text{ Hz}$$

This frequency belongs to the ultraviolet band.

Multiple choice questions and short answer questions

1. Which of the following radiations is not an electromagnetic wave?

   (a) γ - rays   (b) β - rays   (c) X – rays   (d) Thermal radiation

            Answer (b)

2. The frequencies of λ-rays, X-rays and ultraviolet rays are a, b and c respectively. Choose the choice showing the relationships between the frequencies.

   (a) $a > b > c$ (b) $a < b < c$ (c) $a = b = c$ (d) $a > c > b$

            Answer (a)

3. A certain source of power 4 kW, produces 10^{20} photons per second. If all these photons are of the same wavelength to which band of the spectrum do they belong?

   (a) microwaves   (b) UV - rays   (c) X – rays   (d) γ - rays

            Answer (c)

   Energy of a photon $E = \dfrac{\text{Power of the source}}{\text{Number of photons emitted}}$

   $$E = \dfrac{4 \times 10^3 \text{ J s}^{-1}}{10^{20} \text{ s}^{-1}}$$

   $$= 4 \times 10^{-17} \text{ J}$$

   But, $E = hf = \dfrac{hc}{\lambda}$

   $$\therefore \lambda_2 = \dfrac{\left(6.6 \times 10^{-34} \text{ J s}\right) \times \left(3 \times 10^8 \text{ m s}^{-1}\right)}{4 \times 10^{-17} \text{ J}}$$

   $$= 49.7 \times 10^{-9} \text{ m}$$
   $$= 5 \text{ nm}$$

This wavelength belongs to the X-ray band.

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4. An evidence to the fact that the electromagnetic waves are a type of transverse waves is that they can be

   (a) polarized   (b) interfered   (d) reflected   (d) refracted

                                                               Answer (a)

5. Name the electromagnetic wave which is used to study the crystal structures of solids and state the frequency range of it.

                  Answer : X-rays, frequency range 10^{18} Hz - 3×10^{21} Hz

6. Which constituent of the sun's radiation is absorbed by the ozone layer?

   Answer :   UV rays

7. The cylindrical filament of a 100 W electric bulb is of a diameter 8×10^{-5} m and length 0.60 m. If the emissivity of the filament is 0.70, calculate the operating temperature of it. (Stefan's constant is $5 \cdot 7 \times 10^{-8}$ W m^{-2} K^{-4})

   Surface area of the cylindrical filament $= 2\pi r l$

                                                     $= 2\pi \times 4 \times 10^{-5}\ _{m} \times 0 \cdot 6$ m

                                                     $= 1 \cdot 5 \times 10^{-4}$ m^2

   The amount of energy emitted from a unit area of the filament in a unit time.

   $$E = \frac{100\ \text{W}}{1.5 \times 10^{-4}\ \text{m}^2}$$

   $$= 6 \cdot 62 \times 10^{5}\ \text{W m}^{-2}$$

   According to $E = \sigma T^4$

          $6 \cdot 62 \times 10^5 = 5 \cdot 7 \times 10^{-8}\ T^4$

             $\therefore\ T = 1827$ K

Chapter two

Photoelectric effect

2.1 The phenomenon of photoelectric effect

In 1887 Heinrich Hertz found that, when ultraviolet light falls on a metal surface, electric charges are emitted by that surface. Although this phenomenon was found in the above year, it could not be explained until J.J. Thompson discovered the electron in 1899. In an experiment done by Philipp Lenard in 1900 it was confirmed that those charges were electrons and he was awarded the Nobel prize for physics in 1905 for the same.

The emission of electrons from a metal surface when electromagnetic radiation falls on it, is called photoelectric emission.

Figure 2.2 J.J. Thompson   Figure 2.2 Heinrich Hertz   Figure 2.3 Phillipp Lenard

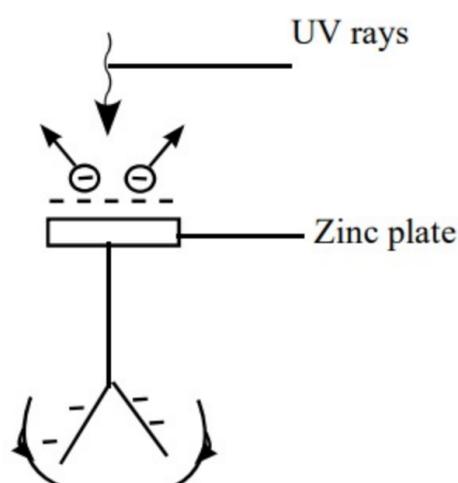**Experiments which can be used to demonstrate photoelectric effect**

Figure 2.4   Fall of leaves of a negatively charged electroscope

Figure 2.4 shows a pure plate of zinc placed on the metal cap of a gold leaf electroscope which is negatively charged. The leaves of the electroscope diverge as there are negative charges. It can be observed that leaves fall when ultraviolet light emitted by a mercury lamp is made to fall on this plate. The leaves fall because the negative charge on the electroscope gets decreased gradually as photoelectrons emit and leave the plate of zinc. When this experiment is repeated with placing a glass plate between the lamp and the zinc plate, it is observed that the falling of the leaves stops. The reason is that the glass plate cuts off the ultraviolet rays largely.

2.2 Demonstration of photoelectric effect using a photocell

Figure 2.5 shows an experimental set-up which is used for the demonstration. The apparatus needed are, a variable voltage supply, a photocell (vacuum type), a monochromatic beam of light with an appropriate frequency, a micro-ammeter, a voltmeter and a rheostat.

The cathode C and the anode A are two shiny plates made of the same alkali metal such as caesium or potassium. They are mounted in a vacuum tube made of quartz and are connected to an external electric circuit. The negative terminal and the positive terminal of the cell system has been connected to the cathode C, and anode A respectively. When the photo cell is kept in the dark it can be observed that the micro-ammeter reading is zero. Nevertheless, when a monochromatic beam of light having an appropriate frequency, is made to fall on the cathode, the micro-ammeter indicates an electric current. So, it is clear that an electric current is flowing across the gap b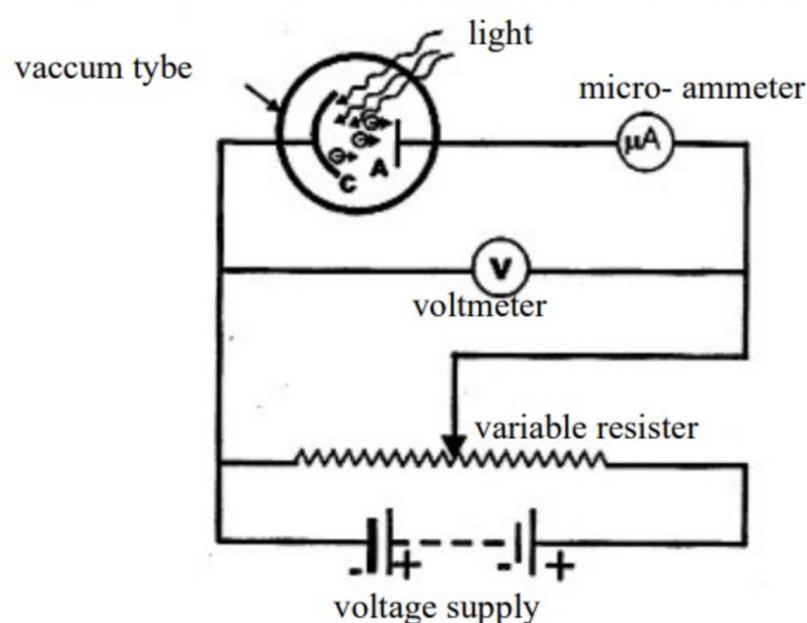etween C and A. When light is made to fall on the cathode furthermore and a wire is connected in place of the cell system in the circuit, there also the micro-ammeter indicates a current. According to this, it is clear that , although there is no potential difference between the cathode and the anode, electrons are emitted by the cathode and they reach the anode. Then they travel through the external circuit and arrive at the cathode.
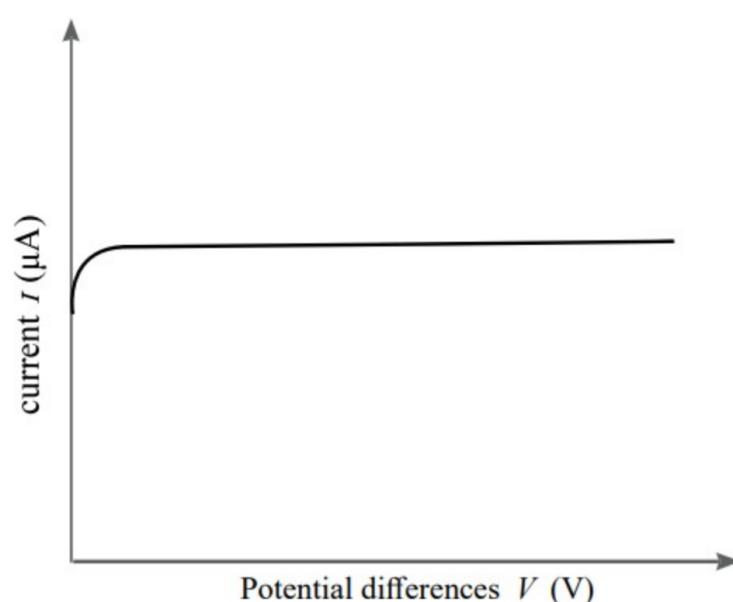

Figure 2.5 The experimental set-up used to study the photoelectric effect

Figure 2.6   Graph of current Vs. potential difference
(intensity is kept constant)

2.2.1   To vary the potential difference between cathode and anode by keeping the intensity constant

The above mentioned conducting wire is removed and the cells are connected again as shown by Figure 2.5. After the circuit is set, although a potential difference is applied between cathode and anode by the cells. there is no change in the micro-ammeter reading. Even though the potential difference between the cathode and the anode is increased gradually, keeping the intensity of light falling on the cathode constant, the current through the micro-ammeter remains constant. This confirms that the number of electrons emitted due to the photoelectric effect, does not depend on the potential difference applied across the cathode and the anode.

2.2.2   To reverse the direction of the potential difference across the cathode and the anode

Let us now consider, what happens when the direction of the potential difference between the cathode and the anode is reversed keeping the intensity of light falling on the cathode constant. Now the plate A is at a negative potential as the cells provides electrons. So, the direction of the potential difference is reversed and the intensity of light is kept constant. When the potential difference is increased gradually starting from zero, the current through the micro-ammeter decreases gradually as shown by Figure 2.7 and at a certain value of potential difference it shows a zero current. The value of the potential difference at the instance where current is zero is called the stopping potential.

This outcome can be explained in terms of the kinetic energy of electrons. Photoelectrons emitted by the cathode undergo a repulsion on reaching A. Under a given potential difference, only the electrons which have a sufficient value of kinetic energy to overcome that potential difference, reach A. The photoelectrons which have less kinetic energy than this value, are repelled from A. This result indicates that every electron emitted due to

photoelectric effect is not with the same kinetic energy. When the potential difference just reaches the stopping potential (V_0), the current flows only due to the emitted electrons which have the maximum kinetic energy.
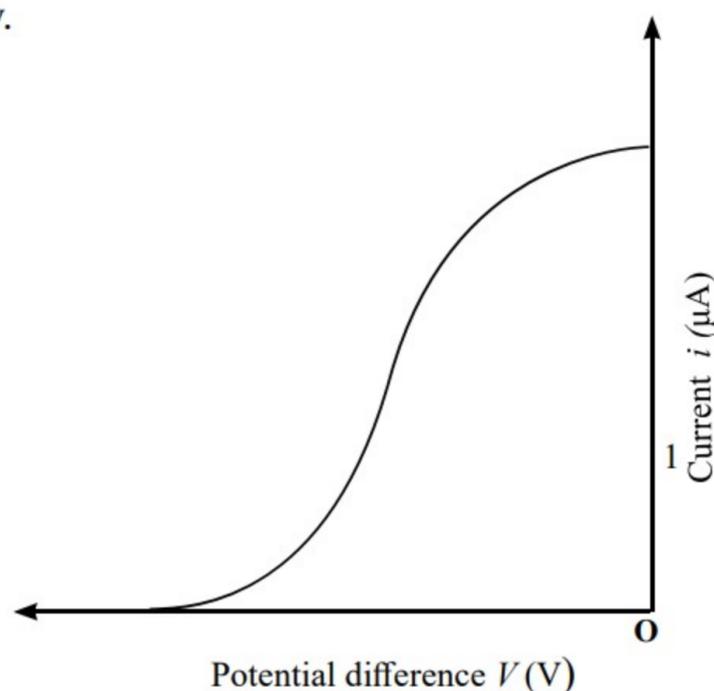

Figure 2.7   **Graph of current Vs. potential difference (under the condition where the potential differnece across C and A is reversed and the intensity of light is kept consant.)**

When the experiment is repeated under different I_1, I_2, and I_3 intensities of light, the graph obtained for the current i against the potential difference V is shown by Figure 2.8 (a).

A curve corresponding to a particular light intensity shown in Figure 2.8 (a) is a combination of the curves shown in Figure 2.6 and Figure 2.7 for the same light intensity.
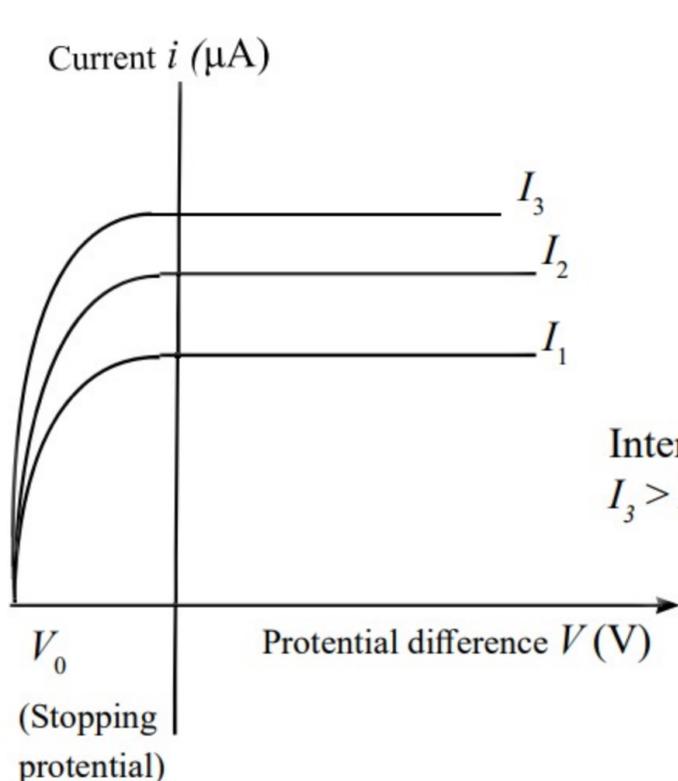

Figure 2.8(a) Graph of current Vs. potential difference (when the intensity of light is changed)
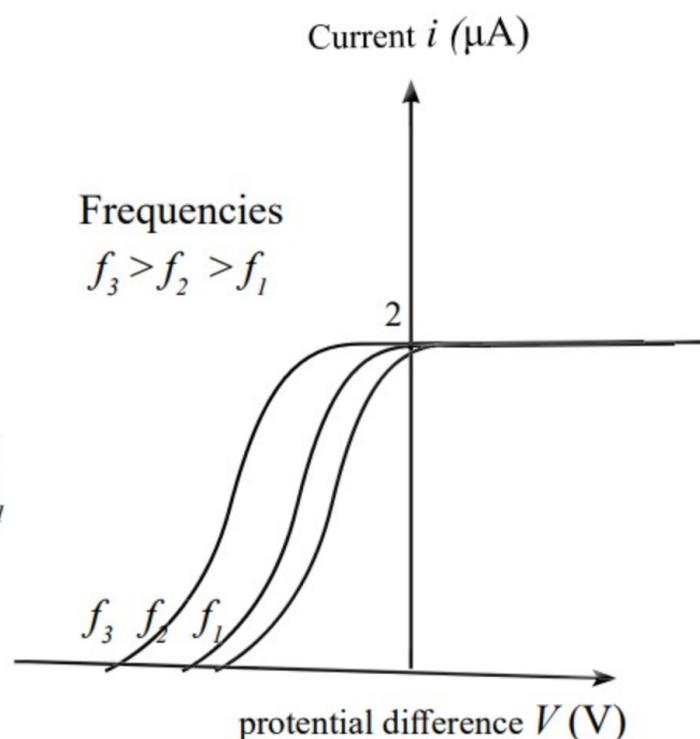
Figure 2.8(b) Graph of current Vs. potential difference (when the frequency of light is changed keeping the intensity constant)

According to Figure 2.8 (a), it seems that the current increases as the intensity increases. That means when the intensity of light increases, a larger number of electrons are emitted within a unit time.

However, it can be concluded from this graph that the stopping potential does not depend on the intensity of light. That is, the maximum kinetic energy of the emitted electrons does not depend on the intensity of light.

When the experiment is repeated keeping the intensity constant at the same value and using light with different frequencies, the graphs shown by Figure 2.8 (b) are obtained. From those graphs it seems that, although the intensity is the same, the stopping potential increases as the frequency of light increases. Therefore, it can be concluded that the light with a higher frequency emits electrons with a higher maximum kinetic energy.
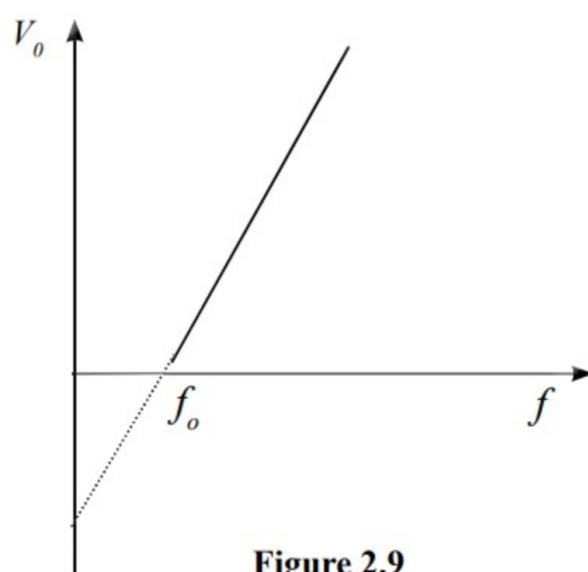

Figure 2.9

When the variation of stopping potential (V_o) with the frequency (f) of falling light is plotted on a graph, it is a straight line as shown in Figure 2.9. The frequency at which the value of the stopping potential becomes zero, is known as the threshold frequency (f_o). The photoelectric emission takes place only when the frequency of the falling light is greater than a certain minimum value known as the threshold frequency.

When the frequency of the falling light is made less than the threshold frequency, photoelectrons are not emitted and therefore the current stops. When the experiment is done using different metals for the cathode, several straight lines are obtained as shown by Figure 2.10. It is clear by these graphs that the gradients of all the straight lines take the same value and that the threshold frequencies are different.
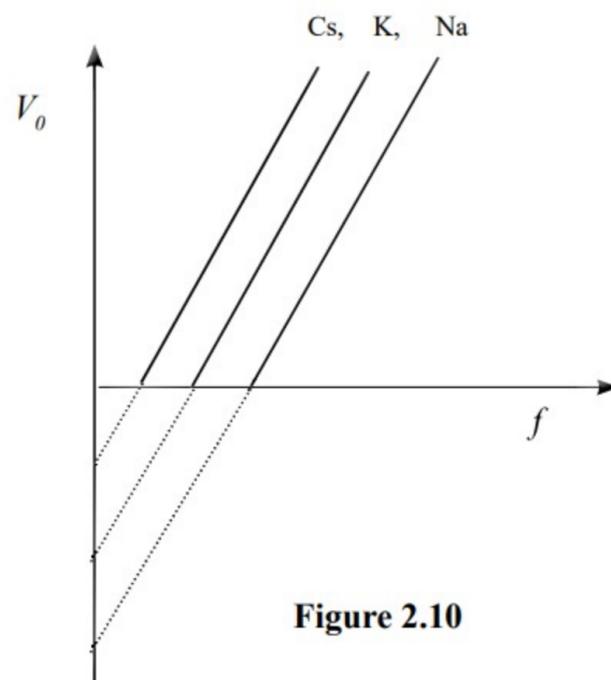
Figure 2.10

Even in the case where the anode is maintained at a negative potential relative to the cathode, there flows a current because of the reason that, the electrons with a kinetic energy greater than the required work done against the potential difference, are emitted. When this potential difference is equal to the stopping potential value (V_o), the maximum kinetic energy that an electron can have (K_{max}) is equal to the amount of work which should be done against the potential difference (eV_o). That is,

$$K_{max} = eV_0$$

According to this equation the maximum kinetic energy is proportional to the stopping potential. Therefore, the graph of maximum kinetic energy against frequency should take the same form as the graph of stopping potential against frequency, as in Figure 2.9 and this is shown in Figure 2.11.

For most of the metals the threshold frequency lies in the ultraviolet range (wavelength 200-300 nm) while those for the metals cesium and potassium lie in the wavelength range 400-700 nm of the visible spectrum.
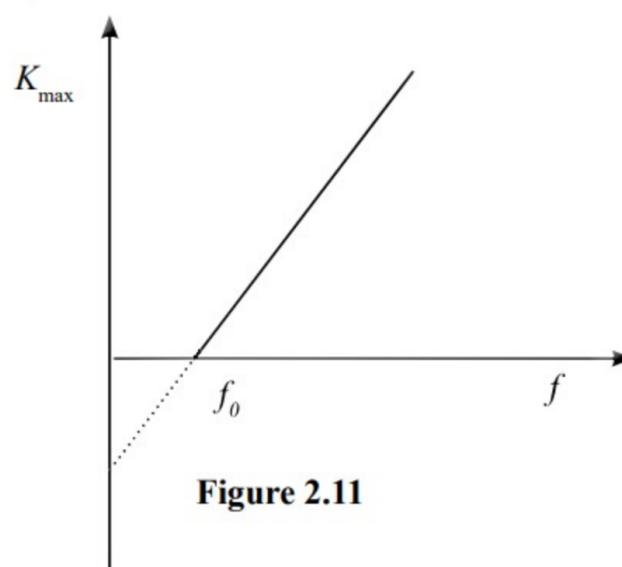

Figure 2.11

The results obtained from the above experiments can be stated as follows.

- The emitted photoelectrons have various kinetic energies from zero to a certain maximum value. With the increase of the frequency the maximum kinetic energy also increases.

- For any element, electron emission occurs when the frequency of the incident light is greater than a certain value called threshold frequency. Ultraviolet rays can emit electrons from the metal zinc even at a very low intensity, but infra-red rays cannot even at a much higher intensity.

- The threshold frequency depends on the metal used. For the most reactive elements it takes a lower value. For example, potassium has a lower threshold frequency than zinc has.

- The maximum kinetic energy of the emitted electrons depends only on the frequency of the incident light. It is proportional to the difference between the frequency of light and the threshold frequency.

$$K_{max} \propto (f - f_o)$$

- The minimum amount of energy required to make an electron free from a metal surface depends on that metal.

- The kinetic energy of the emitted photoelectrons does not depend on the intensity of light.

- The phenomenon of photoelectric emission is an instantaneous process. As soon as light is incident on the cathode, without delay, within a time less than 10^{-9} s, the emission of photoelectrons starts.

In classical physics, light is considered to be a kind of wave. The energy of a wave is dependant upon its amplitude, and the intensity of light is the amount of energy passing through a unit area, due to the wave. According to this, the emission of electrons from a metal surface due to light, should have been dependent upon the intensity of light and not upon the frequency. The electrons can be emitted easily by the light with a higher intensity. When the intensity falls down below a certain amount, the emission of electrons should stop. The kinetic energy of the emitted electrons should depend, not on the frequency but on the intensity of light. If a light with much lower intensity is incident then, to get the energy required to emit an electron, a certain length of time has to be spent. It cannot be expected to emit electrons as soon as the light is incident on the metal surface.

Therefore, at the beginning of the 20th century it had been a big problem to give a theoretical explanation to the experimental observations regarding the photoelectric effect.
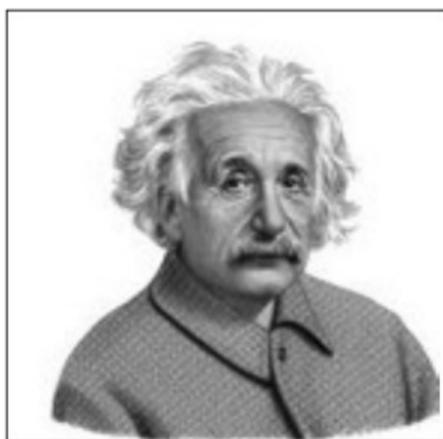
Figure 2.13 Albert Einstein

Using the theory of quantized energy which was developed by Albert Einstein in 1905, it was possible to explain all the observations relating to the photoelectric effect. Einstein was awarded the Nobel Prize for Physics in 1921 in this regard.

According to the theory presented by Einstein, in the photoelectric effect, light behaves as very tiny particles. The energy in one particle is proportional to the frequency of light. Therefore, light can be considered as energy packets or quanta. The electrons are emitted by absorbing these energy quanta. Einstein named these particles as photons. By that time, the concept of energy quanta had been presented by Max Plank. As we discussed in Chapter one, it had been assumed by Plank that the energy E in an energy quantum absorbed or emitted in a black body radiation depends on the frequency according to the equation $E = hf$. When an electron absorbs such an energy quantum in the photoelectric effect, a part of that energy is used to make an electron free from the metal surface and the rest is converted into kinetic energy. The energy required to get an electron free from the metal surface is known as the work function of that metal. If it is denoted by the symbol ϕ, the maximum kinetic energy (K_{max}) that an emitted electron can have, should be given by $K_{max} = hf - \phi$. This equation can also be written as, $eV_o = hf - \phi$ relating to the stopping potential. According to this, the graph of kinetic energy against frequency should be a straight line and its gradient should be equal to Planck's constant. Similarly the graph of stopping potential against frequency should also be a straight line and its gradient should be h/e.

Since the work function is a constant depending on the metal, when the frequency of the incident ray on the metal surface is reduced gradually, the kinetic energy received by the election decreases gradually and at a certain frequency it becomes zero. If the frequency is further reduced beyond this, as the energy given by the photon is not sufficient to emit an electron, the photoelectric effect does not take place. Therefore, the frequency at which the kinetic energy becomes zero, is the threshold frequency.

In this manner, Einstein could easily explain the experimental results shown in Figure 2.9, Figure 2.10 and Figure 2.11.

What happens, in increasing the intensity of the beam of light is, the increase of number of photons. As the frequency remains unchanged, this does not affect the energy of the photon.

The Table 2.1 gives the work function and the threshold frequency of some metals.

Table 2.1 Work function and threshold frequency of some metals

Metal	Work function ϕ (eV)	Threshold frequency f_0 (Hz)
Sodium	2.4	5.8×10^{14}
Calcium	2.9	7.0×10^{14}
Zinc	3.6	8.8×10^{14}
Silver	4.3	1.0×10^{15}

The electronvolt (eV) is a unit of energy. It is defined as the energy gained by an electron when accelerating under a potential difference of 1V.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

$$1 \text{ Megaelectron volt } = 10^6 \text{ eV}$$

Exercises - Photoelectric effect

Planck's constant $h = 6.63 \times 10^{-34}$ J s

velocity of light $c = 3 \times 10^8$ m s^{-1}

$1 \overset{0}{\text{A}} = 10^{-10}$ m, 1nm $= 10^{-9}$ m

1 eV $= 1.6 \times 10^{-19}$ J

1. Light of wavelength λ is incident on a metal of work function ϕ. For the photoelectric effect to take place,

   (a) $\lambda < \dfrac{ch}{\phi}$ (b) $\lambda = \dfrac{ch}{\phi}$ (c) $\lambda > \dfrac{ch}{\phi}$ (d) $\lambda > \dfrac{2ch}{\phi}$ (e) $\lambda = \dfrac{4ch}{\phi}$

2. It was observed that, when a green light is incident on a metal surface, electrons were emitted and as with yellow colour light, they were not. When a red light is incident on that surface,

   (a)   Electrons with a higher energy are emitted.
   (b)   Electrons with a lower energy are emitted.
   (c)   Electron emission depends on the intensity of the incident light.
   (d)   Electron emission does not occur.
   (e)   Electron are emitted with some delay.

3. On a material surface of which the threshold frequency is f_0, a beam of light of frequency f ($f_0 < f$) is incident. Choose the choice showing the kinetic energy of the emitted photoelectrons correctly.

   (a) $h(f - f_0)$ (b) $\dfrac{h}{f}$ (c) $he(f - f_0)$ (d) $\dfrac{h}{f_0}$ (e) he

4. In the process of photoelectric emission, when the intensity of light is reduced, the stopping potential,

   (a) Decreases   (b) Increases

   (c) Remains the same   (d) Increases or decreases depending on the

   (e) None of the above occurs   polarization of light

5. The number of electrons emitted from a photosensitive surface depends on,

   (a) The intensity of the incident light.

   (b) The frequency of that light.

   (c) The wavelength of that light.

   (d) The colour of that light.

   (e) The emissivity of that surface.

6. The photoelectric emission occurs when a light of wavelength 0.6 μm, emitted by a mercury lamp, is incident on a photoelectric cell. The stopping potential relevant to this phenomenon is 0.5 V. When the wavelength of the light coming from the lamp is 0.4 μm, the stopping potential is 1.5 V. The velocity of light is 3×10^8 m s^{-1}. Using the above data the value obtained for h/e is,

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

   (d) 4×10^{-8} V s   (e) 1.6×10^{-19} V s

7. For a particular metal the threshold frequency relating to the photoelectric emission is f_0. A beam of light with a frequency f is incident on a plate made of that metal. For the photoelectrons to emit,

   (a) $f = f_0$ (b) $f = 2f_0$ (c) $f < f_0$ (d) $f > f_0$ (e) $f = \sqrt{2}f_0$

8. In an experiment on photoelectric effect, the graph of stopping potential (V_o) against frequency (f) of light is plotted and it is a straight line. That straight line makes an angle θ with the f axis. If ϕ is the work function of the surface tan θ equals.

   (a) $\dfrac{h}{e}$ (b) $\dfrac{e}{h}$ (c) $\dfrac{-\phi}{e}$ (d) $\dfrac{eh}{\phi}$ (e) $\dfrac{\phi}{e}$

9. The ratio of the work functions of two metals named A and B is 1 : 2. The light falling on A and B are of the frequencies f and $2f$ respectively. $f > f_o$ and $2f > f_B$ are the threshold frequencies of A and B. The ratio of maximum kinetic energies of the electrons emitted by each surface is,

   (a) 1:1   (b) 1:2   (c) 1:3   (d) 1:4   (e) $1:\sqrt{2}$

10. The work functions of the metals A, B and C are 4.5 eV, 4.3 eV and 3.5 eV respectively. Light with wavelength $4000\overset{\circ}{A}$ is incident on them. Then, what is the most accurate statement out of the following statements ?

    (a) The photoelectrons are emitted only by A

    (b) The photoelectrons are emitted only by B

    (c) The photoelectrons are emitted only by C

    (d) The photoelectrons are emitted by all the above metals

    (e) The photoelectrons are emitted by none of the above metals.

11. When light with the wavelength $40000 \overset{0}{A}$ is incident on a metal, of which the work function is 2 eV, the kinetic energy of the emitted photoelectrons is approximately,

    (a) 0.5 eV   (b) 1.1 eV   (c) 2.5 eV   (d) 3 eV (e) 2 eV

12. The concept developed by the quantum theory of light is.

    (a) electrons   (b) photons

    (c) positrons   (d) neutrons   (e) The concept of quark

13. In an experiment relating to photoelectric effect, the gradient of the graph of maximum kinetic energy (E_k) against the frequency (f) of the incident photons gives,

    (a) Charge of the electron

    (b) Work function of the metal

    (c) Planck's constant

    (d) Ratio of Planck's constant and charge of the electron

    (e) Ratio of charge of the electron and Planck's constant

14. In an experiment relating to the emission of photoelectrons from a metal surface, the graph of the stopping potential (V_o) against the frequency of incident light (f) is a straight line. The Planck's constant is given by,

    (a) The gradient of the graph.

    (b) Product of the gradient of the straight line and the amount of electronic charge.

    (c) Ratio of the intercept on the V axis and the electron charge.

    (d) Product of the intercept on the f axis and the electron mass.

    (e) Product of the gradient and the electron mass.

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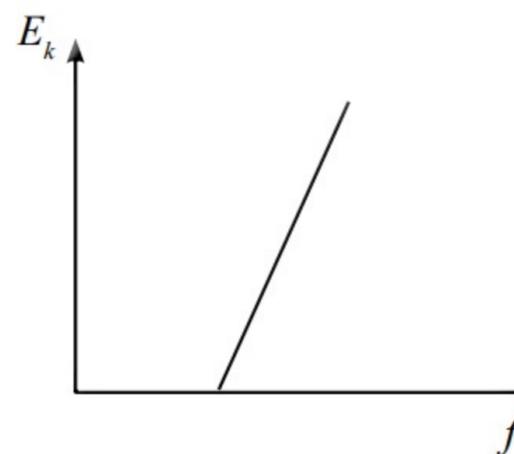
15. The time taken to emit a photoelectron when a light photon is incident on a photosensitive surface is approximately,

(a) 10^{-1} s   (b) 10^{-4} s   (c) 10^{-10} s   (d) 10^{-7}s   (e) 1.0 s

16. On a photosensitive surface, light energy with the wavelength $5000 \overset{\circ}{A}$ is incident at a rate of 10^{-8} J s^{-1}. The number of photons received per second is,

(a) 2.5×10^{10} (b) 2.5×10^{11} (c) 2.5×10^{13}

(d) 2.5×10^{9} (e) 2.5×10^{6}

Answers

1 - (a),	2- (d),	3 - (a),	4 - (c),	5 - (a),	6 - (c),
7 - (d),	8 - (a).	9 - (b),	10- (d),	11 - (d),	12 -(b),
13 - (c),	14 - (b),	15 - (c),	16 - (d)		

Chapter three

The Wave nature of matter

3.1 Introduction

Considering the wave nature of light (electromagnetic radiation) the phenomena of interference, diffraction and polarization could be explained successfully. On the other hand, phenomena relating to energy and momentum such as photoelectric effect have been explained, based on the quantum nature of radiation.

In the photoelectric effect, a light photon with sufficient energy (having a greater energy than the work function of the relevant metal) is incident on a metal surface and assigns all its energy to one electron in an atom, and then that electron is emitted from the metal surface.

The Compton effect is the scattering of a photon (to change the direction of travel of that photon) by an electron or any other charged particle. Arthur Compton who discovered this phenomenon, also found that in addition to its direction change, the wavelength of the photon increases (energy of the photon decreases) and the electron recoils in another direction.

Both the phenomena, the photoelectric effect and the Compton effect, can only be described by assuming the particle aspect of the radiation and not by the wave theory of radiation.

According to this, it is clear that, light (electromagnetic rays) on some occasions behaves as waves and on some other occasions behaves as particles. This is known as the wave-particle duality of radiation.

In the phenomenon of seeing something with our eyes, both these explanations (wave aspect and particle aspect) are important. The mechanism of collecting and focusing light is done by the eye-lens and that process is well clarified by waves. On the other hand, for the clarification of absorption of light by rods and cones on the retina, it is essential to apply the photon process.

3.2 De Broglie relationship for matter waves

In 1924, French physicist Louis de Broglie had an argument that, if light waves can behave as particles (photons) why cannot particles behave as waves. He had an idea that nature loves symmetry as there are many symmetrical properties found in nature. Therefore, matter and energy should also be of that symmetrical property. According to his argument, atomic particles such as electrons which behave as particles, perhaps, might behave as waves as well. Such waves are known as de Broglie waves or matter waves. According to the quantum theory and Einstein's mass-energy relationship, the energy associated with

a particle of mass m can be given as $E = mc^2$ (c is the speed of light in free space). Einstein's equation gives that, the energy of a photon having a frequency f, is given by $E = hf$ and, the momentum is given by,

$$p = \frac{E}{c}$$

Using the above two equations, the relationship between the frequency and the momentum of a photon can be written as

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

According to de Broglie's argument this relationship should hold for particle waves also. This means, if a particle of mass m, momentum p and velocity v behaves as a wave, its wavelength can be calculated using the equation, $\lambda = \dfrac{h}{p} = \dfrac{h}{mv}$.

This is known as the de Broglie wavelength of the particle.

This particle of matter may be charged or uncharged. The wavelength associated with the particle is independent of its charge. It is clear, from this fact, that de Broglie waves are not electromagnetic waves. The electromagnetic waves are produced by accelerating charged particles.

In accordance with the above equation, wavelength (λ) takes a lower value for a particle with a higher mass or a higher velocity with higher energy.

Eg : Let us find de Broglie wavelengths of a moving ball and an electron. The mass of the ball is 0.14 kg and it is moving at a speed of 22 m s^{-1}. The mass of the electron is 9.11×10^{-31} kg and it is moving at a speed of 5.8×10^{6} m s^{-1}.

Momentum of the moving ball,

$$p_1 = m_1 v_1 = 0.14 \text{ kg} \times 22 \text{ ms}^{-1} = 3.08 \text{ kg m s}^{-1}$$

$$\therefore \lambda_2 = \frac{6.6 \times 10^{-34} \text{ J s}}{3.08 \text{ kg m s}^{-1}} = 2.15 \times 10^{-34} \text{ m}$$

for the moving electron,

$$p_2 = m_2 v_2 = 9.11 \times 10^{-31} \text{ kg} \times 5.8 \text{ m s}^{-1} \times 10^{6} \text{ m s}^{-1} = 5.28 \times 10^{-24} \text{ kg m s}^{-1}$$

$$\therefore \lambda_2 = \frac{6.6 \times 10^{-32} \text{ J s}}{5.28 \times 10^{-24} \text{ kg m s}^{-1}} = 0.12 \text{ n m}$$

The wavelength obtained for the ball is very small and is almost impossible to be measured. For the macroscopic objects we find in day-to-day life, the above wavelength is very much smaller. Therefore they do not show wave properties. On the other hand sub-

atomic microscopic particles such as electrons and protons show their wave properties much more. De Broglie wavelength value we obtained for the electron, 0.126 nm, is a meaningful and measurable value.

Worked examples

1. Let us consider an electron of mass m and charge e starting from rest and accelerating under a potential difference V. Its kinetic energy k is equal to the work done (eV) on the electron in the field. The momentum gained by the electron,

   $p = mv = \sqrt{2mK}$ (v is the velocity of the electron)

   Write an expression for the De Broglie wavelength for the probe of electrons.

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

   $$\frac{1}{2}mv^2 = Ve$$

   $$v = \sqrt{\frac{2\,eV}{m}}$$

   $$p = mv = \sqrt{2\,mK}$$

   $$= \sqrt{2\,meV}$$

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

   $$\lambda = \frac{h}{\sqrt{2\,m\,eV}}$$

2. Which one of the following has the smallest de Broglie wavelength when each of them has the same amount of kinetic energy?
   electron, proton and α - particle

   The de Broglie wavelength of a particle of mass m and momentum p,

   $$\lambda = \frac{h}{p} \;,\; k = \frac{p^2}{2m} \qquad p = mv \text{ (v is velocity of the particle)}$$

   $$\lambda = \frac{h}{\sqrt{2mk}} \qquad \text{since the kinetic energy is the same,}$$

   $$\lambda \propto \frac{1}{\sqrt{m}}$$

The mass of an α - particles is four times the mass of a proton and the mass of a proton is 1836 times of an electron. Therefore, among these particles, α - particles has the smallest e Broglie wavelength.

3. A particle is moves with a velocity which is three times the velocity of an electron. The ratio of the de Broglie wavelengths of the particle and the electron is 1.813×10^{-4}. Calculate the mass of the particle. Identify the particle.

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

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

For the electron. $m_e = \dfrac{h}{\lambda_e v_e}$

Let m be the mass of the particle, then $\dfrac{v}{v_e} = 3$ and $\dfrac{\lambda}{\lambda_e} = 1.813 \times 10^{-4}$

$$m = \frac{\lambda e}{\lambda} \cdot \frac{v_e}{v} \, m_e$$

$$= \frac{1}{1.813 \times 10^{-4}} \times \frac{1}{3} \times 9.11 \times 10^{-31}$$

Since, $\quad m_p = 1.673 \times 10^{-27}$ kg $\quad$ and

$\quad m_m = 1.675 \times 10^{-27}$ kg

This particle may be a proton or a neutron.

3.3 Diffraction of electrons

By their experiments carried out in 1927, two American scientists, C.J. Davisson and L.H. Germer verified for the first time that a moving electron has a wave nature. In an experiment done independently by G.P. Thomson in 1928 similar results were obtained. He was able to get diffraction patterns by targeting a beam of electrons on a crystal. Both, C.J. Davisson and G.P. Thomson were awarded the Nobel Prize for Physics in 1937 for their experimental discovery of the diffraction of electrons by crystals.

By aiming a beam of electrons moving with a constant speed towards a thin foil of metal, a diffraction pattern can be obtained on a screen and that pattern is similar to that of X-rays. This is what was shown by Thomson. By the results of those experiments de Broglie's wave-particle theory was confirmed.
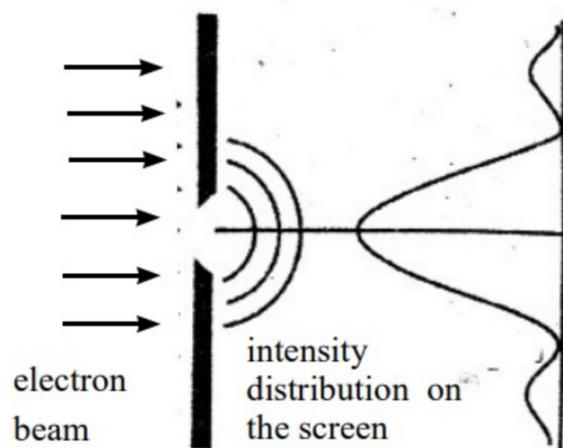
Figure 3.1 Electron diffraction formed by a single slit

3.4   X-ray diffraction

To obtain a diffraction pattern from visible light, the diffraction grating is used widely. Diffraction grating is a large number of slits situated very close to each other. To obtain a diffraction pattern from a beam of light of a particular wavelength, the width of the slits in the grating should be less than or approximately equal to that particular wavelength.

The wavelength of X-rays is about 1 nm. The width of the slits in a grating used with visible light, is much greater than the wavelength of X-rays. Therefore with such a grating X-rays cannot be diffracted and practically it is very difficult to make a grating with a slit width of 1 nm.

In 1913, Max Von Laue showed that such gratings were there in nature. He found that the regular small spacing of atoms in a lattice of a crystal (e.g. sodium chloride) would provide a natural plane grating, which can form diffraction patterns. By directing a beam of X-rays towards a sodium chloride crystal, a diffraction pattern with circular fringes can be obtained on a photographic film. This occurs when the gap between atomic planes (width of the slit) is approximately of the order of the wavelength of X-rays.
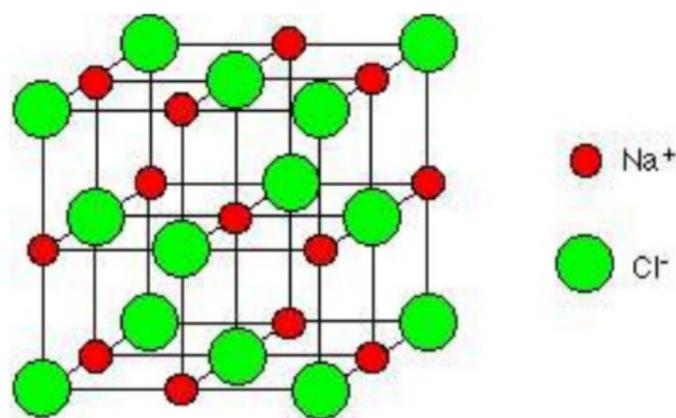

Figure 3.2 Max Von Laue

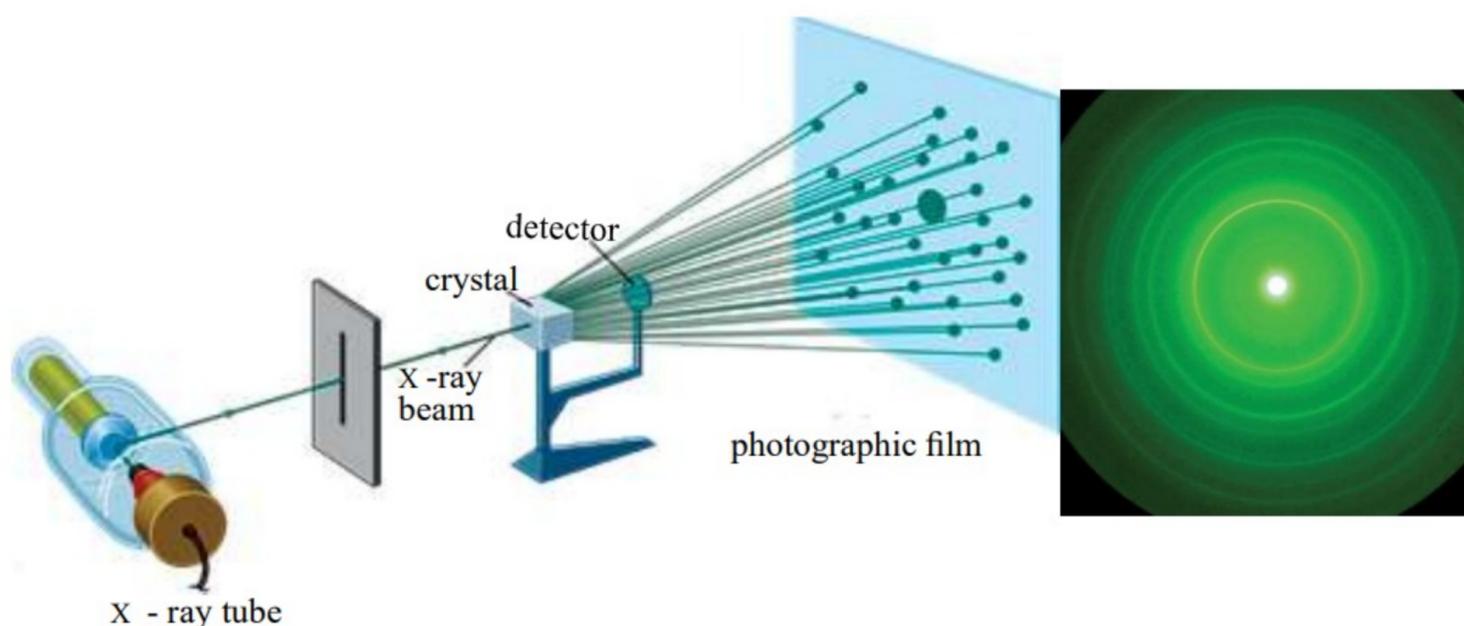**Figure 3.3 Crystal of sodium chloride**

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Figure 3.4 X-ray diffraction pattern

3.5 Electron microscope

Electron microscope is very important in the technical field as well as in medical research. This instrument has been designed based on the wave properties of electrons. We can see an object when light rays reach the eye after being reflected by that object. If the object is smaller than the wavelength of the light used, then the light is not reflected well. Because of this reason, we cannot see the object even with the help of a microscope having a very high magnifying power.

As the wavelength of visible light is about 400 nm – 700 nm, using a microscope working with visible light, we can see only those objects which are larger than 400 nm. That means the limit of resolving power of an optical microscope obtainable is about 400 nm. The electrons have wave properties. Therefore, by accelerating an electron beam to a high velocity, waves of very short wavelengths can be obtained. Using those waves, electron microscopes of high resolving power have been produced.

There are two types of electron microscopes, one of them is the transmission electron microscope which makes two dimensional images. The other one is the scanning electron microscope which gives there dimensional images.

The structures of the optical microscope which uses visible light and the electron microscope which uses electron beams are shown in Figure 3.5 and Figure 3.6 respectively.
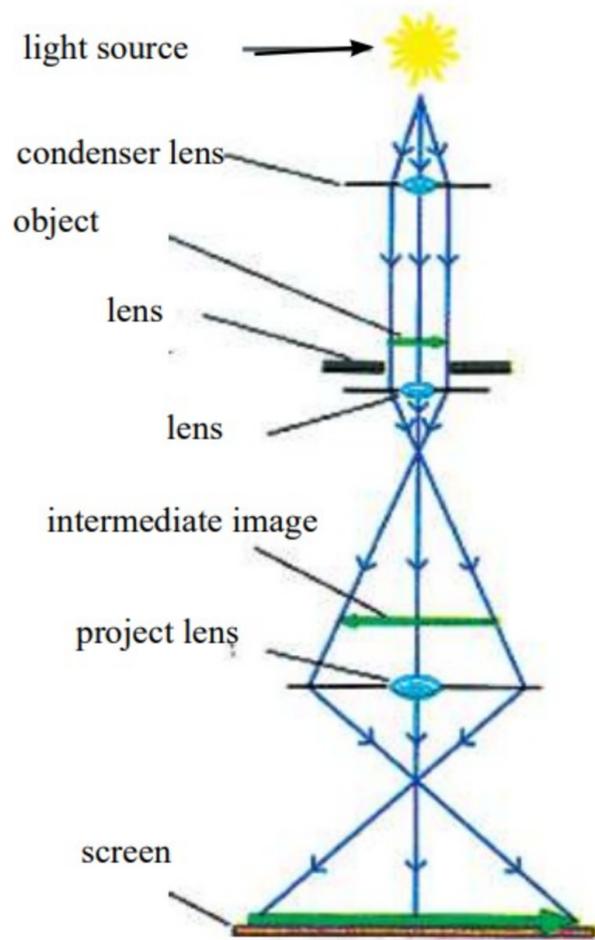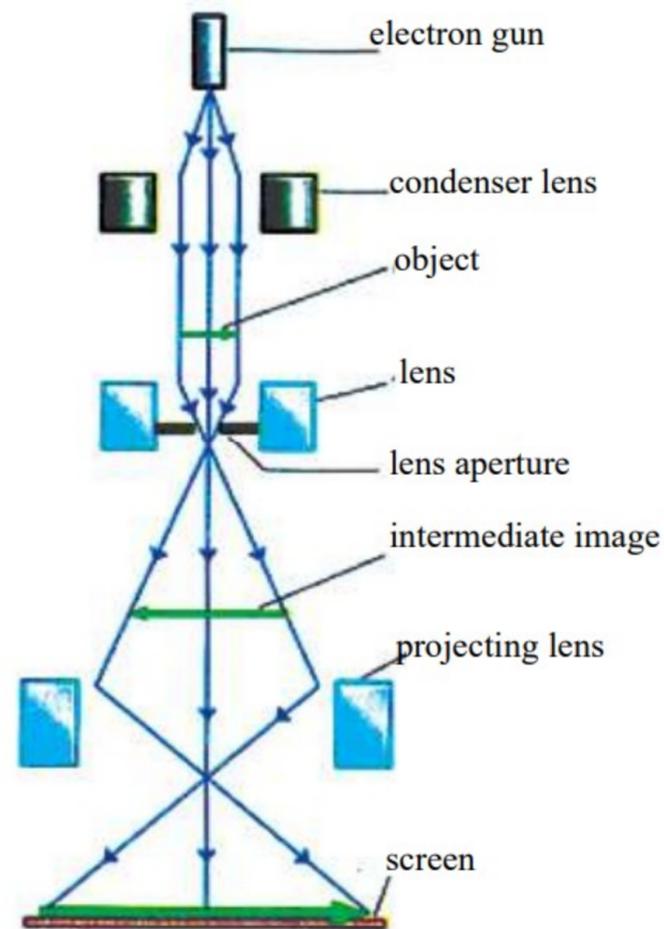
Figure 3.4

Figure 3.5

What is done here is, accelerating a beam of electrons emitted by heated filament using a higher potential difference, and giving the electrons a higher kinetic energy. If this potential difference is V, electron charge is e, electron mass is m and velocity is v then the kinetic energy gained by the electron,

$$\text{Momentum of the electron } p = mv$$
$$= \sqrt{2eVm}$$

$$\text{De Broglie wavelength } \lambda = \frac{h}{p} = \frac{h}{\sqrt{2eVm}}$$

Electron mass	=	9.1×10^{-31} kg
Electron charge	=	1.6×10^{-19} C
Planck's constant (h)	=	6.6×10^{-34} J s

When we take V = 3600 V

Using the above formula, $\lambda = 2 \times 10^{-11}$ m

This value is very much smaller than the wavelength of light. Therefore the electron microscope has a resolving power which is very much greater than that of the optical microscope.

Table 3.1 Comparison of properties of the optical microscope and the electron microscope

Property	Optical microscope	Electron microscope
maximum obtainable magnification	1,000 - 1,5000	more than 100,000
maximum resolution	0.2 μm	0.5 nm
source	visible light	beam of electron
propulsive medium (inside the microscope)	air	vaccum (of high level)
lens type	glass	electro - magnetic
cause of contrast	differential absorption of light	irradiation of electrons
focusing process	positioning the lenses	changing the current through the electromagnets

Chapter four

X-Rays

4.1   Cathode rays

In 1870 William Crookes discovered that, when a high voltage was maintained in glass tubes containing low pressure gases, those gases could conduct electricity. In his experiments, he could observe some remarkable effects such as colourful glowing of the gas in the tube. When neon gas was there in the tube, it glowed in dark red-orange colour. A glow of violet was obtained for oxygen and nitrogen.
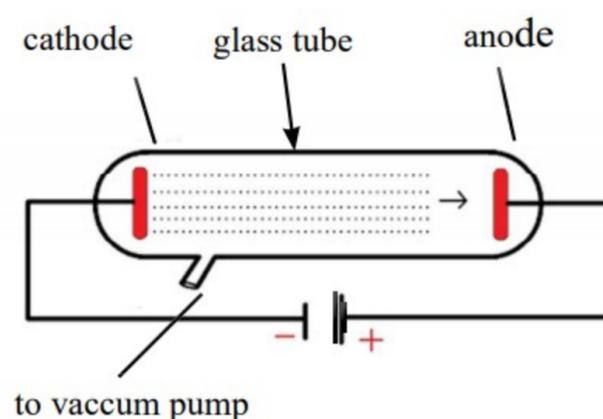

Figure 4.1 William Crookes

Figure 4.2   Discharge tube

J.J. Thomson could identify the electron in 1879 with the help of the facts discovered by Crookes and others who had studied further about gas discharge. He observed that not only the gas in the tube but the glass wall behind the anode also glowed. He assumed that it might have been due to a flow of rays coming from the cathode. Accordingly those rays were named cathode rays. During the latter part of the 19th century, Thomson did a lot of experiments. From those experiments the following facts about cathode rays have been justified.

- Cathode rays consist of a flow of negatively charged particles.

- They start from the cathode and travel rectilinearly.

- Regardless of which gas or which cathode (metal) is used, these rays are with the same properties.

- When they collide with matter under appropriate conditions, X-rays are produced.

- They are deflected by electric fields as well as magnetic fields.

- They posses kinetic energy.

Thomson's experiments paved the way for the production of the cathode ray tube which was used in television sets, computer monitors and oscilloscopes until recently.

4.2 X -rays

In 1895 Wilhelm Rontgen, a German, made an unexpected observation as follows while experimenting on discharge through air. The discharge tube he used, contained low pressure air under high voltage. It could fluorescence a fluorescent screen coated with barium platinocyanide. Also, he observed that a photographic film well wrapped in a black paper, had become fogged. Based on that, he decided that some kind of ray had been emitted by the discharge tube. He experimented, keeping various materials with various thicknesses between the tube and the screen. There he observed that the fluorescent intensity had reduced but even an aluminium plate with a thickness of about one centimeter could not stop the flourescence. For the reason that Rontgen could not understand the nature of those rays at that time, he named them X - rays.

Figure 4.3 Wilhelm Rontgen

A modern type of X-ray tube used to produce X-rays is shown in Figure 4.4. The cathode and the anode are positioned in the evacuated tube. The anode is at a very high positive voltage of 10^5 V relative to the cathode. This voltage is known as the operating potential difference. By heating the tungsten filament with a low voltage, it can be made to emit electrons due to thermionic effect. The electrons emitted by the heated filament get accelerated due to the potential difference, and hit the target metal (anode) with a very high kinetic energy.

When an electron beam travelling with a very high speed is stopped instantly as it hits the target metal (anode), most of its energy is converted into heat. This heat increases the temperature of the target metal. Tungsten or molybdenum is used as the target metal. In the target metal, the electrons are decelerated and a part of their energy is emitted as high energy electromagnetic rays (photons). What is named as X-rays is this high energy electromagnetic radiation.The wavelength range of X-rays is from $\lambda = 0.005$ nm to 0.01 nm.

As the electrons get decelerated in the target, X-rays are produced. The rays which are emitted due to deceleration of electrons are also known as breaking radiation. Until these decelerating electrons come to rest, they emit X-rays continuously. X-ray tube is kept in a lead shield with a small window. About 99% of the kinetic energy of the electrons are transformed into heat. Therefore the copper rod is cooled by circulating water. To remove heat generated in the anode, a copper rod with a higher thermal conductivity is used.
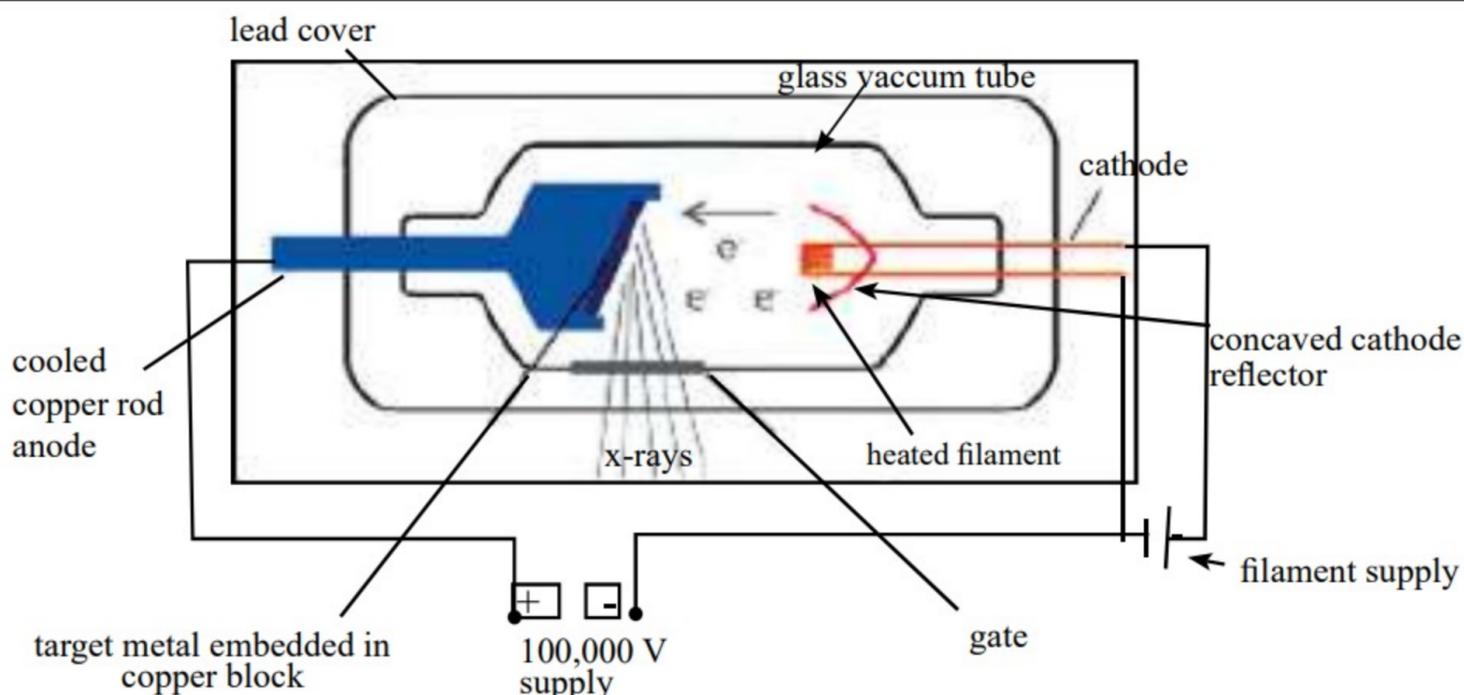
Figure 4.4 A modern x-ray tube

In this case X-rays are produced by the bombardment of electrons on matter. So, this can be considered as the inverse process of the photoelectric effect. X-ray photons coming out through the window, can have various energies within a certain range. When an electron makes a head-on collision with an atom in the target metal, all the energy of the electron may be absorbed. In such a case, the X-ray photon has the maximum energy. When the total energy in an electron is converted into an X-ray photon at once, that photon has the maximum energy. On that occasion, if the frequency of an X-ray photon is f, then the kinetic energy in the electron reaching the target can be given as $K = eV$. Here V is the operating potential difference and e is the electron charge. c is the velocity of light.

$$k = eV = hf_{max} = h\frac{c}{\lambda_{min}} \qquad (h \text{ is Planck's constant})$$

Here, λ_{min} is the minimum wavelength that continuous X-rays can have.

$hf_{max} = h\dfrac{c}{\lambda_{min}}$ is the maximum energy that a continuous X-ray photon can have.

Unlike in the case of visible light, for X-ray transition the innermost energy levels are involved. It is essential to have a metal with high atomic mass and high melting point as the target metal. The metals such as tungsten and molybdenum can be used for this.

Figure 4.5 shows an X-ray tube used for diagnostic purposes. It provides X-rays with a higher intensity without making the anode highly heated.
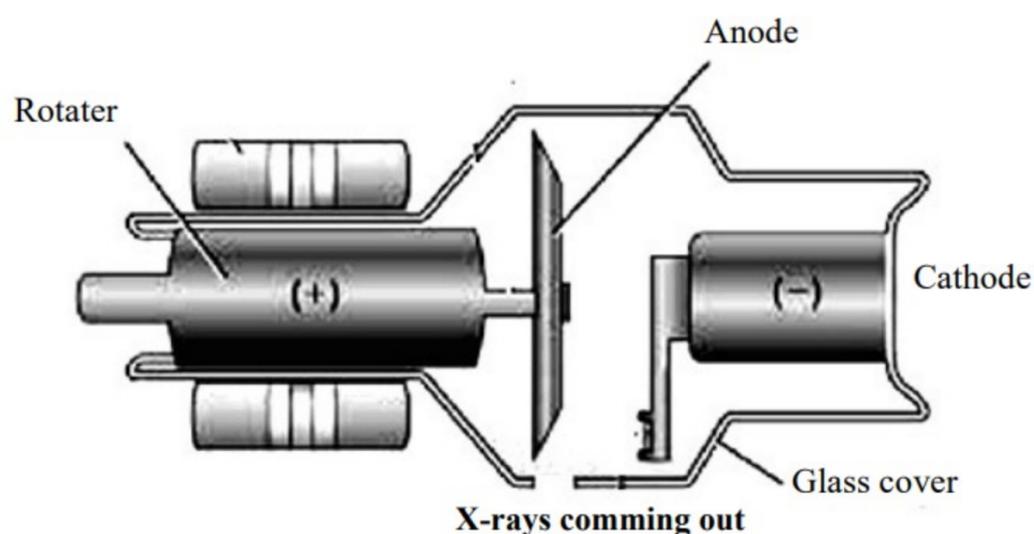
Figure 4.5 X-ray tube with a rotating anode

4.2.1 Controlling the X-ray beam

To obtain a high quality X-ray image, both the hardness and intensity of the X - ray beam need to be controlled. The penetrating ability of X-rays can be increased by increasing the operating potential difference. X-rays with a higher frequency (i.e. with a shorter wavelength) have more penetrating ability. They are hard X-rays. X-rays with a lower frequency (i.e. with a longer wavelength) are known as soft X-rays and their penetrating ability is less.

The intensity of X-rays depends on the number of electrons reaching the anode. By controlling the current flowing through the filament, the intensity of X-rays can be vaned. By increasing the rate at which the electrons are incident on the target, the intensity of X-rays emitted by the target metal increases.
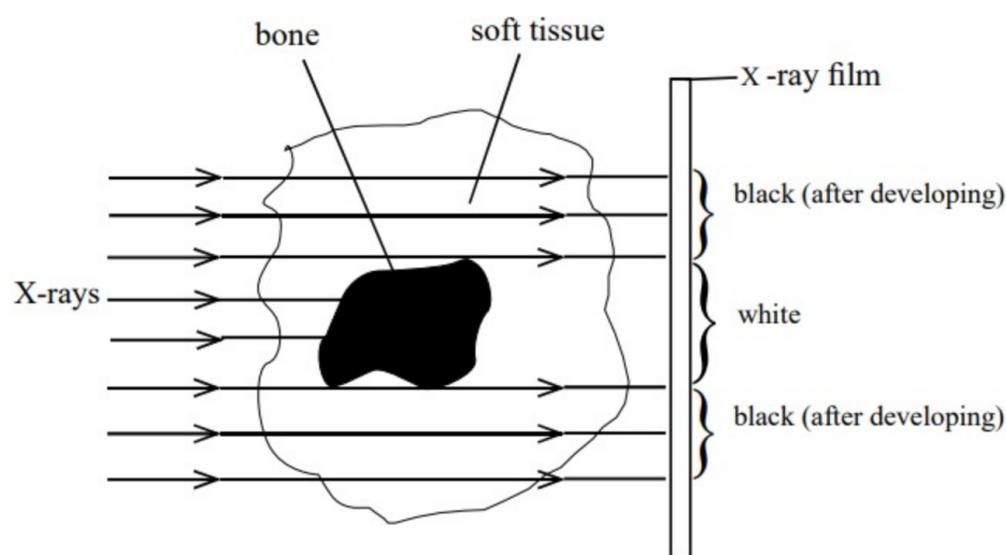

Figure 4.6   X-ray photo

Figure 4.7 X-ray image

The X-ray image shown in Figure 4.6 is not like a real image obtained using a lens. This image in fact is a shadow as shown in the figure. The X-rays are incident on a part of the patient's body and then penetrate it. In that process a very low amount of energy is lost when the X-rays penetrate the parts such as the skin fat and soft muscles. Therefore, after the photographic film is developed, it gives gloomy image regions corresponding to the soft tissues. When penetrating bones, the intensity of X-rays is highly reduced. Therefore the image regions corresponding to bones appear to be white. As the parts of bones, muscles, soft tissues and blood of the human body are with various densities, they absorb X-rays in different amounts. The X-rays which are transmitted through such parts give shadow images so that broken or dislocated bones can be identified. Also the muscles with extraordinary growth and foreign bodies like pieces of rocks and metals can easily be identified. To obtain a sharp image, a parallel beam of X-rays is required.

Barium can absorb X-rays well. To examine stomach disorders the patient is given a drink of barium sulphate solution. When an X-ray photo is taken while meals mixed with barium passing through the intestine, as barium absorbs X-rays well, when there is some blockage or extraordinary growth, abnormalities of absorption of X-rays occur. Then, such disorders can be observed. To destroy cancerous cells, hard X-rays (with high frequency and high photon energy) are used as an alternative to radium treatment. The X-ray images used in the process of treatment in medical and dental fields are generally shadow images. Bones and teeth absorb X-rays much strongly. By passing X-rays through a metal (aluminium) filter, low energy photons can be separated. Then, it minimizes the harmful effects on the soft tissues associated with bones and teeth.

4.2.2 Properties of X - rays

- X -rays are electromagnetic waves of very short wavelength. In a vacuum, they travel with the velocity of light.
- They are not deflected by electric and magnetic fields. This proves that they are not a kind of charged particles.
- X-rays can penetrate into matter. They can be absorbed almost totally by a plate of lead with a thickness of about 1 mm. To get protected from X- rays, covers made with plates of lead are used.
- X-rays cannot be focused on by lenses. When travelling through different media, they get deviated very little. For all substances, the refractive indices of them are very nearly equal to one.
- They can be diffracted by a crystal lattice.
- Gases get ionized when X-rays are travelling through them.
- Photographic films are sensitive to X-rays.
- They make fluorescence when incident on some minerals and salt (such as PbS, ZnS and barium platinocyanide)

- X-rays make photoelectric emission in which metal surfaces emit electrons due to photoelectric effect.

4.2.3 X-ray spectrum*

The rays emitted by an X-ray tube are analyzed using a spectrometer and then a graph of intensity against wavelength is plotted. The graph is as shown by figure 4.8. When the potential difference across the tube is increased, then the minimum wavelength decreases.

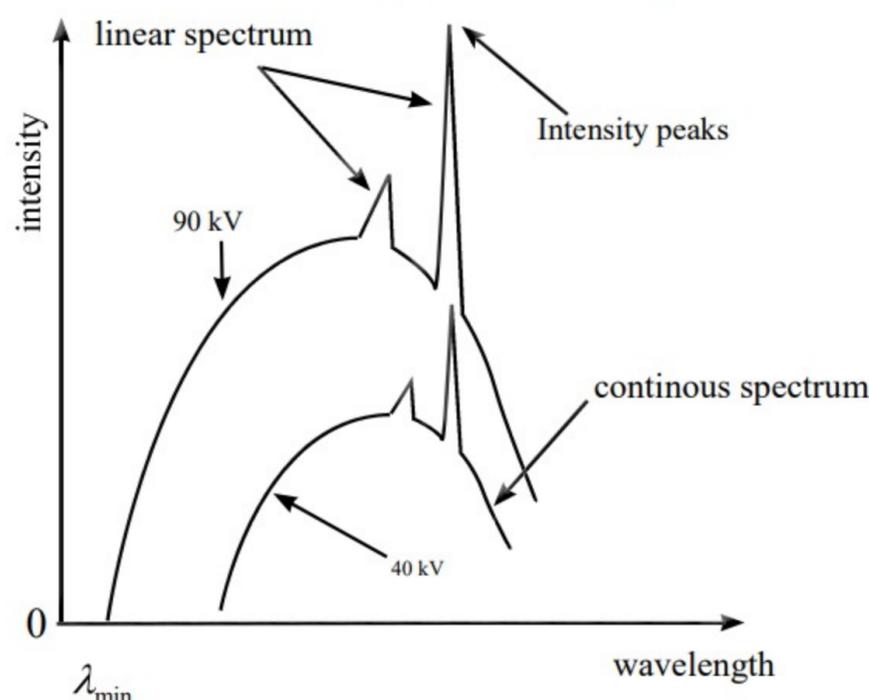The X-ray spectrum consists of two major parts as line spectrum and continous spectrum.

Figure 4.8 - Intensity Vs. wavelength for an X-ray tube

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* Section 4.2.3 ; X-ray spectum is not included in the G.C.E. Advaned Level physics syllabus which is implemented from 2017.

Continuous spectrum with a minimum wavelength (λ_{min}) which depends on the potential difference applied to the X-ray tube: when the potential difference increases the value of λ_{min} decreases. All the target metals emit this type of radiation.

Line spectrum with several intense points: these wavelengths are characteristic of the target metal. They do not depend on the high voltage applied to the X-ray tube. The wavelength of emitted X-ray depends on the deceleration of electrons.

The electrons do not have the same deceleration and the deceleration values lie in a wide range. To make this clear, let us calculate the possible minimum wavelength of X-rays which are produced by a tube with potential difference of 30 kV between cathode and anode.

Electron charge is 1.6×10^{-19} C, velocity of light is 3×10^8 m s^{-1} and Planck's constant is 6.6×10^{-34} J s.

X-rays with a minimum wavelength (photons with a maximum energy) are obtained when the total energy of an electron is converted into a photon. The total kinetic energy of an electron which accelerates under a potential difference V is eV and the energy of a photon of wavelength λ *is* $\dfrac{hc}{\lambda}$. Therefore, when the total energy of an electron is totally converted into a photon, it can be written as,

$$eV = \frac{hc}{\lambda_{min}}$$

$$(1.6 \times 10^{-19} \text{ C}) \times (30 \times 10^3 \text{ V}) = \frac{(6.6 \times 10^{-34} \text{ J s}) \times (3 \times 10^8 \text{ m s}^{-1})}{\lambda_{min}}$$

$$\lambda_{min} = 4.1 \times 10^{-11} \text{ m}$$

It should be considered that the probability of converting total energy in an electron into a photon, is very low. In most cases, what happens is the emission of photons with a part of that energy. Therefore, photons of any wavelength, which is greater than the minimum possible wavelength for a given potential difference, can be emitted. It is because of this process, that the continuos part of the X-ray spectrum is obtained.

4.2.4 Other uses of X-rays

1. In the study of outer space, it has been found that celestial objects such as systems of binary stars, neutron stars, some comets and the sun also emit X-rays.

2. In the engineering and industrial field, X-rays are used to find faults in the internal metal structure of joints such as welds and rivets.

3. To identify metals and alloys, their X-ray diffraction patterns are used. This kind of analysis was first done with a crystal of sodium chloride which is a simple compound. Later, by those experiments it was possible to have a detailed understanding of atomic structures of complex molecules including DNA.

4. In security measures, in airports and other important places, X-rays are used to examine the contents of the parcels and baggage without opening them. In this process they are exposed to X-rays and the relevant images are obtained directly on a computer screen.

Chapter 05

Radioactivity

5.1 Introduction

In 1896 Henry Becquerel observed that a uranium compound placed on a photographic film wrapped in black paper has made black spots on the film. Then he experimented, introducing plates of cardboard, aluminum and lead between the compound and the film. In those cases also the same results were obtained. From those observations it was decided that the uranium compound emits a particular radiation with a penetrating ability. After doing further experiments about those rays Marie Curie found that they were different from the X-rays, and she named that phenomenon as radioactivity.

Figure 5.1 Henry Becquerel   **Figure 5.2 Marie Curie**

The elements which emit radiation as mentioned above, are called radioactive elements. Later, Marie Curie and Pierre Curie could find two radioactive elements, radium and polonium by extracting pitchblende which was a naturally existing mineral. For the discovery of polonium and radium they were awarded the Nobel Prize for Physics in 1903. So far, it has been found that there are about 40 radioactive elements. The elements with atomic number (Z) greater than 82 are unstable and radioactive. Radium and Thorium can be taken as examples. The nuclei of atoms of heavy elements are unstable. This unstableness causes radioactivity.

5.2 α, β and γ radiation

Three types of radiation are emitted by radioactive elements. They are named as follows; the radiation with the minimum penetrating ability as the α - particles, the radiation with a higher penetrating ability than α - particles, as β - particles, the radiation with the maximum penetrating ability as γ - radiation.

γ - rays can penetrate cardboard and even aluminum plates.Thick lead plates can stop γ - rays. β - particles can pass through cardboard but not through aluminum. α - particles are stoppable even with cardboard.
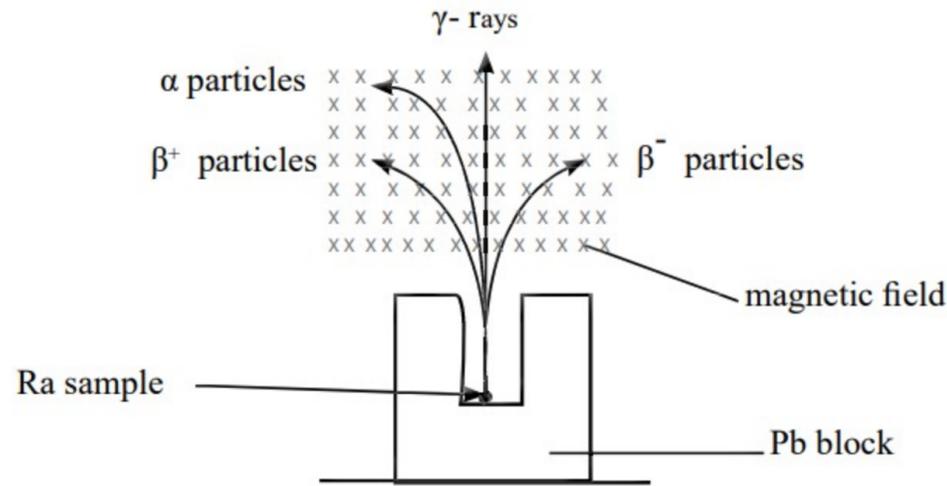

Figure. 5.3

An experiment used to study the nature of α - particles, β - particles and γ - rays is shown in Figure 5.3. A sample of radium is placed in a small cavity made in a block of lead. The radiation coming out of the hole is subjected to go through a perpendicular magnetic field. Then, one type of radiation proceeds without any deviation and the other two types get deviated sideways. According to Fleming's left hand rule, it is clear that the radiation deviated left hand side is positively (+) charged and the radiation deviated towards right hand side is negatively (-) charged. They are named as α - particles and β - particles respectively. The radiation which travels without getting deviated is uncharged and it is an electromagnetic radiation with a very high frequency (γ - rays). When the above experiment is done using the electric field in place of the magnetic filed, the results obtained are shown in Figure. 5.4.
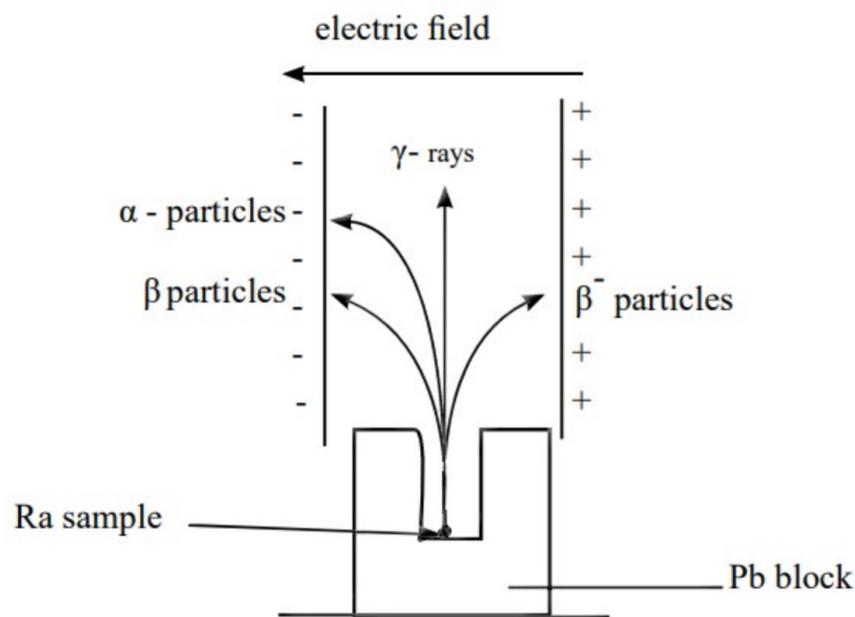

Figure 5.4

In that experiment, it has been observed that all the α - particles are deviated towards the negatively charged electrode by the same amount and β - particles are deviated towards the positively charged electrode by different amounts.

It has been found that all α - particles are deviated by the same amount for the reason that each of them has the same amount of energy, and that β - rays deviated by different amounts as their energies are different from one another.

5.2.1 α particles $\left({}^{4}_{2}\text{He} \right)$

1. These particles have been identified as helium nuclei. Each particle bears a charge which is twice the charge of the proton.

2. The mass of an α - particle is approximately four times the atomic mass of hydrogen.

3. The approximate velocity of α - particles is 0.06 times the velocity of light. This velocity depends on the source by which they are emitted.

4. The penetrating ability of α - particles is about $\frac{1}{100}$ of that of β - particles and about $\frac{1}{10^4}$ of that of γ - rays. The reason for that, is the higher mass of α - particles relative to others. α - particles can travel about 5 cm through air at standard temperature and pressure. α - particles can penetrate through a plate of aluminum of thickness less than 0.01 cm.

5. α - particles can ionize gases highly.

6. Make florescence when fallen on materials such as barium palatinocyanide and zinc sulphide.

7. Get deviated by electric fields and magnetic fields.

8. They are subjected to scattering by thin metal foils.

9. α - particles can cause skin burns.

5.2.2 β - particles

1. β⁻ particles holds a negative charge the same as the electron.

2. β⁺ particles holds the same amount of charge equivalent to that of the electron, but it is a positive charge.

3. Since the mass of β - particles is less, they have a higher penetrating ability. They can penetrate through an aluminum plate of thickness less than 0.1 cm.

4. Less ability to ionize gases.

5. Make influence on photographic plates.

6. β - particles can cause artificial radioactivity.

6. Can be deviated by electric fields and magnetic fields.

7. They can be considered as electrons moving with approximately the velocity of light.

5.2.3 γ - rays

1. Travel with the velocity of light

2. Cannot be deviated by either electric fields or magnetic fields.

3. γ- rays are electromagnetic waves with the frequency in the range

   5×10^{22} - 3×10^{18} Hz.

4. Very weak in ionizing gases.

5. Penetrating ability is very high. They can penetrate through a metal plate having the thickness of few centimeters.

6. Has influence on photographic films.

7. Wavelength is very short. They are used to destroy harmful bacteria and to sterilize food and medical equipment.

8. Able to pull out electrons from the surface when fallen on a surface.

9. Used to destroy cancerous cells as a medical treatment.

10. The rest mass of a photon of γ- ray is zero.

5.3 Radioactive decay

The process of emitting charged particles and energy from the nuclei of a particular element due to their unstableness, is known as radioactivity. In the process, most of the time the initial element converts into another element. For example, if we take one gram of radium, and measure the radium content of it, after a sufficient period of time, then it can be found that it is less than one gram. Therefore, this process is known as **radioactive decay.**

The conversion of each nucleus into a nucleus of another element by emitting charged particles and energy, due to radioactivity, is called **disintegration**.

Since the radioactivity is related to the internal stability of nuclei, it is a phenomenon which does not depend on external factors such as temperature and pressure. It cannot be forecast, which atom of a radioactive element disintegrates at which time.

When a radioactive element disintegrates an α particle or a β particle is emitted. These two particles are not emitted at the same time. An atom does not emit more than one particles of α or β at a time.

The nucleus becomes more stable by emitting an α - particle or a β - particle. That emission changes the number of protons and neutrons in the nucleus. The initial nucleus is called the parent nucleus and the nucleus obtained as a result of disintegration is called the daughter nucleus.

5.4 Radioactive isotopes

A nucleus is made by combining some number of protons (Z) and neutrons (N). The element to which a nucleus belongs is identified by the charge, that is the number of protons, in that nucleus. This is also known as the atomic number. What is known as the atomic mass number (A) is the sum of the number of protons and neutrons in the nucleus ($Z + N$).

A kind of nucleus with a certain number of protons and neutrons is called a nuclide. It is symbolized by $^{A}_{Z}X$, where X denotes the relevant element.

Nuclides having the same number of protons as well as different number of neutrons are there in nature. They belong to the same element as their atomic number is the same, but their mass numbers are different from each other. This type of nuclides are known as **isotopes.** For a given element there may be several isotopes while some of them may be stable and some may be unstable (radioactive) isotopes.
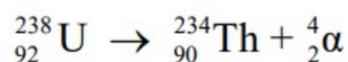
5.5 α - emission (α - decay)

After emitting an α - particle, the daughter nucleus gets its mass number decreased by four and its atomic number decreased by two. The formation of elements after radioactive decay process of some element, is called **transmutation.**

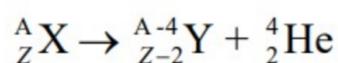α - emission can be expressed as a nuclear equation as follows.

The α - emission from Radium

$$^{226}_{88}\text{Ra} \rightarrow \,^{222}_{86}\text{Rn} + \,^{4}_{2}\alpha$$
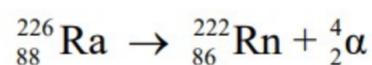
The α - emission from Uranium

$$^{238}_{92}\text{U} \rightarrow \,^{234}_{90}\text{Th} + \,^{4}_{2}\alpha$$

The general equation for the α - emission can be given as follows.
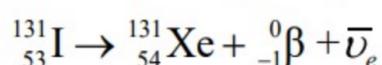
$$^{A}_{Z}\text{X} \rightarrow \,^{A-4}_{Z-2}\text{Y} + \,^{4}_{2}\text{He}$$
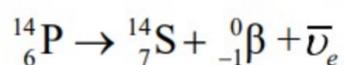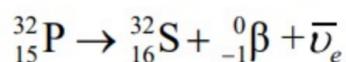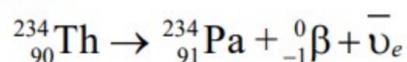
This equation states that the nucleus X having the mass number A and the atomic number Z becomes the nucleus Y which has the mass number A-4 and the atomic number Z-2 after emitting a helium nucleus.

5.6 β - emission (β - decay)

Some radioactive nuclei emit electrons or positrons to come to a more stable state. This is called the β⁻ emission. Positron is a particle similar to electron in all its properties other than the charge. The positron has a positive (+) charge which is equal to the electron change in magnitude. The position is regarded as anti-particle of the electron. When the number of neutrons is greater than the number of protons in the nucleus, β⁻ emission takes place. The process of emitting an electron is known as β⁻ emission. In this process, the mass number remains unchanged and the atomic number increases by one.
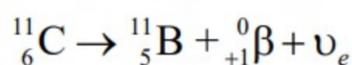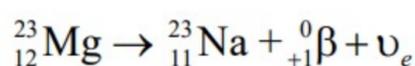
Examples:

$$^{234}_{90}\text{Th} \rightarrow \ ^{234}_{91}\text{Pa} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$$

$$^{32}_{15}\text{P} \rightarrow \ ^{32}_{16}\text{S} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$$

$$^{14}_{6}\text{P} \rightarrow \ ^{14}_{7}\text{S} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$$

$$^{131}_{53}\text{I} \rightarrow \ ^{131}_{54}\text{Xe} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$$

$$^{14}_{6}\text{C} \rightarrow \ ^{14}_{7}\text{N} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$$
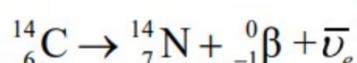
In the above decay process in addition to a β⁻ particle another particle called an anti-neutrino υ_e is emitted. (Emitting a particle called anti-neutrino in β⁻ emission, is required, for that process to obey the law of conservation of energy and the law of conservation of momentum). The anti-neutrino is an uncharged fundamental particle having a negligible mass. In case where there is a number of more neutrons in the nucleus ($N>Z$), a neutron is transformed into a proton and an electron. This proton remains in the nucleus while the electron and the anti-neutrino leave the nucleus at a very high speed.
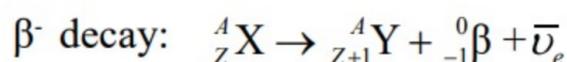
The process of emitting a positron ($^{0}_{1}\beta$) which is the anti-particle of the electron, is known as β⁺ decay.
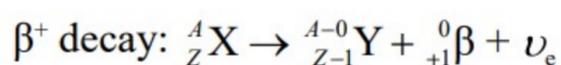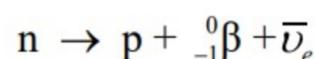
Examples :

$$^{23}_{12}\text{Mg} \rightarrow \ ^{23}_{11}\text{Na} + \ ^{0}_{+1}\beta + \upsilon_e$$

$$^{11}_{6}\text{C} \rightarrow \ ^{11}_{5}\text{B} + \ ^{0}_{+1}\beta + \upsilon_e$$

where υ_e denotes a neutrino.

The above decay process can be given in the general form as follows.

β⁻ decay: $^{A}_{Z}\text{X} \rightarrow \ ^{A}_{Z+1}\text{Y} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$

In β⁻ decay, a neutron transforms into a proton.

$$\text{n} \rightarrow \text{p} + \ ^{0}_{-1}\beta + \bar{\upsilon}_e$$

β⁺ decay: $^{A}_{Z}\text{X} \rightarrow \ ^{A-0}_{Z-1}\text{Y} + \ ^{0}_{+1}\beta + \upsilon_e$

In β⁺ decay: a proton transforms into a neutron.

$$p \rightarrow n + \ ^{0}_{+1}\beta + \upsilon_e$$
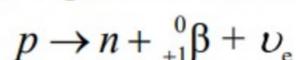
5.7 γ - emission (γ - decay)

In general when a radioactive nucleus is decaying, the daughter nucleus obtained after emitting α- particles or β - particles, is in an excited site. This daughter nucleus then comes to a lower energy state or the ground state by emitting γ - rays. This does not change the element that nucleus belongs to. As an example the way this process happens, can be represented by equations as follows.

$$^{12}_{5}B \rightarrow \,^{12}_{6}C^* + \,^{0}_{-1}\beta + \bar{\upsilon}$$
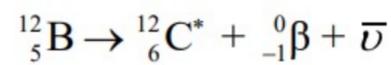
Here, * denotes that C (carbon) nucleus is in an excited state. This excited nucleus (C) then emits a γ - ray and comes to the ground state.

$$^{12}_{6}C^* \rightarrow \,^{12}_{6}C + \gamma$$
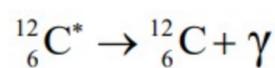
In some cases this emission of γ - rays occur in two steps. Given below is an example for such an occasion.

$$^{60}_{27}Co \rightarrow \,^{60}_{28}Ni^* + \,^{0}_{-1}\beta + \bar{\upsilon}_e$$

$$^{60}_{28}Ni^* \rightarrow \,^{60}_{28}Ni + \gamma$$
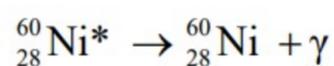
First the Co nucleus emits a γ - ray and becomes an excited Ni nucleus. Then it comes to the ground state by emitting two γ - rays as shown in Figure 5.5.
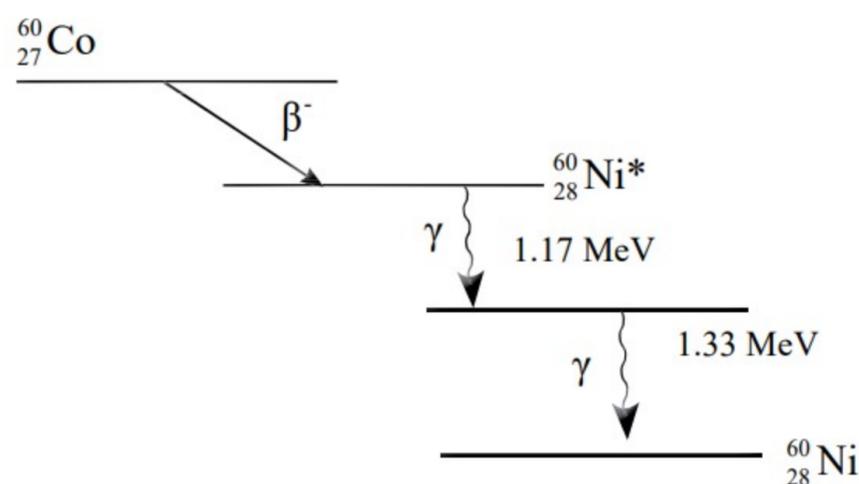

Figure 5.5.

5.8 Radioactive nuclides

Radioactive material used in various industries and in medical treatments (radioactive nuclides)

Cobalt-60
- Sterilization of surgical instruments
- Destruction of cancerous cells
- Food irradiation for preservation

Iron-55
- Detection of the presence of sulphur in air

Sodium-24
- To locate leakages in industrial pipelines

Uranium-235
- Nuclear power plants
- Nuclear propulsion systems (specially in submarines)
- To produce fluorescent glassware, colour glazes and wall tiles

Plutonium-238
- As a power source in satellites

    (Has been supplying power for NASA space crafts since 1972)

Thorium-229
- In the production of welding rods
- Helps fluorescent lamps last longer

Polonium-210
- To minimize static charges in the production of photographic films

Iridium - 192
- To test the integrity of aircraft parts
- Tumour irradiation

Americium-241
- To determine where oil wells should be drilled
- To test the level of harmful lead in samples of dry paint

Californium-252
- To detect explosives hidden inside luggages at airports

Krypton-85

- To check whether the thickness of thin plastic or metal sheets is correct with the required accuracy

Iodine-125

- To measure the volume of blood in the body

Iodine-123

- For kidney function test and thyroid test

5.9 Radioactive disintegration law

As it has been mentioned earlier, radioactivity is a random process. That means we can not forecast on the disintegration of a nucleus. Nevertheless, when there is a large number of radioactive nuclei, the way the number of nuclei decreases with time can be calculated easily. For that, the law known as radioactive disintegration law is applied.

That law states that, the rate of disintegration of a given sample of radioactive elements at any moment is directly proportional to the number of radioactive nuclei present at that moment.

Let N be the number of nuclei in the sample. If ΔN is the number of nuclei subjected to decay within a very short period of time Δt, then the rate of disintegration of the sample can be written as ;

$$\frac{\Delta N}{\Delta t} = -\lambda N$$ where λ is a constant called as the decay constant.

Suppose that a sample of elements having the number of nuclei N_o at the start, undergoes disintegration for a period of time t. If N is the remaining number of nuclei after time t, then using integration in mathematics it can be written as,

$$N = N_0 e^{-\lambda t} \text{ -------------(1)*}$$

According to this, if the remaining number of nuclei (N) at any time is plotted against time (t), then we obtain a graph as shown in Figure 5.6.

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* The above question (1) is not included in the G.C.E. Advance Level physics syllabus which is implemented from 2017.
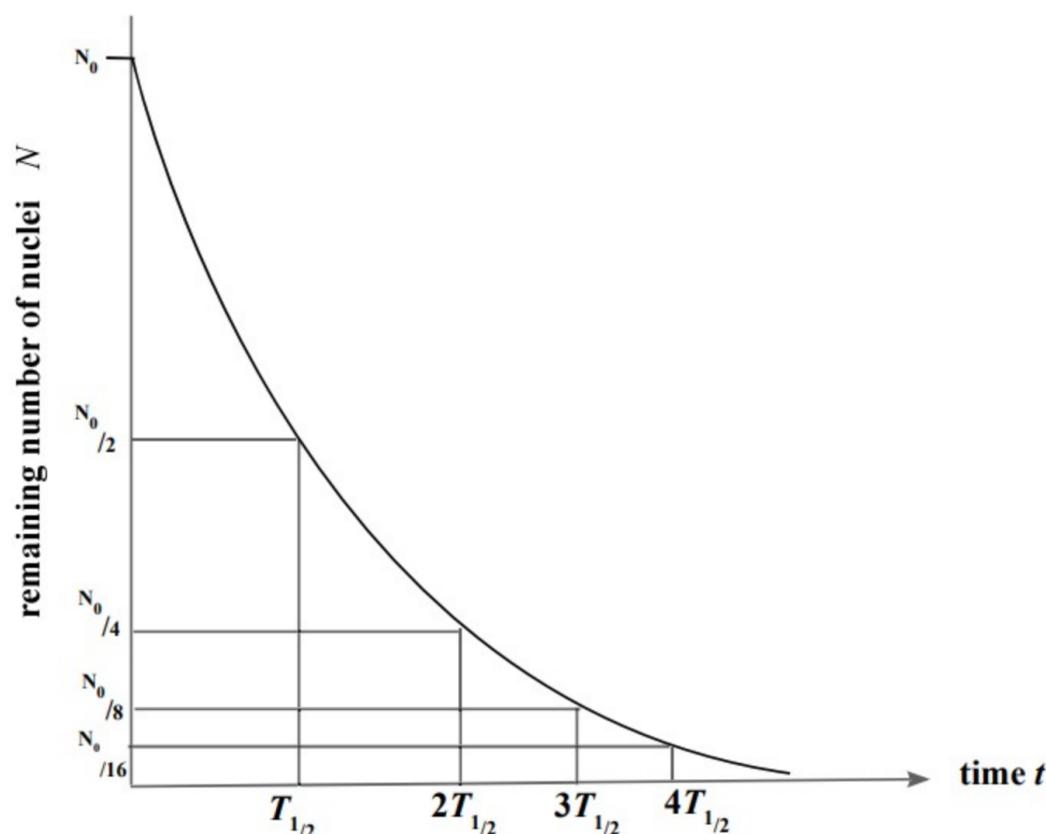
Figure 5.6

The time taken for the initial number of nuclei in a sample of radioactive element, to become half, is called the half life of that radioactive element. The half-life does not depend on the initial number of nuclei, and is a constant for a given kind of nuclei. In general , the symbol $T_{1/2}$ is used to denote the half-life.

Figure 5.6 shows how the initial number of nuclei (N_o) decays gradually with time. After a period of time $T_{1/2}$ from the beginning, the remaining number of nuclei is $N_o/2$. In another period of time $T_{1/2}$ the remaining number of nuclei is $N_o/4$. In this manner the remaining number of nuclei is halved after each period of time $T_{1/2}$.

It was mentioned earlier that, if the initial number of nuclei is N_o and the remaining number of nuclei after time t is N,

$$N = N_o e^{-\lambda t}$$

According to the definition of half-life , after a time $T_{1/2}$ from the initial state, the remaining number of nuclei should be $\dfrac{N_0}{2}$

---

* The above question (2) is not included in the G.C.E. Advanced Level physics syllabus which is implemented from (2017).

By substituting this in the above equation,

$$\frac{N_0}{2} = N_0 e^{-\lambda T_{\frac{1}{2}}}$$

$$\frac{1}{2} = e^{-\lambda T_{\frac{1}{2}}} \quad or \quad 2 = e^{-\lambda T_{\frac{1}{2}}}$$

Therefore, $T_{\frac{1}{2}} = \frac{1}{\lambda} \ln (2)$

5.10 Activity of a radioactive element (*A*)

The activity of a sample of radioactive material is the rate of decay or the number of disintegrations that occurs in 1 second.

At a given time if there are N number of nuclei then the rate at which this number is decreasing, can be written as $-\frac{dN}{dt}$.

The minus sign here indicates that it is a decrease. At a given situation, the relationship between the number of nuclei (N) and the initial number of nuclei (N_o) can be given as

$N = N_0 e^{-\lambda t}$

By differentiating the previously mentioned equation $N = N_o e^{-\lambda t}$ we get,

$$\frac{dN}{dt} = -\lambda N_0 e^{-\lambda t} \quad \text{----------(2)*}$$

Therefore, the activity can be written as, $A = -\frac{dN}{dt} = -\lambda N$.

The unit of measure of activity is becquerel (Bq) and one Becquerel is defined as one disintegration per second. The unit called curie (Ci) is also used to measure activity.

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

The half life of a radioactive isotope can also be defined as the time taken for the activity to fall to half of the starting value. Some radioactive elements and their half lives are given in the Table 5.1.

Table 5.1 - Some radioactive elements and their half-lives

Radioactive element	Half – life
Boron-12	0.02 seconds
Radon-220	52 seconds
Iodine-128	25 minutes
Radium-226	1602 years
Carbon-14	5730 years

5.11 Radioactive dating or carbon dating

Radioactive dating is the use of properties of radioactive carbon, to determine the age of organic samples (parts of animals and plants) found in archaeological excavation.

Most of the carbon in our environment prevail as $^{12}_{6}C$ (carbon-12) isotope. A very few percentage prevail as $^{14}_{6}C$ (carbon-14) which is a radioactive isotope.

Carbon-14 isotope is produced with the help of cosmic rays. Cosmic rays are high speed charged particles coming to the earth from outer space. These charged particles collide with air molecules in the atmosphere and produce neutrons and several other fundamental particles. The neutrons thus produced, collide with nitrogen nuclei in the atmosphere and produce carbon-14 as shown in the following equation.

$$^{1}_{0}n + ^{14}_{7}N \rightarrow ^{14}_{6}C + ^{1}_{1}p$$
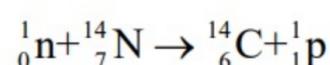
This carbon-14, after combining with oxygen in the atmosphere produces carbondioxide and then gets added to the food chain of animals through the plants.

The half life of carbon-14 isotope is about 5730 years. Therefore, the carbon-14 in a body of an animal or in a plant decays slowly. As long as the animal or the plant is alive, their ratio of carbon-14 to carbon-12 is constant because new carbon-14 is coming through food or air. The value of this ratio is 1.3×10^{-12} and it has been nearly a constant throughout thousands of years. For the living parts of plants and animals, the above disintegration process can be given by;

$$\frac{^{14}_{6}C}{^{12}_{6}C} = 1.3 \times 10^{-12}$$

After death, carbon-14 percentage decreases gradually as the outside carbon does not enter into dead parts. Therefore, by measuring the ratio of carbon-14 to carbon-12 of a dead part of an animal or a plant, the age of that part can be determined.

A sample found in an archeological excavation has one gram of carbon with the activity A. If A_0 is the activity of it when the sample is alive and t is the age of the sample, then

$$A = A_0 e^{-\lambda t} \quad \text{--------------- (3) *}$$

_____

* The above equations (3) and (4) are not included in the G.C.E. Advanced Level physics syllabus which is implemented from 2017.

from which we get,

$$t = \frac{1}{\lambda} \log_e \left(\frac{A_0}{A} \right) \quad \text{--------- (4)*}$$

The present activity of the sample can be measured with the help of a Geiger counter or other suitable apparatus. Initial activity can be calculated as follows.

Decay constant of the carbon -14 nucleus

$$\lambda = \frac{0.698}{T\,\frac{1}{2}} = \frac{0.698}{5730 \times 365 \times 24 \times 3600} S^{-1} = 4.00 \times 10^{-12} S^{-1}$$

Number of carbon-14 nuclei in 1 gram of live sample $N = \left(\frac{6.023 \times 10^{23}}{12} \right) \times 1.3 \times 10^{-12}$

Activity of 1 gram of carbon in the live sample.

$$A_0 = \lambda N = \left(\frac{6.023 \times 10^{23}}{12} \right) \times 1.3 \times 10^{-12} \times 4.00 \times 10^{-12} \, Bq = 0.26 \ Bq$$

Substitute the values for A, A_0 and λ in the equation (4) the age of the sample can be estimated.

5.12 Units of measuring radiation

The amount of radiant energy or dose absorbed by some matter (a material or an organism) is measured using the measuring unit Gray (Gy).

$$1 Gy = 1 \ J \ kg^{-1}$$

The radiation dose related to producing biological harm or influence on living bodies, by various types of radiation, is measured by the effective dose of radiation. Its measuring unit is sievert (Sv).

(Effective radiation dose = Q-factor × absorbed dose of radiation)

where the Q-factor or RBF-factor (Relative Bilogical Effectiveness) is dependent upon the nature of radiation.

Q-factor for several types of radiation is given in the following table.

Type of radiation	Value of Q factor
β, γ, X	1
n	5 to 20
α	20

5.12.1 Background radiation

Radioactivity is a natural phenomenon. There is a little amount of radioactive nuclides in rocks such as granite. About 51% of the background radiation is due to radioactive radon and its daughter elements. In addition to that, radiation enters the body in the ways such as from radiation sources (X-ray), through food and various drinks we consume, from cosmic rays and from air breathing in. Because of this reason, a person normally receives a radiation dose of about 0.0015 Sv per year. Radiation workers must not exceed the receiving radiation dose of 0.05 Sv in a year.

Background radiation source	Amount of radiation
Radon and its daughter elements	51%
Devices such as X-ray machines used for medical purposes	12%
Consumption of food	14%
γ - rays emitted by soil and rock	10%
Cosmic rays coming from outer space	10%
Random occasions (nuclear explosions, radiation leakage in nuclear power plants)	01%

5.13 Radiation hazards

Living tissues get damaged as a result of exposure to natural radiation such as α, β and γ rays. This type of nuclear radiation ionizes the atoms in the living cells and hence the damage occurs. Exposure to this harmful radiation may cause damage to reproductive system, mutation of genes, sterility, leukemia (as a result of the destruction of blood producing cells) and other types of cancer, blindness and immune deficiency. If somebody gets exposed to a high dose of radiation (eg. produced in a reaction) then that may lead to a sudden death.

Radioactive sources should not be touched with the hand. You should always be as far as away from those sources and should minimize the time during which you are close to them.

- Radiactive sources should be labelled and stored in safety (lead-concrete) cupboards.

- When handling them gloves and forceps should be used.

- Refrain from having meals at places where there are radioactive sources and the eye and nose should not be directed towards the sources.

- Waste material such as pieces of cloth and paper used in experiments relating to radioactivity, should be removed in the proper way.

5.14 Radiation detectors

When α particles, β-particles, X-ray and γ-rays travel through a gas, the gas molecules get ionized and make positive and negative ions. The number of ions thus produced depend on the amount of radiation passed through the gas. To measure the number of ions produced, various types of detectors are used.
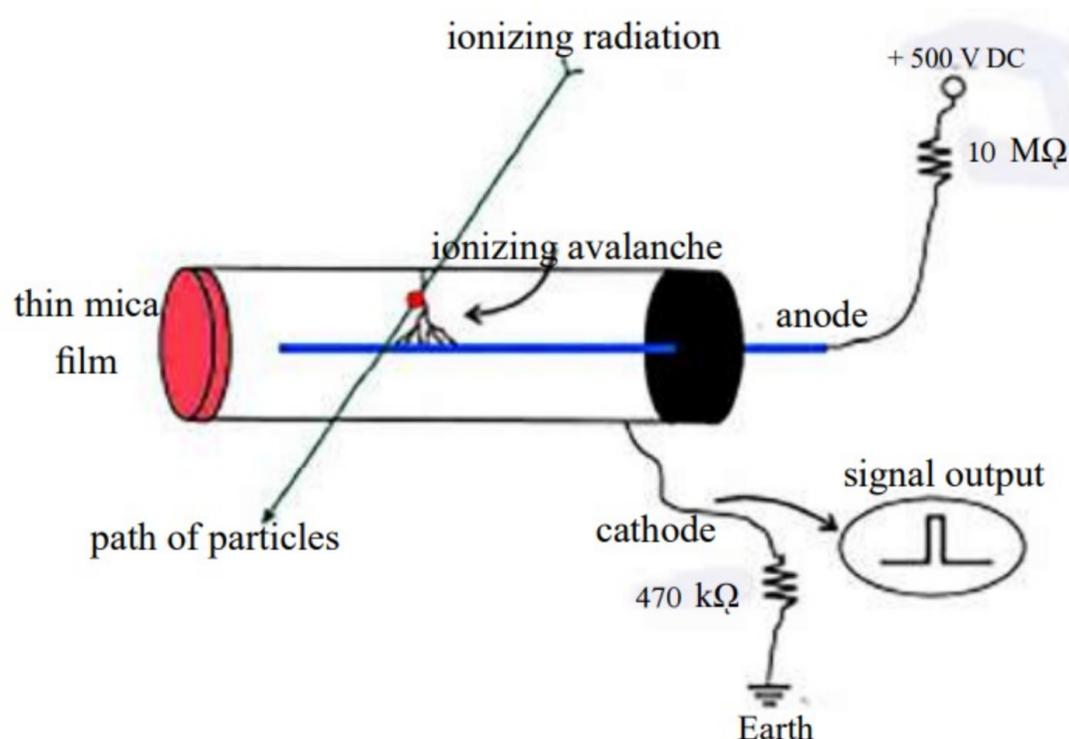
Geiger Mueller tube

Figure 5.7

Geiger tube has been made so that there is a cylindrical cathode and an anode wire kept along the axis of that cylinder. At one end of the tube, there is a window made with a very thin mica film and the other end has been closed with a lid made of an insulting material. A potential difference of about 500 V is applied across the cathode and the anode. Geiger tube is sealed and has been filled with low pressure (about 10 mm Hg) gases of argon and a little amount of halogen. As shown in Figure 5.7, when an ionizing radiant particle travels across the tube, the argon atoms get ionized, forming electrons and positive ions. Because of the potential difference across the anode and the cathode the electrons gain high kinetic energy and make collisions with argon atoms and hence ionize gas atoms more and more. (This process is called as the **Avalanche effect.)** As a result, a large number of electrons reach the anode at once and create an electric current pulse in the external circuit.

According to this, even with a single radiant particle entering the tube, in one occurrence of ionization, it is possible to have a large current pulse, making about 10^8 free electrons within a very short period of time $\frac{1}{10}\mu s$. After the occurrence of one avalanche at the anode, positive argon ions reach the cathode. These ions are neutralized and then the

57

current pulse through the cathode is stopped. This is done by the halogen (bromine) gas in the tube. As a result of the above process, only one current pulse is created per one radioactive photon entering to the tube. A voltage pulse of about 1 volt is created across the 10 megaohm resister in the external circuit, due to this current pulse. This voltage pulse is then amplified and sent to a rate-meter. With a rate-meter, the rate at which the radioactive particles (photons) enter the tube can be measured. To prevent sparks at the free end of the anode, the end point is covered with a bead of glass.

Worked Examples

01. A particular radioactive nucleus (A) transforms into a stable nucleus (C) as given below. B is an intermediate nucleus which is radioactive.

    $A \rightarrow B \rightarrow C$
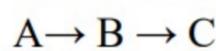
    At the beginning there were N_0 number of nuclei of A. Draw the graphs of a number of atoms of A and B against time, to show how those numbers vary.

Answer

At the beginning ($t = 0$) $N_A = N_0$ and $N_B = 0$

The number of A atoms (N_A) decreases exponentially with time and tends to zero when $t \rightarrow \infty$. The existing number of B atoms increases with time and reaches a maximum and then decreases exponentially until it becomes zero.
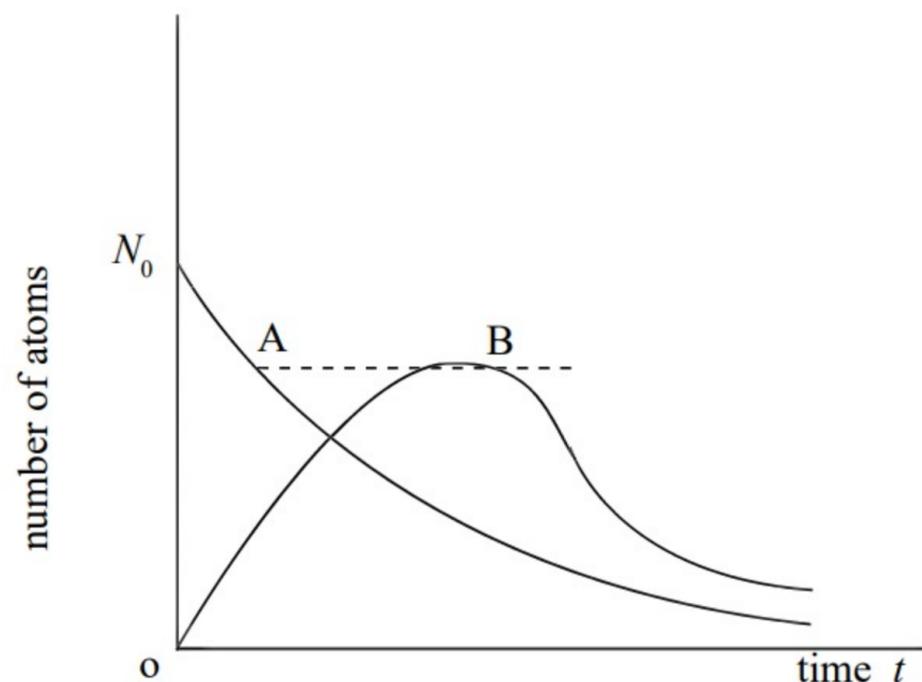
02. A fission reactor of 1000 MW takes a period of 5 years to consume half of its fuel. What amount of $^{235}_{92}U$ was there at the beginning? Assume that all the energy is generated by fission and that the time during which the reactor operates is 80% of the total time. Consider that 200 MeV of energy is released by the fission of a uranium nucleus.

Answer

Energy released by one nucleus of uranium = 200 MeV

Energy generated by the fission of 1 kg of uranium

$$= \frac{200 \times 10^6 \times 6.023 \times 10^{23} \times 1000}{235}$$

$$= 5.106 \times 10^{32} \times 1.6 \times 10^{-19} \text{ J}$$

$$= 8.17 \times 10^{13} \text{ J}$$

Total energy generated in 5 years

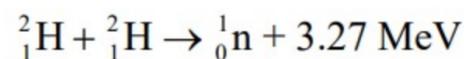$$= 1000 \times 10^6 \times 0.8 \times 5 \times 365 \times 24 \times 3600$$

$$= 1.2614 \times 10^{17} \text{ J}$$

The amount of $_{92}^{235}\text{U}$ used in 5 years

$$= \frac{1.2614 \times 10^{17}}{8.17 \times 10^{13}}$$

$$= 1544 \text{ kg}$$

Mass at the beginning $= 2 \times 1544 \text{ kg}$

$$= 3088 \text{ kg}$$

03. Calculate the time in which a 100 W electric lamp can be lit by the energy obtained from fusion of 2.0 kg of deuterium. The relevant fusion reaction in given below.

$$_1^2\text{H} + _1^2\text{H} \rightarrow _0^1\text{n} + 3.27 \text{ MeV}$$

Answer

Number of atoms in 2.0 kg of deuterium
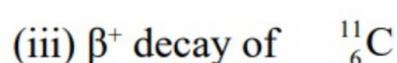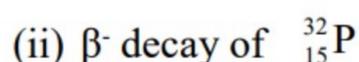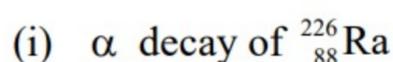
$$= \frac{6.023 \times 10^{23} \times 2000}{2}$$

$$= 6.023 \times 10^{26}$$

Energy emitted by the fusion of 2 atoms = 3.27 MeV

Total energy emitted $= \dfrac{3.27}{2} \times 6.023 \times 10^{26} \text{ MeV}$

$$= 1.635 \times 6.023 \times 10^{26} \times 10^6 \; 1.6 \times 10^{-19} \text{ J}$$
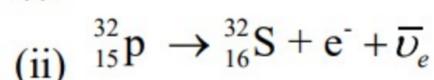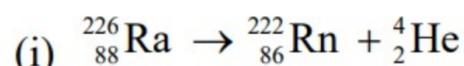
$$= 1.575 \times 10^{14} \text{ J}$$

If t is the time during which this amount of energy can be used at a power of 100 W.

$$t = \frac{15.75 \times 10^{13}}{100}$$

$$= 15.75 \times 10^{11} \text{ s}$$

$$= \frac{15.75 \times 10^{11}}{365 \times 24 \times 3600} \text{ years}$$

$$= 4.99 \times 10^{4} \text{ years}$$

04. Write down the relevant equations for the following nuclear reactions.

   (i) α decay of $^{226}_{88}\text{Ra}$

   (ii) β^{-} decay of $^{32}_{15}\text{P}$

   (iii) β^{+} decay of $^{11}_{6}\text{C}$

Answer

   (i) $^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$

   (ii) $^{32}_{15}\text{P} \rightarrow {}^{32}_{16}\text{S} + \text{e}^{-} + \bar{\upsilon}_{e}$

   (iii) $^{11}_{6}\text{C} \rightarrow {}^{11}_{5}\text{B} + \text{e}^{+} + v$ where e^{+} is the positron

05. The half-life of a radioactive isotope is T. Calculate the time taken for its activity to fall to 3.125% of the initial activity.

Answer

If the initial activity is A and the final activity is A_{0}.

$$\frac{A}{A_{0}} = \frac{3.125}{100}$$

Since the activity falls to half in each half life, after n number of half-lives it can be written as,

$$\frac{A}{A_{0}} = \left(\frac{1}{2}\right)^{n}$$

Therefore, to find the required time we should find, to which number of half lives the required time is equal to. For that, the value of n corresponding to the value 3.125/100 should be found, that is,

$$\frac{3.125}{100} = \left(\frac{1}{2}\right)^n$$

$$2^n = \frac{100}{3.125} = 32$$

$$\underline{\underline{n = 5}}$$

∴ The time taken is $5T$

6. The ratio $^{14}C : {}^{12}C$ of a piece of fossil bone is 1/2 of that of a live animal bone. If the half-life of ^{14}C is 5730 years, calculate the age of that fossil.

Answer

age of the animal bone t,

half life of ^{14}C, 5730 years

$$\frac{A}{A_0} = \left(\frac{1}{2}\right)^{t/T_{1/2}}$$

$$\frac{1}{16} = \left(\frac{1}{2}\right)^{\frac{t}{5730}}$$

$$\left(\frac{1}{2}\right)^4 = \left(\frac{1}{2}\right)^{\frac{t}{5730}}$$

$$4 = \frac{t}{5730}$$

$$t = 5730 \times 4$$
$$= 22920 \text{ years}$$

Exercises

1. Three α – particles and two positrons are emitted by a radioactive nucleus. At the beginning, the mass number and the atomic number of that nucleus were A and Z respectively. In the end the ratio of neutron to proton of the nucleus is,

(a) $\frac{A-Z-4}{Z-2}$ (b) $\frac{A-Z-8}{Z-4}$ (c) $\frac{A-Z-4}{Z-8}$ (d) $\frac{A-Z-12}{Z-4}$ (e) $\frac{A-Z-4}{Z+4}$

2. When a γ – ray is emitted by a nucleus,

   (a) Both the neutron number and the proton number get changed.

   (b) Neither the neutron number nor the proton number gets changed.

   (c) Only the neutron number gets changed.

   (d) Only the proton number gets changed.

   (e) Only the mass number gets changed.

3. The β⁻ particles with negative charge emitted in the process of radioactive decay,

   (a) are the electrons which were in the nucleus.

   (b) are the electrons produced as a result of the decaying of the neutrons which were in the nucleus.

   (c) are the electrons produced as a result of collision among atoms.

   (d) are the electrons produced as a result of the decaying of the protons which were in the nucleus.

   (e) are the electrons which revolve around the nucleus.

4. The mass of a particular radioactive material becomes $\frac{1}{16}$ of its starting mass after 2 hours. The half-life of this material is,
   (a) 30 minutes   (b) 90 minutes   (c) 45 minutes
   (d) 60 minutes   (e) 16 minutes

5. The half-life of a radioactive material is 3.6 days. At the beginning there was a mass of 20 mg of that material. The mass remaining after 36 days is,

   (a) 0.0019 mg   (b) 1.109 mg   (c) 1.019 mg   (d) 0.019 mg   (e) 0.19 mg

6. The activity of a sample of radioactive material becomes $\frac{1}{3}$ of its starting activity after 3 days. The activity after 9 days is,

   (a) $\frac{1}{3}$ of the starting value

   (b) $\frac{1}{9}$ of the starting value.

   (c) $\frac{1}{18}$ of the starting value.

   (d) $\frac{1}{27}$ of the starting value.

   (e) $\frac{1}{81}$ of the starting value.

7. At the beginning there were 4×10^{10} active nuclei in a sample of a radioactive element. The half-life of the element is 10 days. After 33 days what is the number of nuclei decayed ?

    (a) 0.5×10^{10} (b) 2×10^{10} (c) 3.5×10^{10} (d) 1×10^{10} (e) $\frac{4}{3} \times 10^{9}$

8. The half-life of radium is about 1600 years. If the starting mass of a sample of radium is 100 g, the time required for the mass to become 25 g is, in years.

    (a) 4800   (b) 6400   (c) 2400   (d) 3200   (e) 400

Answers

   1. (c)   2. (b)   3. (b)   4. (a)   5. (d)   6. (d)
   7. (c)   8. (d)

Chapter six

Nuclear energy and its uses

6.1 Atomic Structure

Atoms of all elements are made up of a nucleus and electrons which are revolving around the nucleus in various energy levels. The nucleus is made up of protons and neutrons. The neutron is a neutral particle without any charge. In 1935, James Chadwick was awarded the Nobel Prize for Physics for the discovery of the neutron. These subatomic particles are bound with a high energy. The electrons have a negative charge and they are revolving around the nuclear in various orbits. The mass of the electron is very small when compared with the mass of the atom. The above mentioned subatomic particles (protons and neutrons) are generally called nucleons. According to modern inventions, protons and neutrons are made up of quarks which are known as the most fundamental particles.

Figure 6.1 James Chadwick

Subatomic particle	Symbol	Charge	Mass
Electron	e	-1.6×10^{-19} C	9.11×10^{-31} kg
Proton	p	$+1.6 \times 10^{-19}$ C	1.6726×10^{-27} kg
Neutron	n	0	1.6748×10^{-27} kg

As mentioned above, it is clear that protons and neutrons are approximately equal in mass and that the mass of an electron is about 1/2000 of the mass of a proton or a neutron. In general, there are equal number of protons and electrons in a neutral atom. More than 99.9% of the total mass of the atom is in the nucleus. The radius of the nucleus is about $\frac{1}{10^4}$ of that of the atom.

If the atom can be enlarged to the size of a school classroom, then the nucleus will be of the size of a pin point. The nuclear radius of ^{12}C is 2.7×10^{-15} m and its atomic radius is 0.9×10^{-10} m. When these values are concerned it is clear that the atomic radius of ^{12}C is about 33000 times the nuclear radius of it. The reason for being nuclear radius being of a very small value is that the nucleons in it are bound to each other by very strong attractive forces.

Nuclear Notation

In the standard nuclear notation, the chemical symbol of an isotope, the mass number and the atomic number are shown as follows.

$$_Z^A X$$

X is the chemical symbol of the relevant element.

Z is the atomic number or the number of protons in the nucleus.

A is the mass number.

$$A = Z + N$$

Here, N is the number of neutrons.

The uniqueness of the atom is dependent upon the number of protons in the nucleus (atomic number – Z).

Eg: The number of protons in the nuclei of a carbon atom is 6.

For atom lead (Pb), it is 82.

For atom copper (Cu), it is 29.

6.2 Isotopes

Various forms of the same elements are called isotopes. In some elements, although the number of protons in their nuclei is equal , they have a different number of neutrons in them. Those atoms are called isotopes. According to the above notation, the elements having the same atomic number (Z) and different masses can be named as isotopes.

Eg : $_{92}^{238}U$, $_{92}^{235}U$, $_{92}^{233}U$ are three isotopes of the element uranium.
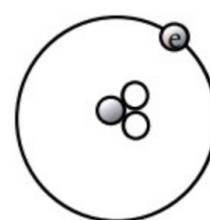
Since there is the same number of protons in isotopes, in each uncharged atom there is an equal number of electrons. They have similar chemical properties as chemical reactions depend on the electron pattern around the nucleus. Figure 6.2 shows three isotopes of hydrogen. In the nucleus of ordinary hydrogen, there is only one proton. That nucleus makes a neutral atom by combining with one electron. In the isotope called deuterium there is one neutron in addition to the proton. Since the charge of it is 1, there is also, one electron in the neutral atom. In the tritium nucleus, there are one proton and two neutrons, but there is one electron in the neutral atom.

$$_1^1 H$$

$$_1^2 H$$

$$_1^3 H$$
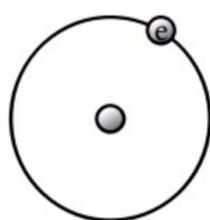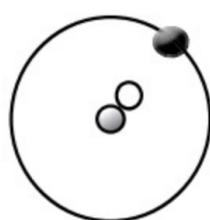
Normal Hydrogen   deuterium   Tritium
This is an unstable nucleus,
not exist in nature.

Figure 6.2

There are isotopes in natural chlorine gas and about 75% of them in the $^{35}_{17}Cl$ isotope. The remaining 25% is in the $^{37}_{17}Cl$ isotope. Carbon has four isotopes as, $^{11}_{6}C, ^{12}_{6}C, ^{13}_{6}C$ and $^{14}_{6}C$ .The most available stable isotopes of light elements such as carbon, oxygen and nitrogen have an equal number of protons and neutrons. When the mass of nucleus increases the number of neutrons gradually becomes more than the number of protons. Therefore, it can be considered that more numbers of neutrons are required to maintain the stability of heavy nuclei.

6.3 Nuclear units

In the calculation of nuclear energy the measuring units which are frequently used have been given below.

Unified atomic mass unit
In measuring the masses of atoms and nuclei, the measuring unit used is the unified atomic mass unit (amu). The symbol for this unit is u or amu. This unit has been defined as being equal to one twelfth of the mass of corbon - 12 atorm. According to the measurement obtained using the mass spectrometer, the mass of carbon 12 atom is 1.992647×10^{-26} kg.

Therefore,

$$1 \text{ u} = \frac{\text{atomic mass of } ^{12}_{6}C}{12}$$

$$= \frac{1.992647 \times 10^{-26}}{12}$$

$$= 1.660539 \times 10^{-27} \text{ kg}$$

The amount of energy corresponding to 1 u , can be calculated using Einstein's mass-energy relationship as follows.

$$E = mc^2$$

$$= 1.660539 \times 10^{-27} \text{ kg} \times (2.9979 \times 10^8 \text{ m s}^{-1})^2$$

$$= 1.49 \times 10^{-10} \text{ J}$$

6.3.1 Electron volt (eV)

The electron volt which is used as a measuring unit of energy, is defined as the amount of energy gained by an electron when it is accelerated under a potential difference of 1V.

This amount of energy is equal to 1.6022×10^{-19} J.

$$1 \text{ eV} = 1.6022 \times 1^{-19} \text{ J}$$

$$1 \text{ u} = 1.49239 \times 10^{-10} \text{ J}$$

Accordingly, a mass of 1 u can be expressed in electron volts as follows.

$$1u = \frac{1.49239 \times 10^{-10}}{1.6022 \times 10^{-19}} eV \qquad = 931.5 \text{ MeV}$$

6.4 Energy released in chemical reactions and nuclear reactions

In a chemical reaction either the exchange of electrons or the sharing of electrons occurs among atoms. Ionic bonds are formed due to reception or donation of electrons. Covalent bonds are formed due to sharing of electrons. By these processes of making bonds the chemical reactions take place. There the formation / breaking of ionic bonds and formation / breaking of covalent bond can occur. In a chemical reaction electrons and protons play an important role and no contribution is made by neutrons. The amount of energy liberated in chemical reactions is very much less than that in nuclear reactions.

In a nuclear reaction what happens is that the formation or breaking down of strong nuclear bonds which bind the protons and neutrons together in the nucleus. The energy liberated in a nuclear reaction such as fission or fusion is enormous and emission of radiation also takes place.

6.5 Mass energy equivalence

In 1905, Einstein showed that there is an equivalence between mass and energy. According to him, mass is another from of energy which can be transformed into other forms such as kinetic energy.The well known mass- energy relationship of Einstein's can be written as $E= mc^2$, where c is the speed of light in vacuum. According to this relationship 1 kg of matter is equivalent to $1 \text{ kg} \times (3 \times 10^8 \text{ m s}^{-1})^2$

6.6 Mass defect and nuclear binding energy
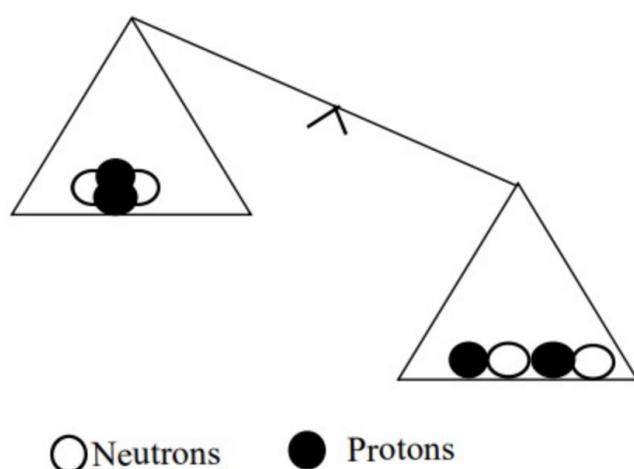

○ Neutrons   ● Protons

Figure 6.3

It has been mentioned previously that the nucleus is made up of neutrons and protons. Therefore it can be expected that the mass of the nucleus to be the sum of the masses of protons and neutrons taken individually. Nevertheless, the mass of the nuclear is less than the above expected value. This difference in mass is called the mass defect. So it is clear that there is a loss of mass when forming a nucleus by combining protons and neutrons.

According to Einstein's mass - energy relationship, this difference in mass is equivalent to some difference in energy. This amount of energy has been used up to make bonds in the nucleus. Therefore, this energy difference is called the binding energy of the nucleus. If the bonds in the nucleus are broken by some process, then that binding energy can be taken out. Let us calculate the binding energy of helium nucleus considering the mass of a proton as 1.007276 u and the mass of a neutron as 1.008665 u.

In the ^4_2He nucleus these are 2 protons and 2 neutrons.

∴ The expected value for the total mass $= (2 \times 1.007276) + (2 \times 1.008665)$

$= 4.031882$ u

But the true mass of the helium nucleus is 4.001508 u.

Therefore, the mass defect (loss of mass) $= 4.031882 - 4.001508$

$= 0.030374$ u

∴ The corresponding energy difference $= 0.030374 \times 931$

$= 28.3$ MeV

Therefore, the binding energy of the helium nucleus is 28.3 MeV.

Let us consider $^{16}_8O$ as another example. It has 8 protons and 8 neutrons. Now let us calculate tthe mass defect of that nucleus.

The expected mass for the $^{16}_8C$ nucleus $= 8 \times 1.00866$ u $+ 8 \times 1.00727$ u

$= 16.12744$ u

But, the true mass of it $= 15.99443$ u

Mass defect $= 0.13301$ u

Binding energy $= 123.83$ MeV
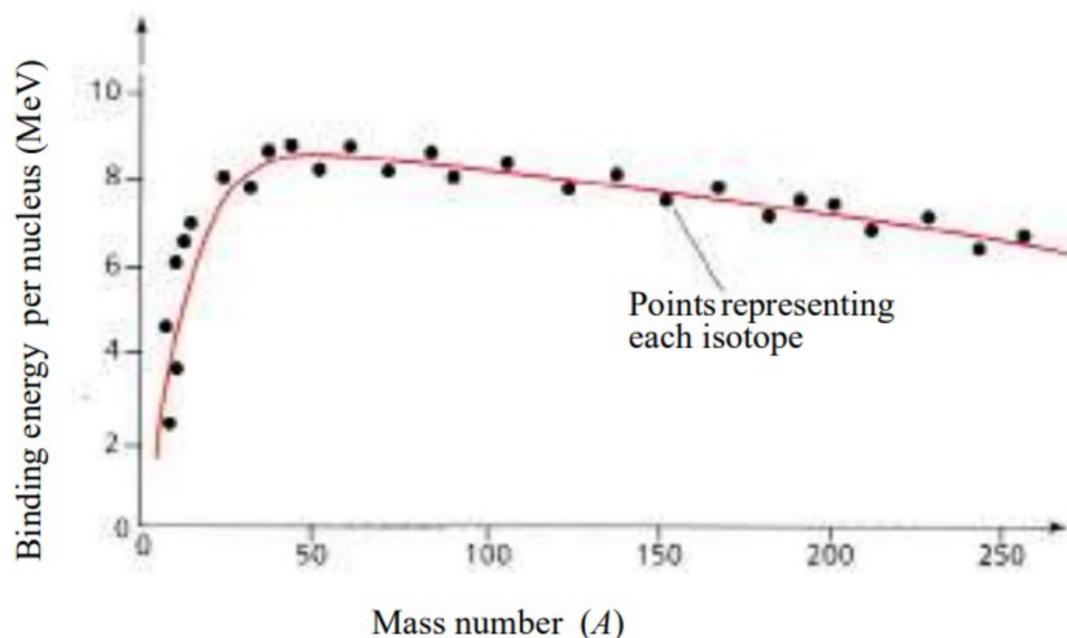
Figure 6.3

The binding energy for a nucleon can be written as $\frac{B}{A}$; where A is the mass number. The graph in Figure 6.4 shows how the binding energy for a nucleon $\frac{B}{A}$ varies with the mass number A. According to the graph B/A remains nearly a constant within the range $30<A<170$. For the light nuclei ($A<30$) and heavy nuclei ($A>170$) the value of B/A is low. It is clear from the graph that $\frac{B}{A}$ takes a maximum value when A is close to 50.

The higher the binding energy of a nucleus the higher the stability of it will be. Therefore the most stable nuclei are the ones of which the mass number is close to 50. When a nucleus of a very high mass number splits into two, there obtain two, more stable nuclei and a large amount of energy is liberated. Also, by combining two very small nuclei such as Helium, more stable and larger nucleus can be obtained. There also a large amount of energy is liberated.

6.7 Nuclear Fission

Nuclear fission is the splitting of a heavy nucleus ($A > 200$) into two light nuclei.

When a neutron is absorbed by a uranium 235 nucleus, it becomes unstable and then splits into two lighter nuclei which are more stable. A number of such nuclear reactions are there and one of them is given below.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U^{*} \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + Q$$
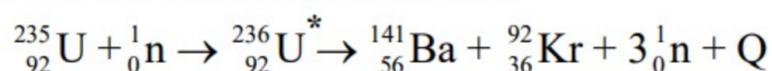
where Q represents the energy liberated. Since this process starts with the absorption of a neutron by the uranium nucleus, it is called an induced nuclear reaction. Here $^{236}_{92}U^{*}$ is the excited state. It is an unstable combined nucleus existing for a very small period of time such 10^{-12} s. This unstable nucleus fissions instantly into Ba and Kr nuclei.

The starting nucleus of this fission, uranium-235, has a mass of 235.44 u. The masses of barium -141 and krypton- 92 are 140.914 u and 91.926 u respectively and the mass of the neutron is 1.009 u. According to this, the difference of mass at the beginning and in the end of this process is,

$$(235.44 + 1.009) - (140.914 + 91.926 + 3 \times 1.009)$$

$$= 0.582 \text{ u}$$

$$= 0.582 \times 931.5 \text{ MeV}$$

$$= 542.133 \text{ MeV}$$

So in this fission, an amount of energy so huge as 542 MeV is emitted.

Instead of the products Ba and Kr of the above reaction, the other pairs of nuclei can also be produced. The following nuclear reaction can be given as an example.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{133}_{51}Sb + ^{99}_{41}Nb + 4^{1}_{0}n$$
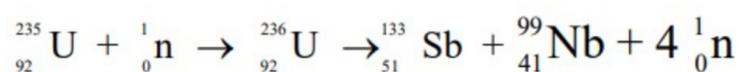
It has been found that about 30 different elements are produced by nuclear reactions taking place in this manner, under various conditions. The fragments produced in the nuclear fission are also radioactive nuclei. They emit β particles and become stable nuclei at the end. Because of the various forms of fission , the average value of energy released by the fission of a uranium nucleus is about 200 MeV.

According to that, the total energy released in the fission of 1 gram of uranium nuclei.

$$= \frac{1}{235} \times 6.023 \times 10^{23} \times 200 \ \text{MeV}$$
$$= 8.2 \times 10^{10} \, \text{J}$$

Therefore, when 1 kg of uranium undergoes fission, approximately about 10^{14} J of energy is generated. When 1 kg of coal is burnt as a chemical reaction, the energy generated is about 10^7 J. So it is clear that the fission energy is enormous.

The disintegration energy generated in the incidences of nuclear fission, first appears as the kinetic energy of the fragments and the neutrons. In the end, that energy transfers to matter in the environment as heat. The source of energy in nuclear reactor is the process of fission. The reactions taking place in nuclear reactors, are controlled and the heat emitted is used to generate electricity.
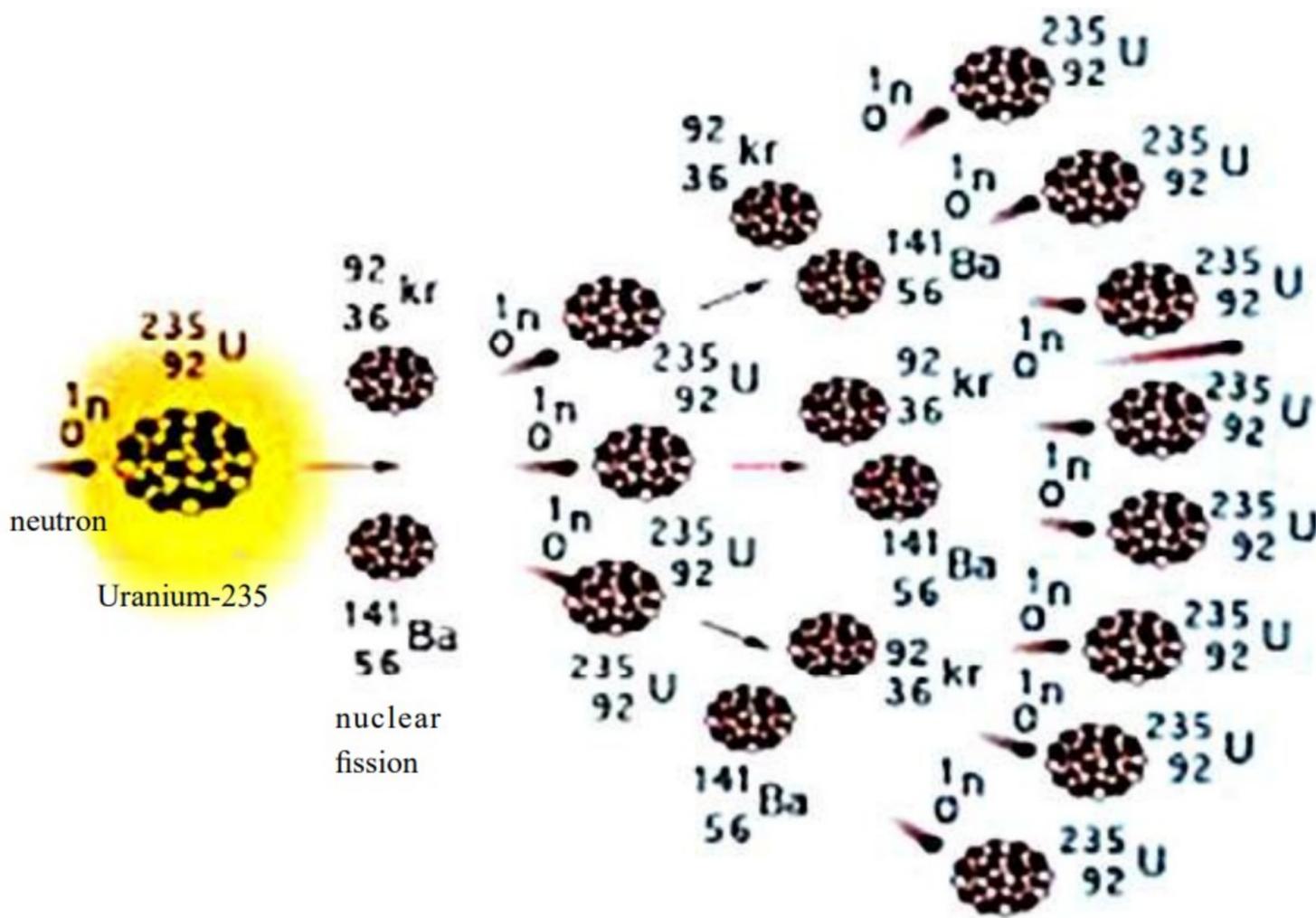
6.7.1 Nuclear chain reactions

Figure 6.5 Chain reaction for ^{235}U

As mentioned earlier the fission of uranium-235 starts with the absorption of a neutron. In that fission, in addition to the two nuclei produced, 3 neutrons are also emitted. If a little amount of neutrons coming outside is made to collide with a sample of uranium-235, some number of uranium nuclei undergo fission. By each nucleus that undergoes such a fission, there emit 3 neutrons each, and by those neutrons more other nuclei of uranium 235 are subjected to fission. This process in known as a nuclear chain reaction. Figure 6.5 shows such a chain reaction. The concept of chain reaction was first suggested by Enrico Fermi.

By controlling this chain reaction in the proper way, a continuous output of energy can be obtained. In any case if it gets out of control then an explosive energy output (like in a bomb explosion) will occur. Care should be taken of the following facts when self-propagating nucleus chain reaction take place.

- Some of the secondary neutrons leave the system without participating in fission process any further. This leakage can be reduced by constructing the system in the proper way.

Figure 6.6   Enrico Fermi

- Impurities which are not fissionable, absorb secondary neutrons. By using pure material which are fissionable this loss can be prevented.

- Natural uranium exists in three isotopes. They are ^{233}U, ^{235}U and ^{238}U. Their availability can be given as 0.006%, 0.741% and 99.28% respectively. ^{235}U is subjected to fission by low speed (with energy of about 0.025 eV) neutrons, but ^{238}U is by high speed neutrons. The percentage of natural ^{235}U is much less than that of ^{238}U. Therefore the number of neutron collisions made with ^{238}U is large. The speed of the neutrons reduces due to collisions made with ^{238}U. Therefore fission of ^{238}U does not occur furthermore. For this chain reaction to occur continuously there should be a mass greater than some minimum mass for the material which is subjected to fission. This minimum mass is known as the critical mass. So long as the mass of the material undergoing fission is greater than its critical mass this chain reaction continues.

6.7.2 Nuclear reactors

The first nuclear reactor was built in 1942. The design and construction of it was done with the supervision of Enrico Fermi.
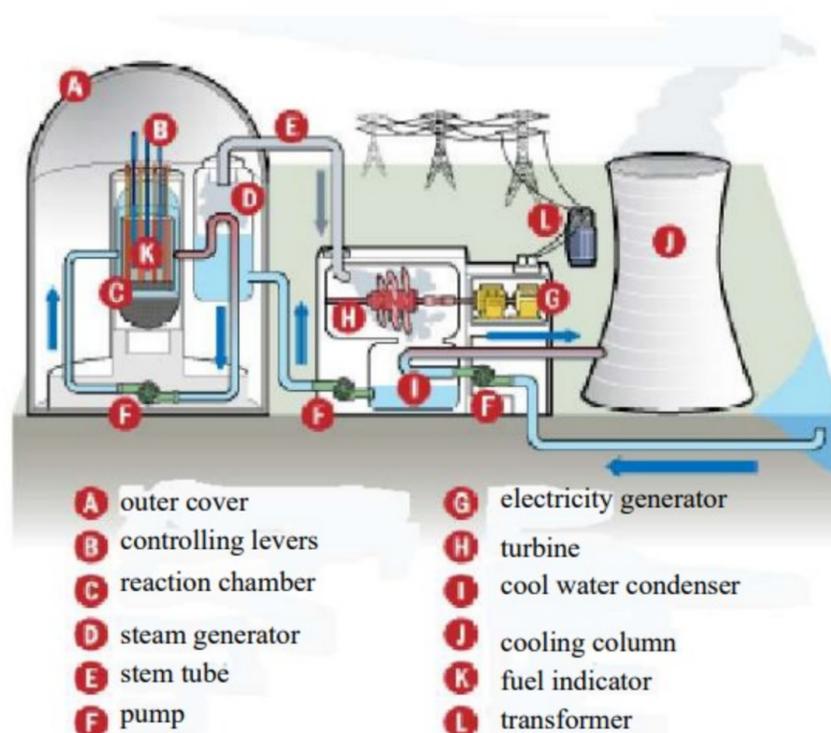

A outer cover
B controlling levers
C reaction chamber
D steam generator
E stem tube
F pump
G electricity generator
H turbine
I cool water condenser
J cooling column
K fuel indicator
L transformer

Figure 6.7 Nuclear reactor

Figure 6.7 shows a rough arrangement of a nuclear power station. In it the heat generated by the controlled nuclear fission reaction, is used to produce electricity. To absorb the generated heat, highly pressurized water is pumped to the chamber where the nuclear reactor is. This water absorbs heat from the reactor and converts the water in the steam generator into high pressure (170 atm) steam at a temperature of 540 °C (super-heated steam). With this steam, the turbines connected to the generators are driven. Power station of this type can produce power of about 650 MV. The nuclear fuel used here is uranium - 235. Uranium, prepared as rods having the diameters of about 2.5 cm are packed in aluminum cylinders and placed in the cavities bored in carbon blocks. By inserting cadmium (Cd) or boron (B) rods in between the uranium rods, the slow neutrons emitted by the uranium rods, are absorbed. These inserted rods are called control rods.

The material, which is used to decelerate high speed neutrons produced in the process of nuclear fission, is called a moderator. This material should be light and should not absorb neutrons. Materials such as heavy water (D_2O), graphite, deuterium and paraffin act as moderators.

Although 2 or 3 neutrons are emitted in one fission reaction, to maintain the chain reaction under control, only one neutron is required. To prevent other neutrons colliding with the uranium nuclear, control rods are used. By removing rods, speed of the reaction can be increased. That in turn, increases the pressure of steam and more electricity can be generated.

In the case of an emergency or when it is required to change fuel, the operation of the power station can be stopped by dropping down the control rods completely. The energy obtained by chain reaction is used for the propulsion of aeroplanes, ships and submarines, and to

produce radioactive isotopes which are necessary in the fields of agriculture, medicine and industry. The fuel cans removed from the reactor after using, are highly radioactive for a long time. The fuel rods after using them up, should carefully be removed from the reactor using remote controllers.

6.7.3   Uncontrolled nuclear fission reactions

Atomic bomb

In an uncontrolled chain reaction more than one neutron causes fission. The number of fissions increases very rapidly and a huge amount of energy is liberated. In the atomic bomb dropped on Hiroshima in Japan at the time of the second world war (1945), ^{235}U (uranium – 235) nuclear reactor had been used. It has been reported that the number of people missing, wounded and died due to this bomb explosion is about 130 000.

In the bomb dropped on Nagasaki, plutonium-239 reactor was used. The amount of energy liberated by the fission of 1 kg of uranium is equal to the energy released by the explosion of 20 000 tons of TNT explosives. Because of the explosion of the Nagasaki bomb, about 66 000 people died and about 69 000 were wounded. In the explosion of these kinds of bombs, more harm is done due to the huge emission of neutrons and γ-rays than due to the vibrations. These emissions cause harm such as the destruction of living cells and mutation of genes. The radioactive waste materials produced in the nuclear fission, spread over the upper atmosphere as dust and gases. This leads to spread the influence of radiation over the area where the explosion occurred.

Figure 6.8   Nuclear bomb

**Figure 6.9 Giant radiation dust cloud made due to a nuclear bomb explosion**

Nuclear hazards

Various countries, including India, in the world use nuclear power stations to generate electricity. There is also a possibility that radioactive elements leak out to the environment in the case of an accident. Such as accident took place in the Chernobyl nuclear power station of Ukraine on 26th of April in 1986. The cause of the accident was an error in the hydro circulating system, and hence the explosion of the core of the reactor due to high heat. An enormous amount of radioactive particles was released to the atmosphere in that incident. Due to wind and rain, they spread up to Western Russia and Europe and harmed the biosphere of those countries. A similar type of nuclear hazard occurred in the Fukushima Daichi nuclear power station of Japan in 2011.

6.8 Nuclear Fusion

Nuclear fusion is the process in which lighter nuclei with lower mass number *(A≤ 8)* such as hydrogen are combined and transformed into more stable nuclei such as helium.

Following is a common fusion reaction.

$$^1_1H + ^1_1H \rightarrow ^2_1H + ^0_1\beta + \text{ energy}$$
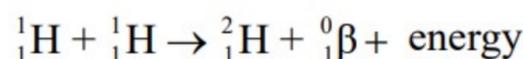
This shows how a deuterium nuclear is formed by the fusion of two protons. The energy liberated in this fusion can be calculated as follows.

Total mass before fusion	= 1.00728 + 1.00728
	= 2.01456 u
Total mass after fusion	= 2.01355 + 0.00055 (mass of the β - particle = 0.00055 u)
	= 2.01410 u
The loss of mass	= 2.01456 - 2.01410 u
	= 0.00046 u
Since 1u	= 931 MeV
Energy liberated	= 0.0046 × 931 MeV
	= 0.4 MeV

Generally, for a proton-proton fusion, a high temperature of millions of kelvin is required. These reactions are called thermonuclear fusion reactions. Those conditions required for the fusion are not easy to create in laboratories.

6.8.1 Process of nuclear fusion in the sun

The temperature of the interior of the sun in our solar system is about 1.5×10^7 K. The interior of the sun consists 90% of hydrogen and helium, and 10% of other elements. The sun does not contain heavy elements. Therefore, it can be considered that the source of energy of the sun is not the nuclear fission. ^1_1H atoms (high energy protons) contribute towards the nuclear fusion process in the sun. The process of the fusion taking place there, consists of several steps. It is known as the proton-proton (p,p) cycle.

$$^1_1H + ^1_1H + \rightarrow ^2_1H + ^0_1e + \upsilon_e + 5.49 \text{ Me V}$$

$$^1_1H + ^1_1H + \rightarrow ^2_1H + ^0_1e + \upsilon_e + 5.49 \text{ Me V}$$

$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\,^1_1H + 12.86 \text{ MeV}$$
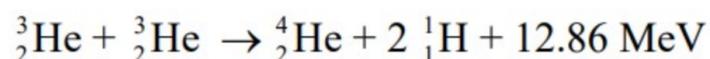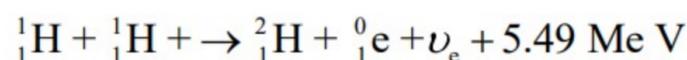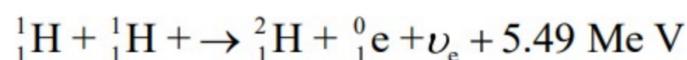
In this chain of reactions, ^4_2He nucleus is formed by the fusion of 4 protons. (i.e. hydrogen nuclei). In addition to that, there emit two positrons (2^0_1e) and energy.

The entire process above can be given as,

$$4^1_1H \rightarrow ^4_2He + 2e^+ + \text{ energy}$$
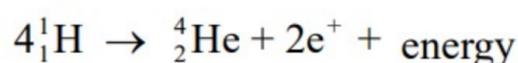
The energy emitted is 26.2 MeV. Therefore it is clear that, in one cycle of the nuclear fusion process in the sun, an energy of about 25 MeV is liberated. The age of the sun at present is approximately 5×10^9 years. It has been estimated that there is an amount of hydrogen in the sun sufficient for another 5 billion years. At the end, the nuclear fusion of hydrogen nuclei ceases and the cooling of the sun begins. Afterward, because of its gravitation the sun starts to contract and its core temperature increases. Finally the outer cover around the sun gets expanded and it transforms into a red giant.

6.8.2 Thermonuclear fusion reactions occuring under control

To operate this type of reactor, a temperature as high as 10^9 K is required. With this temperature the mixture of ions called plasma consisting of lighter nuclei can penetrate the coulomb barrier and combine. At very high temperatures deuterium gets ionized totally and a neutral plasma is created. The above conditions cannot be fulfilled using containers made of solid material. The experiments are being carried out on making these nuclear reactions in **tokomak** or **toroidal** magnetic chambers. There is a possibility of using deuterium gas as a fuel for the power requirements of the future world. Deuterium gas can be obtained by the electrolysis of heavy water content in seawater.

6.9 A comparative view of nuclear fission and nuclear fusion

- Both these processes are enormous sources of energy.
- Both these processes obey Einstein's mass-energy relationship.

- In the fission process, a neutron is used as the relevant projectile.

- In the fusion process two lighter nuclei are made close to each other overcoming the coulomb electrostatic repulsion. The energy required for this can be supplied by increasing the temperature up to 10^8 K.

- In nuclear fission, a heavy nucleus splits into two or three lighter nuclei. What happens in the nuclear fusion is the formation of a heavy nucleus by the composition of two or more lighter nuclei.

- The energy liberated per unit mass in the nuclear fusion is much greater than that in the nuclear fission.

  Eg: the harm done by the hydrogen bomb which is based on the nuclear fusion is very much severe than the harm done by the nuclear bomb which is based on the nuclear fission.

- The products obtained in the nuclear fission are radioactive and cause environmental pollution. Nevertheless the products obtained in the nuclear fusion are not radioactive and not harmful.

- The fission chain reaction can be controlled, but thermonuclear fusion reactions are not easy to control.

Worked examples

1. Nuclear fusion occurs,

    (a) Only between two or more light nuclei.

    (b) Only between two heavy nuclei.

    (c) Only between two light nuclei and between two heavy nuclei.

    (d) Only between two stable nuclei which oppose decay.

    (e) None of the above.

2. If the binding energy per nucleon of the parent nucleus is E_1 and that of the daughter nucleus is E_2,

    (a) $E_1 = 2E_2$ (b) $E_2 = 2E_1$ (c) $E_1 > E_2$ (d) $E_2 > E_1$ (e) $E_1 = E_2$

3. In the element lithium the percentages of two stable isotopes ^6_3Li and ^7_3Li are 7.5% and 92.5% respectively. The masses of those isotopes are 6.0512 u and 7.01600 u respectively. Find the atomic mass of lithium.

    The atomic mass of lithium
    $$= \frac{6.01572 \times 7.5}{100} + \frac{7.01600 \times 92.5}{100}$$
    $$= 6.914 \text{ u}$$

4. The two stable isotopes of boron are $^{10}_5\text{B}$ and $^{11}_5\text{B}$. If the masses of those are 10.01294 u and 11.00931u respectively, then find the percentage amount of each content of isotopes. (atomic mass of boron =10.811u)

    If the percentage of $^{10}_5\text{B}$ is x %

    Then $^{11}_5\text{B}$ percentage $= (100 - x)$ %

    Considering atomic masses,
    $$\therefore \ 10.811 = \frac{10.01294x}{100} + \frac{10.00931(100-x)}{100}$$
    $$= \frac{492.857}{56}$$
    $$\therefore x = 19.9\%$$

    $\therefore$ percentage of $^{10}_5\text{B}$ $= 19.9$ %

    percentage of $^{11}_5\text{B}$ $= (100 - 19.9)$
    $$= 80.1\%$$

5. Obtain the binding energy of the nitrogen nucleus $^{14}_{7}N$ in MeV. The mass of that nucleus is 14.00307 u. Binding energy is the mass defect given in energy units.

   The mass of a proton is 1.007276 u and the mass of a neutron is 1.008665 u.

   mass defect $\qquad = (7 \times 1.007276 + 7 \times 1.008665 - 14.00307) \text{ u}$

   $\qquad\qquad\qquad\qquad = 0.10852 \text{ u}$

   $\therefore$ binding energy $\qquad = 0.10852 \times 931.5 \text{ MeV}$

   $\qquad\qquad\qquad\qquad = 101.1 \text{ MeV}$

6. (a) Calculate the energy liberated by the fusion of 1kg hydrogen in the core of the sun. Also calculate the energy liberated by the fission of 1 kg of ^{235}U in a fission reactor.

   Compare the calculated two energy values .

   The energy liberated by combining four $^{1}_{1}H$ nuclei and forming a $^{4}_{2}He$ nucleus in the interior of the sum (per one event) is 26 MeV.

   $\therefore$ energy liberated by 1kg hydrogen

   $$E_1 = \frac{26}{4} \times 6 \times 10^{23} \times 10^3$$

   $$= 39 \times 10^{26} \text{ MeV}$$

   The energy liberated by the fission of uranium atom is 200 MeV.

   $\therefore$ the energy liberated by the fission of 1 kg of uranium

   $$E_2 = \frac{6 \times 10^{23} \times 10^3 \times 200}{235}$$

   $$= 5.1 \times 10^{26} \text{ MeV}$$

   $$\therefore \frac{E_1}{E_2} = \frac{39 \times 10^{26}}{5.1 \times 10^{26}}$$

   $$= 7.65$$

   $\therefore$ The energy liberated by the fission is about 8 times the energy liberated by the fission.

Chapter seven

Fundamental constituents of matter and their interactions

7.1 Introduction

Even ancient people had the knowledge that all matter in the world was made up of some fundamental particles. According to an ancient Chinese belief, earth, metal, wood and water were accepted to be the primary constituents of the physical world. In the late nineteenth century it was considered that all matter was made up of atoms. Those ideas pointed to a pathway to the explanation of the basic structure of all elements. A lot of information about the structure of the atom was found based on the experiments carried out at that time. With all that knowledge it was concluded that all atoms were made up of the nucleus which has protons and the electrons revolving around the nucleus in various orbits. It had also been confirmed that the nucleus was very small when compared with the size of the atom. To explain the discrepancy between the mass of the atom and the mass of the proton, scientists of the time had to introduce another subatomic particle called the neutron. After Chadwick (English physicist) discovered the neutron in 1932, the proton, electron ad neutron were considered to be the fundamental particles of the atom. Let us now consider the structure of the helium atom as an example.

7.2 Structure of the atom

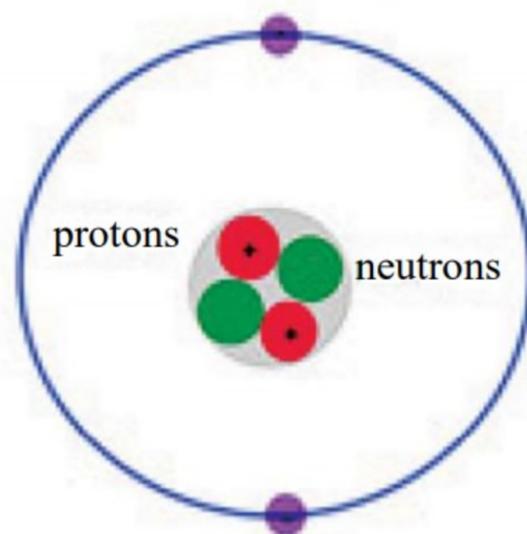Electrons are there in shells around the nucleus. Protons and neutrons are there in the nucleus.

Figure 7.1 - Structure of helium atom

7.2.1 Geiger and Marsden's experiment

In 1911, Rutherford and two of his assistants, Geiger and Marsden, projected a beam of α- particles on a very thin foil of gold and made observations. To identify the direction of travel of α – particles after colliding with the gold foil, a zinc sulphide detector was moved around the gold foil set-up.
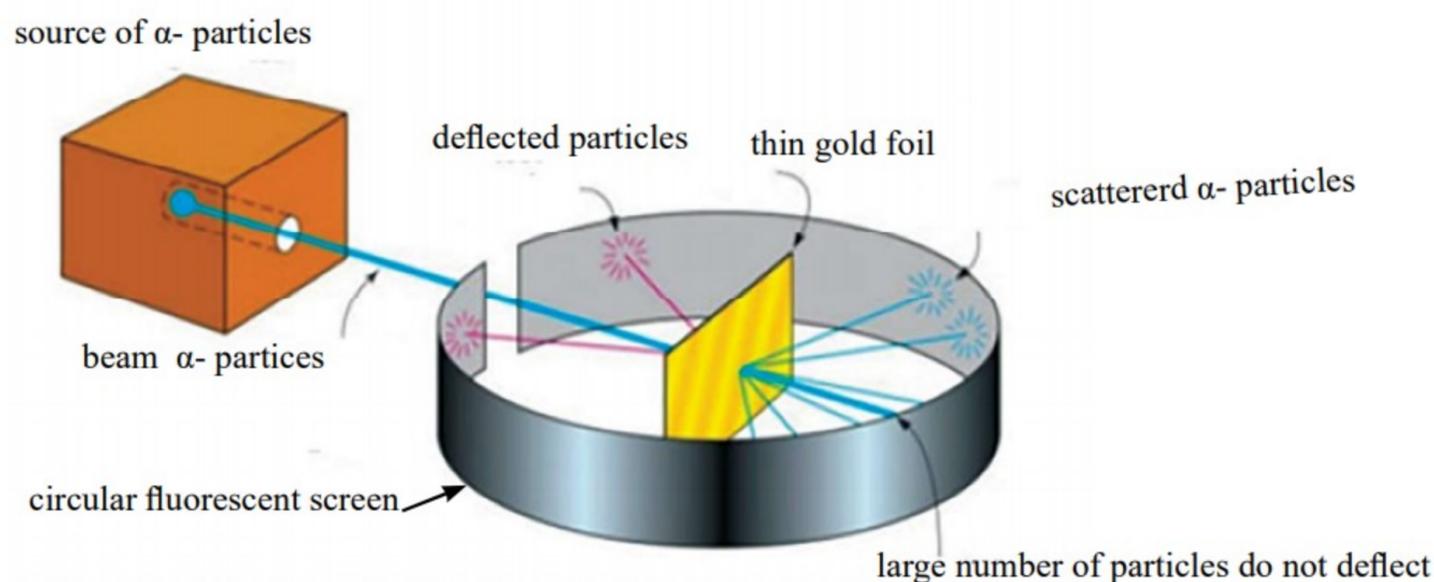
Figure 7.2 – Scattering of α-particles by a gold leaf

In the above experiment they found out that,

- Most of the α- particles were passed through the gold leaf without any deflection.
- Some α- particles were deflected at a small angle in various directions.
- Rarely, an α - particle was deflected at an angle more than 90°.

After analyzing those results, Rutherford came to the conclusion that,

- Large amount of the atom is free space.
- A large percentage of the mass of the atom is confined to a very small region into the centre and that region is positively charged.

Rutherford named that central region (core) as the nucleus of the atom. According to Rutherford's analysis, the way the particles travel can be understood by referring to Figure 7.3.

Figure 7.3 - The way the scattered particles travel

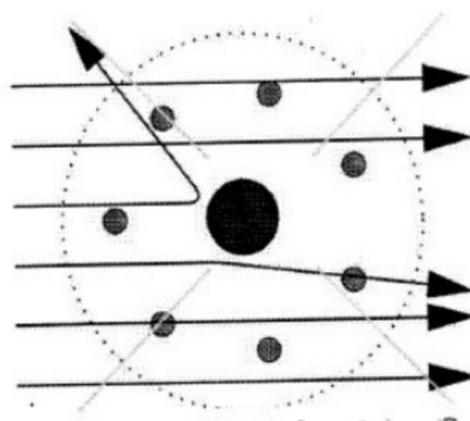According to Figure 7.3, most of the particles travel through empty space without any disturbance. Several particles travelling close to the nucleus deflect a little and a very few particles coming straight towards the nucleus deflect making wide angles.

Geiger and Marsden's experiment was carried out more than a hundred years ago. However, even now most of the experiments done on nuclear and fundamental particles are of the same form as that. That is, in those experiments what is basically done is to make α- particles or some other beam of high speed particles bombard on a particular target.

In Geiger and Marsden's experiment α- particles were obtained from a natural radioactive source. Those α-particles were of an energy of about 5 MeV. Although that energy of α- particles is sufficient to enter the atoms in the gold foil, when they come closer to the nucleus they are repelled easily because of the positive charge in the nucleus.

If particles with energy more than the energy obtainable from natural radioactive sources, can be used, the scientists realized that those particles should be able to reach the nucleus much closer or even break the nucleus on collision.

One method of obtaining particles with such a high energy, is to accelerate the charged particles like α - particles , protons or electrons using an electric field. The other method is to use cosmic rays.

7.3 Cosmic rays

Cosmic rays are high energy rays coming to the Earth from outer space. Cosmic rays were discovered in 1912, by a scientist named Victor Hess. He measured the concentration of ions in the atmosphere using balloons sent upwards to various heights in the sky. According to those measurements it was clear that, when ascending to much higher elevations from the sea level, the ionic concentrations were increasing. According to the measurements obtained when there was a solar eclipse, he found that the cause of it was not due to the rays coming from the sun.

It has been found now, that the contents of cosmic rays are mostly protons and in addition there are α- particles, electrons and nuclei such as lithium, berylium, boron, carbon and oxygen. The energy values of these particles have been found to lie in a large range having very high values up to 10^{20} eV.

Almost all the cosmic rays entering the Earth's atmosphere, collide with the nuclei in the upper atmosphere and produce unstable particles such as pion (π) and kaon (k). Ultimately the particles reaching the sea level at most are, particles named muon (μ) which are produced by the decay of unstable particles, and particles such as electrons, positrons which are produced in collisions.

In the first half of the last century, most of the discoveries about fundamental particles were made based on the study of collisions, that the cosmic rays make with other material. That type of experiments were mostly done by sending the detectors capable of detecting charged particles, high up using balloons, or placing the detectors at very high elevations from the sea level, such as high mountain peaks.

The use of cosmic rays in order to study fundamental particles is not an easy matter. One reason for it is that the particles which reach the sea level are only those remaining after the decay process of cosmic rays. Other reasons are that a much smaller number of cosmic rays pass through a detector per second and the inability to control the type of particles or their energy as required by the experimenters. Therefore, today accelerators are widely used for such experiments.

7.4 Particle accelerators

The apparatus used to accelerate charged particles are known particle accelerators. A cathode ray tube can be taken as a simple example. When the filament in the cathode ray tube is heated, the electrons are emitted and then they travel from cathode to anode as a stream of cathode rays, because the electrons are accelerated by the electric field which is maintained between the cathode and the anode. Nevertheless it is not possible to produce a beam of electrons having a large amount of energy as 5 MeV. To supply an energy of 5 MeV to an electron, it should be supplied with a voltage of 5×10^6 V. It is very difficult to produce such a voltage. Also, it is difficult to maintain such a voltage without being discharged at a short distance between the electrodes.

Therefore, the scientists used various other methods to provide the required acceleration to the charged particles. In all these methods, there are two common features. They are, to use alternating current instead of direct current and, to accelerate step by step using a number of pairs of electrodes along the path of the particles, instead of applying a huge voltage across a single pair of electrodes.

Worked example

Calculate the speed of a proton which has a kinetic energy of 1 keV (take the mass of a proton as 1.67×10^{-27} kg)

Answer

The equation for energy E of a particle moving with a velocity v is $E = \frac{1}{2}mv^2$

Accordingly, the velocity v of a particle having energy E is given by,

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

Substituting values for this equation,

$$v = \sqrt{\frac{2 \times 10^3 \times 1.6 \times 10^{-19} \text{ J}}{1.67 \times 10^{-27} \text{ kg}}}$$

$$= 4.38 \times 10^5 \text{ m s}^{-1}$$

In the beams of protons produced by modern accelerators, there are protons having energy values of the amounts GeV and TeV. When compared with such protons, 1 keV has a very small amount of energy, but you can see that even the proton having that small energy, has a very high speed. When the energy of particles goes up to amounts of GeV or TeV, their speeds are much closer to the speed of light. According to the theory of relativity, when the speed of a particle gets closer to the speed of light, its mass increases. Therefore, the above equation cannot be used to calculate the speed of such particles.

7.4.1 Linear accelerators

The particle accelerators are in various places in the world at present, can be divided into two types as linear accelerators and circular accelerators.
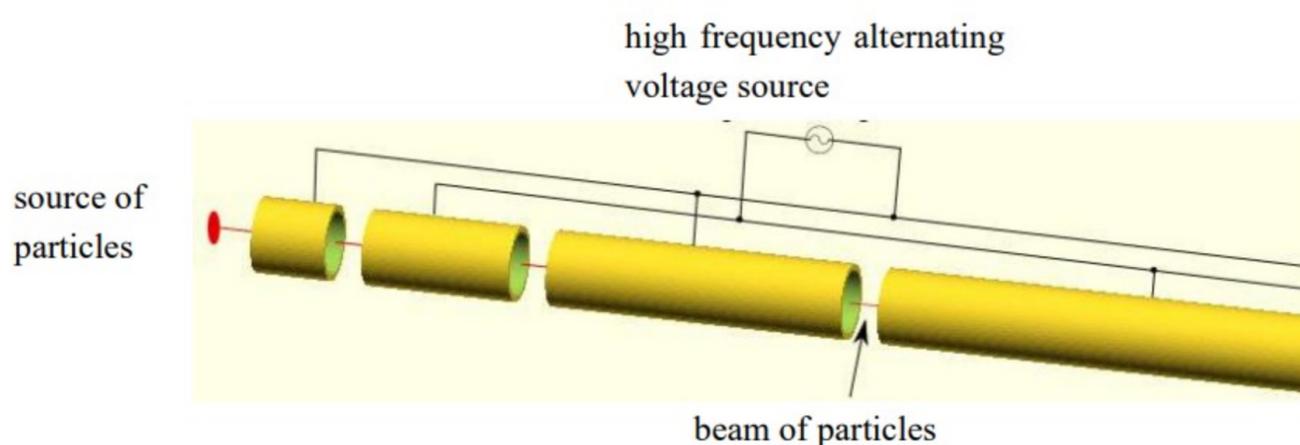

Figure 7.4- Linear accelerator

Figure 7.4 shows how a linear accelerator is made. Here a group of conducting tubes acts as the electrodes. In between every two tubes, there is an applied alternating potential difference obtained from a high frequency source. As the tubes are conductors there is no electric field in them. The particles to be accelerated are entered through one end. If the particles are positively charged, then the acceleration takes place only when the particles are in between two tubes and the direction of the electric field is the same as the direction of travel of the particles. During the period in which the electric field is in opposite direction, the particles are moving inside the tubes. If the particles are negatively charged, acceleration takes place only when the direction of the field is opposite to the direction of the travel of particles. Regardless of whether the sign of the charge in the particles is positive or negative, acceleration occurs only in one half cycle of the alternating voltage. Because of this reason, the beam of particles travels not as a continuous flow but as a bunchy flow.

Worked example.

Consider a proton of kinetic energy of 1 keV enter the first tube of the linear accelerator as shown in Figure 7.4

    (i) If the proton comes out of the tube after a time 1μs, What is the length of the tube ?

    (ii) If the potential difference between this tube and the second tube is 3000 V, What is the energy of the proton when it enters the second tube ?

    (iii) For the proton to travel another period of 1μs in the second tube, what should be the length of that tube ?

Answer

    (i) In the previous example we have found that the speed of a proton having kinetic energy 1 keV is 4.38×10^5 m s^{-1}. So, the distance it travels in 1μs is $4.38 \times 10^5 \times 10^{-6} = 0.438$ m. Therefore, the length of the tube should be 43.8 cm.

    (ii) If the potential difference between two tubes is 3000 V, the energy that proton gain is 3000 eV, since the proton charge is +1. This energy adds up to the previous energy and therefore the new energy is 4000 eV (4 keV).

    (iii) Speed of the proton now, is

$$v = \sqrt{\frac{2 \times 4 \times 10^3 \times 1.6 \times 10^{-19} \text{ J}}{1.67 \times 10^{-27} \text{ kg}}} \quad \left(from \ v = \sqrt{\frac{2E}{m}} \right)$$

$$= 8.75 \times 10^5 \text{ m s}^{-1}$$

Therefore, during the next 1μs it travels a distance of $8.75 \times 105 \times 10^{-6} = 0.875$ m. That is , the length of the second tube should be 87.5 cm. With this calculation you can see that each tube should be longer than the previous tube, for the particles to be in the tube one half cycle of the alternating potential difference.

Figure 7.5 – Stanford linear accelerator

The length of the accelerator shown in Figure 7.5 is 3.2 km and it is the longest linear accelerator in the world today.
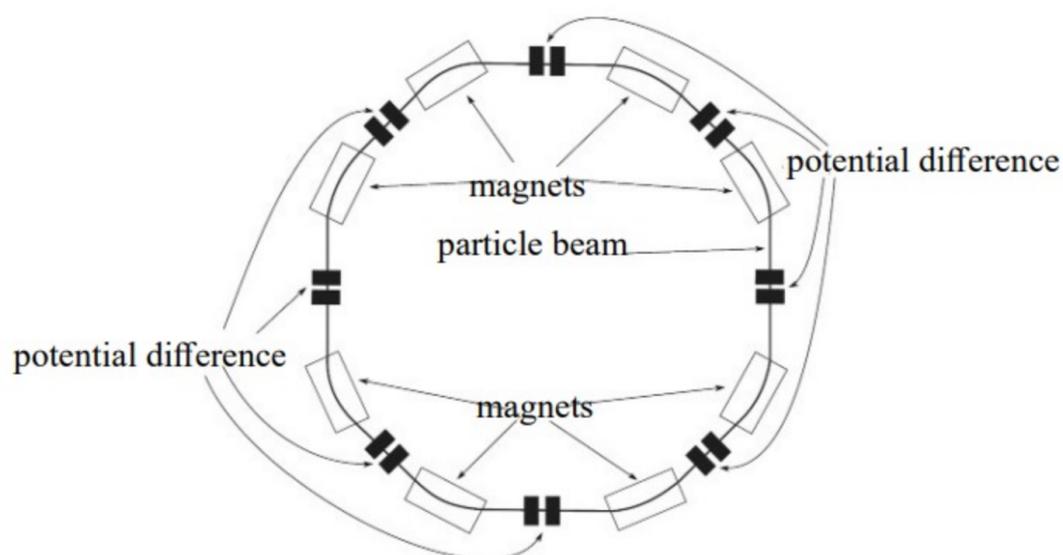

Figure 7.6 - circular accelaration

Figure 7.6 shows the way that a circular accelerator is constructed. In it also to get the acceleration, a potential difference is applied in between electrodes along the path of the particles. Particles are made to travel in a circular path by means of magnets placed in their path. Each magnet deviates from the path of particles by a small angle. Particles travel along a straight line between any two magnets. Therefore the path of these particles is not exactly a circle. The condition which is more important is to make particles travel repeatedly along the same path. In each turn of its travel the particle accelerates. A particle starting with a very low kinetic energy, gains a very high energy after travelling a number of turns.

Worked example

The following figure shows the path of a proton entering a magnetic field. The proton travels at a speed which is equal to half of the speed of light. If the magnetic flux density of the field is 0.1 T and the length of the region prevailing in the magnetic field is 1 m, calculate the angle by which the proton turns.
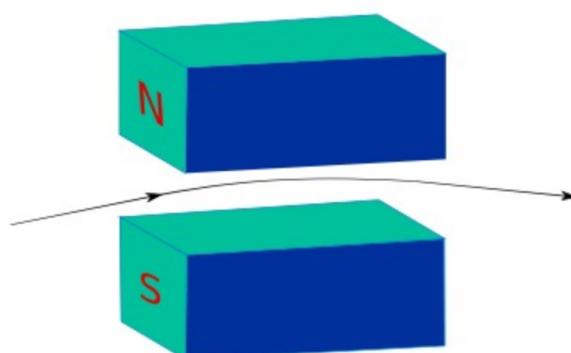
When a charge q moves at a velocity v, perpendicular to a magnetic field of flux density B, the force *(F)* on that charge given by $F = qvB$ and its direction is given by Fleming's left hand rule. Since the force is always perpendicular to the direction of the travel of the charge, its path is an arc of a circle.
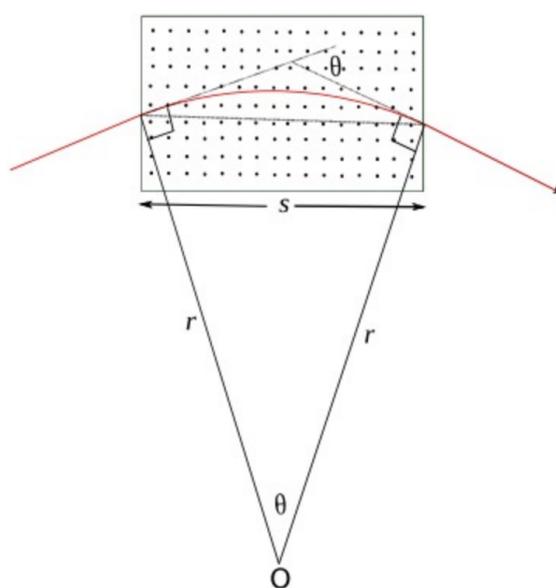
If the radius of that circle is r, the acceleration of the charge towards the centre will be v^2/r. By applying Newton's law we get $qvB = m\dfrac{v^2}{r}$. Accordingly, the radius of the circle is given by $r = \dfrac{mv}{qB}$.

By substituting the values given,

$$r = \frac{\left(1.67 \times 10^{-27}\,\text{kg}\right) \times \left(1.5 \times 10^8\,\text{m s}^{-1}\right)}{\left(1.6 \times 10^{-19}\,\text{C}\right) \times \left(0.1\,\text{T}\right)}$$

$$= 15.65\,\text{m}$$

Using geometry, let us now consider the following diagram to find the turning angle of the proton.

Path of the particle travelling in the magnetic field is an arc of a circle. Within that arc the angle θ, by which the particle turns is equal to the angle subtended by the arc at the centre. Therefore,

$$\theta = 2\sin^{-1}\left(\frac{s}{2r}\right)$$

$$= 2\sin^{-1}\left(\frac{1}{2 \times 15.65}\right)$$

$$= 3.66°$$

The largest circular accelerator in the world today is the accelerator named Large Hadron Collider (LHC) in the European Organization for Nuclear Research (CERN) situated close to the city of Geneva in Switzerland. It has been constructed in a tunnel which is

about 100 metres below the ground level. Its circumference is 26.7 km and it produces two beams of energy 14 TeV, travelling in directions opposite to each other. These beams are made to collide at several points and the particles produced in those collisions are subjected to study using various detectors.
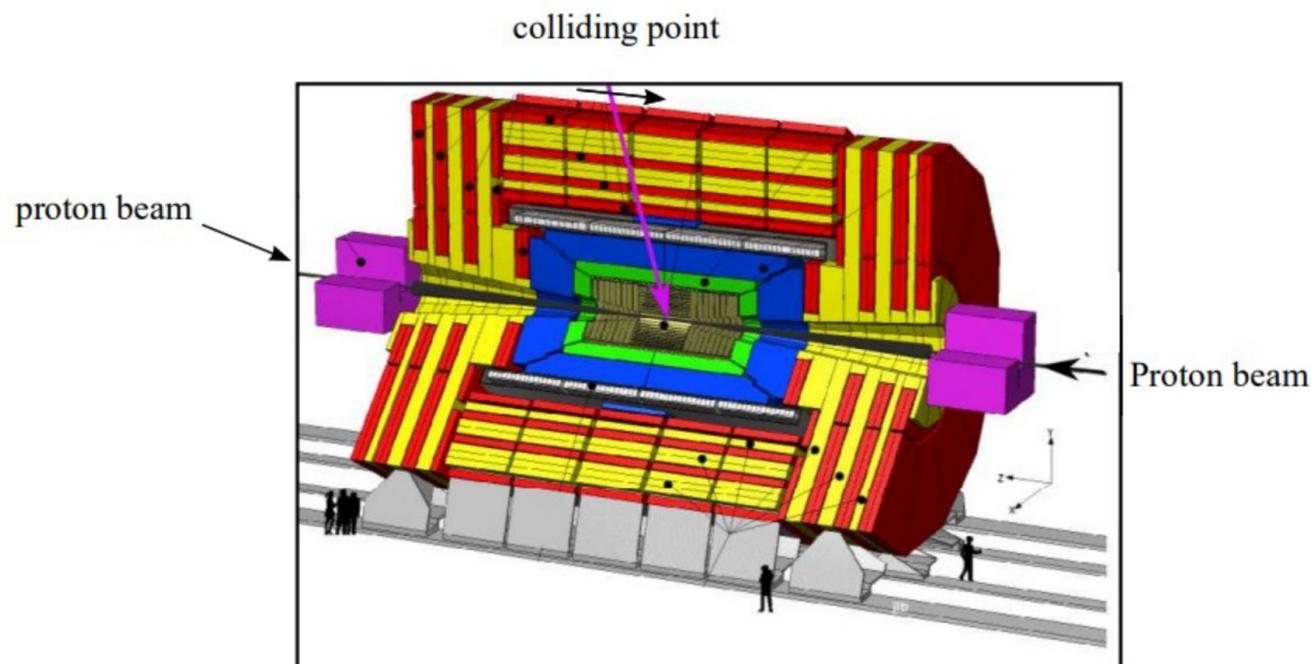

Figure 7.7 - A detector used in LHC detector

Figure 7.7 shows such complex detector. Appropriate arrangement of equipment is there so as to surround the point where protons collide with each other. The properties such as energy, travelling path, mass and charge of the particles produced in these collisions can be measured with a number of instruments which this detector consists of. The detector shown in Figure 7.7 is known as CMS (Compact Muon Solenoid) and its diameter is about 15 m and mass is about 15 tons.

Construction of this kind of detectors, activating them and analysis of data obtained using them require a huge amount of money and labour. Therefore, these experiments are carried out with the participation of thousands of scientists from a number of countries. Apart from Switzerland, this type of accelerators which are used for experimenting about fundamental particles, have been constructed in various other countries in the world.

7.5 Fundamental particles

When we go through history, we can see that the concept about the fundamental particles of matter has gone through changes from time to time. According to Dalton's atomic theory, atoms are the fundamental particles which are non- breakable furthermore. At the beginning of the twentieth century, scientists realized that the atom is made up electrons and a nuclei. Afterwards it was found that the nucleus is made up of protons and neutrons. As a result of experiments done regarding this, at present it is accepted that proton and neutron are also connected to various particles which are more fundamental. The existing fundamental particles are shown in Figure 7.8. For each of these particles there is an anti-particle which is completely opposite to it.

Figure 7.8 - Fundamental particles

These particles react among each other in four basic ways. The four types are gravitational force, electromagnetic force, strong nuclear force and weak nuclear force.

All matter is made up of particles called fermions. Particles called bosons act as mediating particles for basic interactions. For example, two electrostatic charges create as mutual attractive or repulsive force by exchanging photons between them. The strong nuclear force gluon (g) acts as the mediating particle. The bosons W and Z are the mediating particles for carrying the weak nuclear force.

There are two types of fermions. They are leptons and quarks. The electron belongs to the fermion category while the proton and neutron are a combination of three quarks. An important property of quark particles is that the magnitude of their charge is 1/3 or 2/3 of the charge of an electron.

The proton is made up of two u quark particles of charge +2/3 and one d quark particles of charge -1/3. So, the charge of the portion is +1.

The neutron is made up one u quark particle and two D quark particles. Therefore, the charge of the neutron is zero. According to this, most of the matter in the universe are made up of u and d quarks and electrons. All the other fundamental particles can be observed only in the collisions between cosmic rays and high energy particles.

Apart from this, a large number of various particles are made by combining other quarks or anti-quarks. Quarks always exist as combined particles of three quark or anti-quark particles. So far, the quark particles existing in singles have not been observed experimentally.

7.6 Fundamental forces

As mentioned above, according to our knowledge there are four fundamental forces interacting in nature. Among them the most familiar one is the gravitational force. Nevertheless, it is a weaker force than the other three. As you know well, gravitational force appears among masses. The gravitational force due to some mass, spreads over up to infinity.

 The electromagnetic force is dependent upon the electric charge. The electrostatic forces are among stationary charges while the magnetic forces arise from moving charges. Therefore we consider that the electrostatic forces and magnetic forces are two forms of a single force called the electromagnetic force. The electromagnetic force is also a force spreading up to infinity.

The strong nuclear force is the force which binds protons and neutrons together in a nucleus. The strong nuclear force acts in the same way between two protons, between two neutrons or between a proton and a neutron. Among the four fundamental forces, strong force is the strongest. Therefore, when there are a number of protons in a nucleus, the nucleus, the strong nuclear force is able to bind protons hard to the nucleus, overcoming the electrostatic repulsive forces among protons. However, the range of this nuclear force is much smaller. That is the strong nuclear force among protons or neutrons appears only when those particles are at a distance of nuclear diameter (about 10^{-15} m) or less than that.

Although the weak nuclear force is stronger than the gravitational force it is weaker than the other two fundamental forces. Its range is also as small as 10^{-18} m. Because of its weakness we cannot observe the influence of that force easily. The β- emission in the radioactivity has been defined as a phenomenon due to the weak nuclear force. Although it is weak, the weak nuclear force is essential for our existence as β - emission in very important for the functioning of the sun.

The Table 7.1 shows a comparision of fundamental forces described above.

Table 7.1   Comparison of fundamental forces

Force	Relative strength	Upon which it acts	Range	Occasions where it applies
strong force	1	Quark	10^{-15} m	To bind protons and neutrons in the nucleus
electromagnetic force	$\dfrac{1}{100}$	Electric charge	infinite	To keep atoms together
weak force	10^{-4}	Lepton and quark	10^{-16} m	Radioactive decay
gravitational force	10^{-39}	All masses	infinite	To keep the solar system together

Exercises

1. What is meant by fundamental particles?

2. Quarks have fractional charges. The neutron is made up of three quarks. It does not have a charge. Clarify this.

3. Which of the following is/are considered to be fundamental particles?

   electrons, protons, neutrons, quarks

4. Write down the quark composition for,

   (a) proton   (b) neutron

5. Write down the total charge for the following occasion.

   Three u quarks and three d quarks.

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Appendix - I   Some fundamental constants relating to "Matter and Radiation"

	Symbol	Value and unit
Avogadro constant	N_A	$= 6.022 \times 10^{23} \text{ mol}^{-1}$
Motor gas constant	R	$= 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$
Boltzmann constant	k	$= 1.381 \times 10^{-23} \text{ J K}^{-1}$
Stefan constant	σ	$= 5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Gravitational constant	G	$= 6.672 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
Permitivity of free space	ε_0	$= 8.854 \times 10^{-12} \text{ F m}^{-1}$
Speed of light in a vaccum	c	$= 2.998 \times 10^{-8} \text{ m s}^{-1}$
Planck constant	h	$= 6.626 \times 10^{-34} \text{ J s}$
Electronic charge	e	$= 1.602 \times 10^{-19} \text{ C}$
Specific charge	e/m	$= 1.759 \times 10^{11} \text{ C kg}^{-1}$
Electronic mass	m_e	$= 9.109 \times 10^{-31} \text{ kg}$
Proton mass	m_p	$= 1.673 \times 10^{-27} \text{ kg}$
Neutron mass	m_n	$= 1.675 \times 10^{-27} \text{ kg}$
Atomic mass unit	1 u	$= 1.661 \times 10^{-27} \text{ kg}$
Permeability of free space	μ_0	$= 4\pi \times 10^{-7} \text{ H m}^{-1}$