Chapter -19

THE ATOMIC NUCLEUS

19.1. Introduction

The beginning of twentieth century not only witnessed the successful development of atomic hypothesis,the old quantum theory of radiation by planck, and Einsteins special theory of relativity;these years also marked the beginning of nuclear physics as a new field of scientific activity.

In 1896 Henri Bacqueral first observed the phenomena of radioactivity. A year after J.J Thomson discovered the electron. Later on Thomson demonstrated that cathode rays were constituted of electrons.In this way the notion of the atom as the ultimate indivisible unit of matter had to be discarded, and it became evident that atoms included electrons among their structure, and these electrons could be liberated by electromagnetic excitation as in a gas discharge, or spontaneously as in radio activity.

In 1902 Rutherford and Soddy, showed that in radioactive decay an atom transform itself into a different chemical element. This discovery led to the development of models for nuclear structure,and after a period of three decades James Chadwick made another breakthrough by discovering the neutron which laid the foundation of a nuclear model,namely a very small (of the order of 10^{-14}m),roughly spherical in shape,and highly dense object,comprising of protons and neutrons.

19.2. Nuclear Structure

If the nucleus has any sort of structure,then we must argue what are its constituents? To answer this question, let us make a study of the known chemical elements in the order of their atomic numbers. The hydrogen atom which is the lightest atom has one electron and its atomic number $Z=1$, helium has two electrons and its $Z=2$, silver has forty seven electrons and its $Z=47$,and uranium has ninety two electrons and its atomic number $Z=92$ etc. The increase of atomic mass with atomic number suggests that all atoms are simply combinations of hydrogen. Thus the helium atom with $Z=2$ should have 2 protons in its nucleus, silver atom should have 47 protons,etc in order to make the atom neutral in charge.However, atomic masses are not found to increase in steps of the mass of hydrogen atom. Helium atom for example,has a mass four times that of hydrogen, lithium has a mass of about seven times etc. The proton is the nucleus of hydrogen atom. Its mass is 1836 times of the mass of the electron, and it carries a positive charge $e=1.60 \times 10^{-19}$C.

One possible argument to overcome. the above discrepancy in the behavior of atomic masses is that there may be enough protons in the nucleus to account for its atomic mass and several electrons may also be present in the nucleus inorder to neutralize the positive charge of the protons that are in excess of the required number. Thus the helium nucleus whose mass is four times that of proton, through its charge is only +2e may be considered to have four protons and two electrons. This explanation gets support from the observed phenomena of beta activity in which nuclei spontaneously emit electrons and whose occurrence can not be easily explained if the electrons are not assumed to be present in the nuclei.

However there are many arguments against this concept of the existence of electrons in the nuclei. One of the objection against the presence of electron in nucleus is that, inorder to confine an electron inside a nucleus, the electron must have an energy of about 10^3 Mev, whereas the observed energies of the electrons in beta activity is of the order of 2 to 3 Mev only. As such the presence of electron inside the nucleus is ruled out.

The problem was resolved by the Chadwicks discovery of neutron. The neutron has a mass slightly greater than that of the proton and it carries no charge. The term nucleon is used as a generic name for either proton or neutron. The masses of the proton and neutron are determined to be:

$$m_p = 1.6726 \times 10^{-27} \text{ kg}$$

$$m_n = 1.6750 \times 10^{-27} \text{ kg} \qquad \text{-------------}(19.1)$$

The atomic number Z of an atom is the number of atomic electrons in the neutral atom; it is also the number of protons in the nucleous. The atmic mass number A equals the number of nucleons in the nucleous often called as the nucleons number. Since Z is the atomic number (or proton number), the neutron number N is therefore defined as N = A - Z.

A nucleous is completely specified by any two of those three numbers. To identify a nucleous the conventional symbol is $_ZX^A$ where X is the chemical abbreviation for the particular element.

19.3. Isotopes

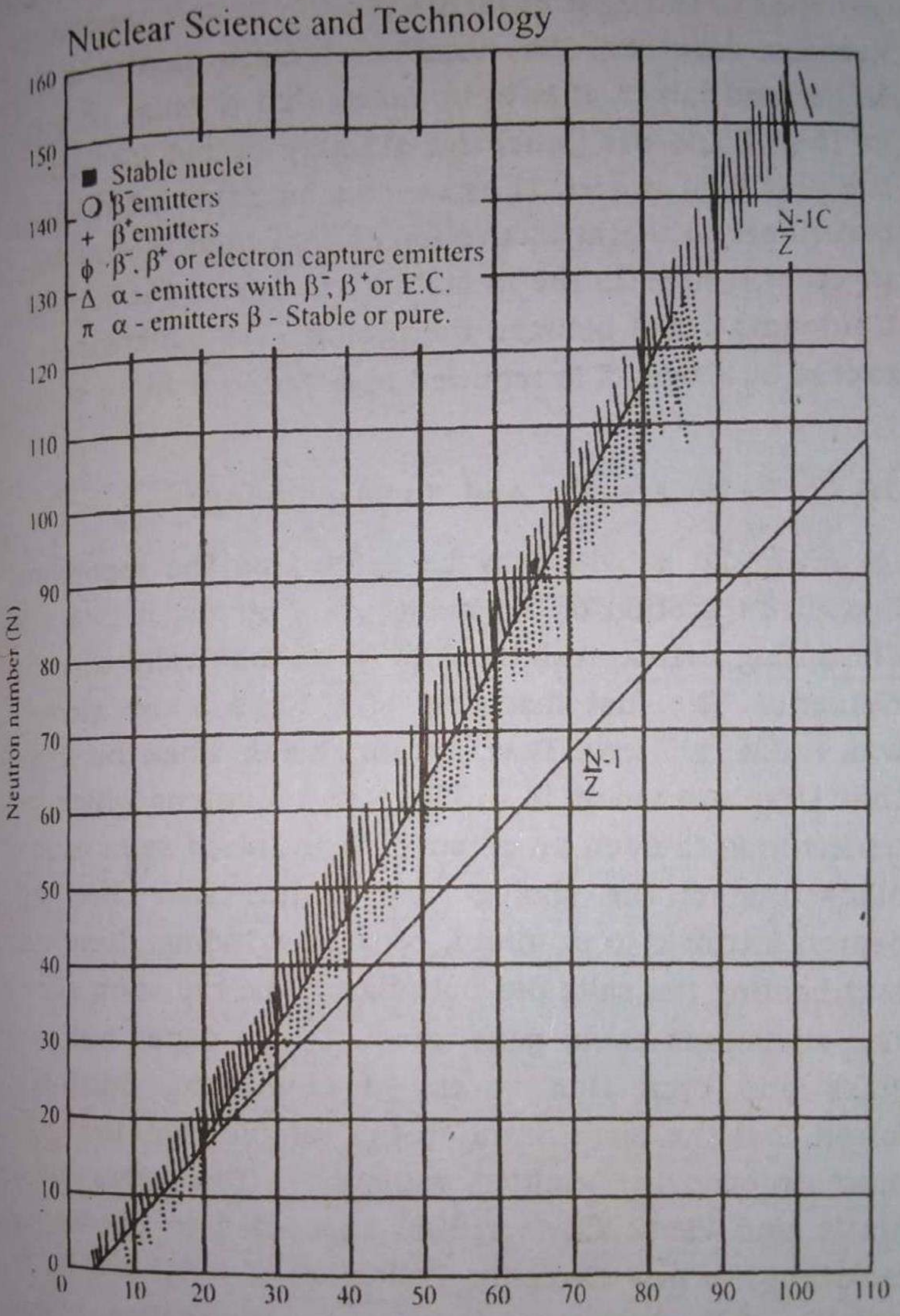
The atomic or proton number Z determines the chemical properties of the element. Many chemical elements have nuclei with more than one value of the mass number A. For example, we have hydrogen, deuterium and tritium for Z = 1, where :

$$A = 1,\ Z = 1 \text{ and } N = 0 \text{ is Hydrogen}$$

$$A = 2,\ Z = 1 \text{ and } N = 1 \text{ is Deuterium}$$

$$A = 3,\ Z = 1 \text{ and } N = 2 \text{ is tritium} \qquad \text{-----------}(19.2)$$

All such nuclei having same Z but different values of N are called ISOTOPES. Deuterium is sometimes expressed by the symbol $^{2}_{1}D$ or $_{1}D^{2}$.



Out of about 1400 nuclei which are known to exist, only about one-fifth are found to be stable. Let us now, analyze them on a chart according to their number of protons and neutrons. As shown in the figure (19.1). if a nucleous has an equal number of protons and neutrons, its position on the graph will be on the 45° line. This is approximately the situation for the commonest isotopes of the light elements. As the atomic number increases, however, the number of extra neutrons gets larger and larger. It is to be noted that N must be greater than Z inorder to achieve stability except for some of the very light nuclei. Thus we conclude that all nucleous contribute to the attractive forces that hold the nucleous together, where as the in stability is due to the repulsive Coulombs forces between the protons. As Z increases, an excess of N over Z is required in order to achieve stability.

19.4. Radio Activity and Nuclear Changes

Radio activity may be defined as the sopontaneous disintegration of the nucleous of atoms. It is a self-disrupting activity exhibited by some naturally occuring elements. The first discovery of a radio active element was made by Henri Bacqueral in 1896, when he found that Uranium atoms (Z = 92) emits radiations which are penetrating to such an extent that uranium salts causes blackening of the photographic plates. This effect appeared intrinsic to uranium, because grinding, dissolving and heating the salts did not change the radiation effect. The radiations could penetrate not only paper but also glass and even thin sheets of aluminum. Bacqueral found that the more uranium the sample contained, the more intense the emitted radiations. Two years later, Marie and Pierre Curie (1898) succeeded in chemically isolating two new elements, Pollonium (Z = 84) and Radium (Z = 88) which were found to be radioactive. It has been demonstrated that all the elements with Z greater then 83 are radioactive. Rutherford and his co-workers were able to prove with the help of experiments that the radiations emitted by radioactive substances are of three different types.

This can be demonstrated with the help of a simple experiment illustrated in Fig. 19.2 - (a) & (b).

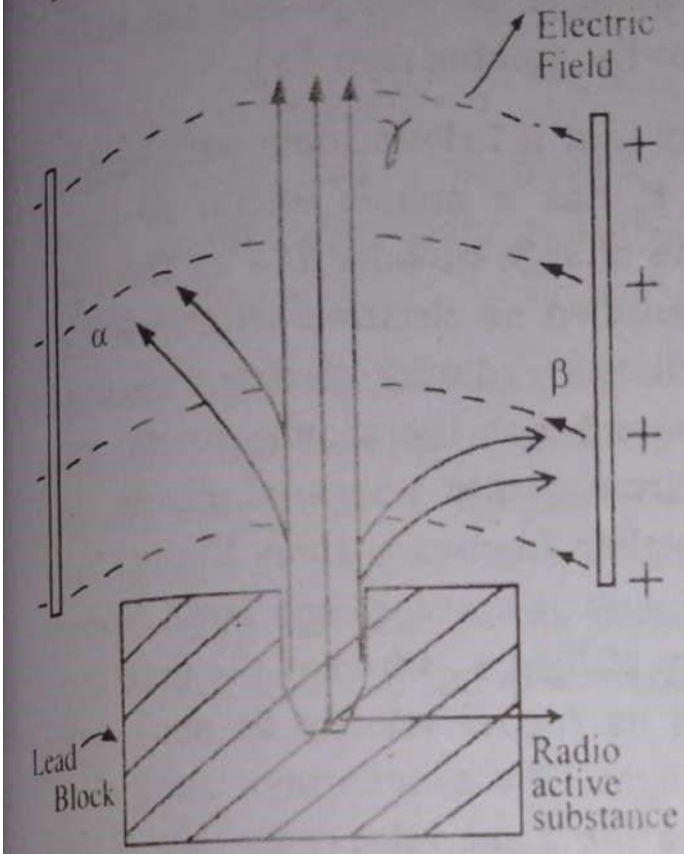


Fig.19.2 (a) Rutherford Experiment

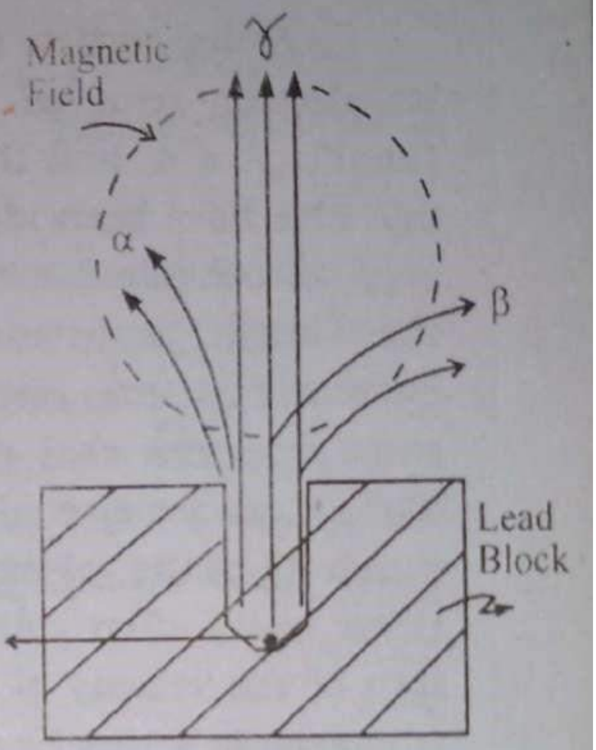


Fig.19.2 (b)

A small amount of Radio active substance is placed at the bottom of a Cavity drilled in a block of Lead. When the narrow beam of radio active rays is allowed to pass through the space between two charged plates as shown in fig.19.2 (a) the path of some of the rays bends towards the positive plate and some rays sends towards the negative plate while others go undeflected by the influence of electric field between the plates. Similar effect is observed in the presence of a transverse magnetic field as shown in fig.19.2 (b). The rays bending towards the negative plate indicate that they consist of positively charged particles, while those bending towards the positive plate indicate negatively charged particles.

Further experiments confirmed that the positively charged particles are nuclei of Helium atoms called Alpha particles (α), while the negatively charged particles are electrons, and are called Beta particles (β). The rays which go undeflected indicate no charge and are therefore energetic photons or the gamma rays (γ).

Alpha particle is just a helium atom with both of its electron removed. It has a atomic weight or mass number $A = 4$, and the charge number $Z = 2$. The beta particles have been identified as electrons with more energy as compared with the ordinary electrons because their origin is nucleus and not the atomic orbits. The gamma rays are electromagnetic waves of nearly the same or some what higher frequency than X-rays. The alpha rays are ejected with a speed of one tenth to one hundreth of the velocity of light c. whereas the beta particles travel often with as higher velocity as about one fifth of the velocity of light. The gamma rays being electromagnetic waves have the same velocity as that of the velocity of light.

19.5. The Disintegration Of Radioactive Elements

A nuclear species corresponding to given values of A & Z is called a nuclide and is denoted by ${}_{Z}X^{A}$, where X is the chemical symbol for the particular element, e.g carbon is denoted by ${}_{6}C^{12}$ etc.

The nuclear volume is directly proportional to A, which leads to the important result that the density of nuclear matter is essentially constant for all nuclides. The main cause of radio activity is the instability of nuclides of heavy elements. The unstable nuclides in nature decay by the phenomena of radio activity taking place by the process of emission of α or β particles, which may be accompanied by γ-rays. As the mass number of α-particle is $A = 4$ and the charge number $Z = 2$, the decay product after alpha particle emission will have as mass number (A–4) and charge number (Z–2) i.e a parent nucleus $_{Z}X^{A}$ will decay into $_{Z-2}X^{A-4}$ due to α - emission viz:

$$_{Z}X^{A} \text{ ---------- } _{Z-2}X^{A-4} + {}_{2}He^{4} \text{ (α-particle) ------(19.3)}$$

(Parent Nucleus) (Daughter Nucleus)

In this process the daughter-nucleus may also remain unstable and under go further disintegration till it attains stability.

The process of beta particle emission involves no effect on mass number A, but it does change the charge number Z by +1 or -1 depending upon whether the emitted particle is negative beta particle β^- (electron) or a positive beta particle β^+ (positron). Thus beta activity may lead to either of the following disintegrations:-

$$_{Z}X^{A} \longrightarrow {}_{Z-1}X^{A} + \beta^{+}$$

or, $$_{Z}X^{A} \longrightarrow {}_{Z+1}X^{A} + \beta^{-} \text{ ----------------(19.4)}$$

Most frequently the α or β emission leaves the daughter nuclide in an excited state, and that one or more γ-rays are emitted as it goes back to the ground or normal state (un excited state). Since the gamma rays are massless photons, γ-emission will cause no change on either A or Z. These decay schemes are shown below fig.19.3-(a) and (b) by the respective energy level diagrams indicating decay directly to the ground state or to an excited state of the daughter nucleus.

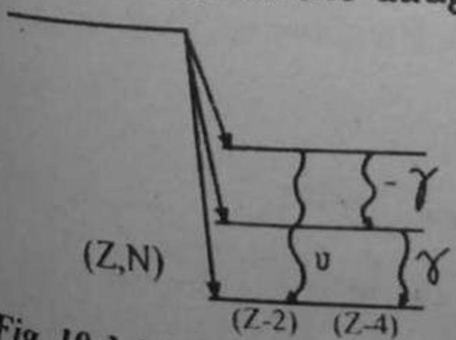


Fig. 19.3 (a) An Alpha-emitter

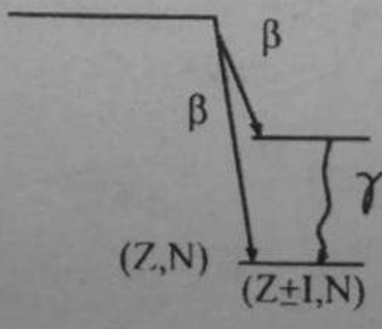


Fig. 19.3 (b)-A Beta emitter.

Example 19.1.

A nucleus consists of 11 protons and 12 neutrons. What is the conventional symbol of this nucleus?

Solution

Given that, there are 11 protons: hence the atomic number Z is 11. From the periodic table the chemical element of atomic number Z = 11 is Sodium, whose chemical symbol is Na. The mass number of the nucleus is therefore: $A = N + Z = 12 + 11 = 23$ Hence, the symbol of the given nucleus will be $_{11}Na^{23}$

Example 19.2.

What element will be formed due to the emission of β- particle from the nuclide $_{82}Pb^{214}$

Solution

In β- emission the charge number Z is enhanced by 1 where as the mass number A remains unaltered. Hence we have:

$$_{82}Pb^{214} \xrightarrow{\overline{\beta}} {}_{82+1}X^{214} \text{ or } {}_{83}X^{214} \text{ ---------(19.5)}$$

But, from the periodic table of elements the chemical element with Z = 83 and A = 214 is bismuth whose symbol is Bi. Hence, the element formed in the given decay will be $_{83}Bi^{214}$.

Example 19.3.

Find the element formed due to the disintegration of $_{88}Ra^{226}$ by the emission of an alpha particle.

Solution

Since the α - emission involves a change in Z by 2 & A by 4. We have

$$_{88}Ra^{226} \xrightarrow{\alpha} {}_{88-2}X^{226-4} \text{ or } {}_{86}X^{222} \text{ --------(19.6)}$$

But, from the periodic table the element with Z =

86 and A = 222 is Radon with symbol R_n. Hence the element formed will be ${}_{86}R_n^{222}$.

19.6. The Law Of Radioactive Decay

The rate of decay in a radio active process is experimentally found to be directly proportional to the number of parent nuclides present in the unstable nuclides of a given species, then the number of disintegration ΔN occuring in a time interval Δt will be given by :

$$\Delta N \propto N$$

$$\propto \Delta t$$

$$\Delta N = -\lambda N_0 \Delta t \quad \text{----------------}(19.7)$$

or,

where, λ is the constant called the disintegration or the decay constant. The negative sign in Equation (19.7) is introduced to indicate the decrease in the number N with time.

From equation (19.7) it is seen that if λ is large, more nuclei will be decaying in the same time interval i.e the element decays rapidly. On the other hand if λ is small, the element will decay slowly. The decay constant is a characteristic of the substance that decays and is absolutely independent of all external conditions such as temperature, pressure etc. from equation (19.7) we may also write:

$$\frac{\Delta N}{\Delta t} = -\lambda N_0 \quad \text{- - - - - - - - - - - -} (19.8)$$

The number of disintegrations per second is called the activity A and is taken as a positive number. Hence, from (19.8) the activity at any time t may be expressed as :

$$A = \lambda N_0 \quad \text{- - - - - - - - - - -} (19.9)$$

The ratio N/N_0 is defined as the relative activity. where N_0 is the number of the parent nuclei at the initial or starting time t = 0'. Thus, if we plot the relative activity versus time we get the following trend of the decay curve fig. (19.4).

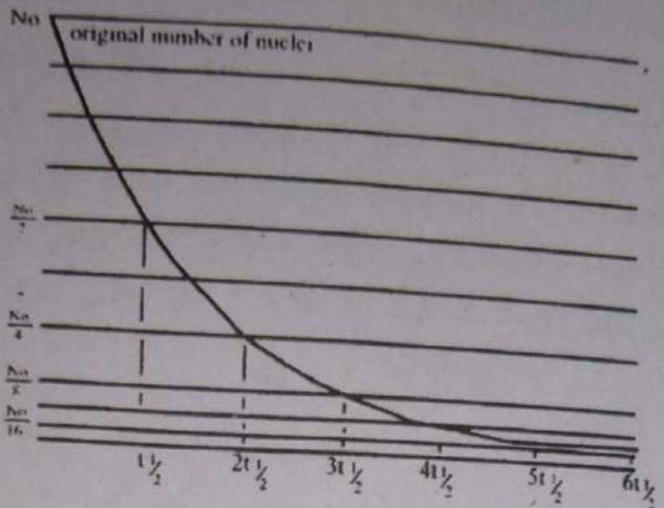


Fig.(19.4)

The above curve shows that the radio active decay process is exponential in nature i.e the number of radio active atoms decreases rapidly in the beginning and then the decay slows down as the time passes. From this nature of decay we may infer that the activity may be mathematically expressed in the following form:-

$$\frac{N}{N_o} = e^{-\lambda t} \quad \text{-----------------(19.10)}$$

where, e is the Natural Logarithm base. Thus we have the following famous form of the exponential law of radio active disintegrations:-

$$N = N_o e^{-\lambda t} \quad \text{-----------------(19.11)}$$

19.7. The Half Period Or The Half Life Of The Radio Active Nuclide

Equation (19.11) established in article 19.6 above indicates that an infinite time is required for the radio activity to disappear completely, since all the substances are the same in this regard, a more qualitative and useful term Half Life is often used to distinguish one radio active substance from the other. Half Life time or simply the Half Life denoted by $T_{1/2}$ is defined as the time required for the radio active element to decay to one half of its initial number N_0. Thus, to determine the Half Life, we can solve equation (19.11) to get

$$T_{1/2} = \frac{0.693}{\lambda} \quad \text{-- -- -- -- -- --} \quad (19.12)$$

Equation (19.12) shows that the half life of a radio active element is inversely proportional to the decay constant λ, which can be used to distinguish one substance from the other eg: Half life of Radium is 1590 years while for Radon it is only 3.825 days. This mean that Radium is long lived where as Radon is short lived.

19.8. Nuclear Changes And The Conservation Laws

All types of radio active decays obey some simple and .basic rules which are based on conservation laws. The common conservation laws are as follows:-

(1) Conservation of Nucleon Number A.

(2) Conservation of Charge Number Z.

(3) Conservation of Energy.

(4) Conservation of Linear Momentum.

(5) Conservation of Angular momentum.
(including spin)

The first rule is a sort of generalization of a variety of observations, whereas by all the other conservation laws we simply mean that the total charge, total energy, and total momenta of the system remains the same before and after the concerned change or transformation.

We may illustrate these rules by considering the example of the disintegration of ${}_{90}Th^{227}$ into ${}_{88}Ra^{223}$ and a alpha particle i.e

$${}_{90}Th^{227} \xrightarrow{\quad} {}_{88}Ra^{223} + {}_{2}He^{4} \ (\alpha\text{-particle}) \quad \text{---} (19.13)$$

Using the mass of $_{90}Th^{227} = 227.027$ U, the mass of $_{88}Ra^{223} = 223.018$ U and mass of $_{2}He^{4} = 4.002$ U. where atomic mass unit (U) is defined as one twelfth of the mass of an atom of $_{6}C^{12}$.

The kinetic energy of the α - particle have been found to be 6.04 MeV We may now examine how these facts agree with the rules.

1. By adding the number of nucleons on both sides of equation (19.13) we may verify that no nucleus have been increased or decreased, i.e

$$A = 227 = 223 + 4.$$

2. The total charge number is Z = 90 before and after the decay i.e

$$Z = 90 = 88 + 2.$$

3. The difference in mass before and after the decay is :

$$227.027 \text{ U} - 223.018 \text{ U} - 4.002 \text{ U} = 0.007 \text{ U}$$

This mass difference corresponds to a difference of energy given by :

$$(0.007 \text{ U})(931 \text{ MeV/U}) = 6.517 \text{ MeV}$$

This energy of 6.517 MeV should show itself as the Kinetic Energy of the decay product. It has been observed that α - particle come out with an energy of 6.04 MeV. This experimental value of the energy of α - particle is this in close agreement to our calculated energy 6.517 MeV with a small difference of 0.11 MeV. This apparent difference is taken care of in the fourth and fifth rules of the conservation of momenta. In our present example this energy of 0.11 MeV is nothing but the Kinetic energy of recoil of the daughter nucleus Radon.

All the radioactive decays or nuclear reactions involves the release of some energy which is commonly denoted by the symbol Q, and in the general terminology of Nuclear physics it is refered to as the Q-value of the reaction. If Q is positive, energy is released and the reaction is exothermic; whereas for negative Q-value, energy is required to be supplied in order to let the reaction go and the reaction is said to be endothermic.

Example 19.4.

Find the Q-value of the reaction, when $_{94}Pu^{239}$ makes a alpha decay.

Solution

The reaction in the above decay may be written as:

$$_{94}Pu^{239} \rightarrow {}_2He^4 + {}_{92}U^{235} + Q$$

The Isotopic masses in the above reaction are :

$$_{92}U^{235} = 235.0439 \text{ u}$$

$$_2He^4 = 4.0026 \text{ u}$$

i.e sum of the masses = 239.0465 u

Now, mass of $_{94}Pu^{239}$ is given by :

$$_{94}Pu^{239} = 239.0522 \text{ u}$$

$\therefore$ Change in mass $(\Delta m) = 239.0522 - 239.0465$

$= 0.0057$ u

Hence, the Q - value will be :

$$Q = (\Delta m)c^2 = (0.0057)\ 931 \text{ MeV}/\mu$$

$$= 5.7 \times 10^{-3} \times 931$$

$$= 5.306 \text{ MeV.}$$

19.9. Mass Energy Relation and The Mass Defect:

We have learnt in mechanics that the Kinetic energy associated with a body of mass m moving with velocity V is given by $\frac{1}{2}$ mv^2 This expression is only an approximation suitable for moderate range of velocities.

However for atoms and subatomic particles which can be accelerated to velocities approaching Velocity of light c, this approximation breaks down, but Einstein showed that

$$m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}} \quad \text{-----------------(19.14)}$$

In view of the mass variation formula (19.8) Einstein proposed that the expansion for the Kinetic energy (K.E) of an object moving at high velocities ought to be of the form :

$$K.E = (m - m_o)c^2 = (\Delta m)c^2 \quad \text{-------------(19.15)}$$

In other words, the change in mass of the object (Δm), when multiplied by the square of the speed of light, gives the energy of the object. Einstein showed that equation (19..15) is applicable to any form of energy, and this relation predicts that energy has mass.

This suggests that mass and energy are interconvertable and the relation provides us an equivalence of mass and energy.

Example 19.5.

The rate of radiation of energy from the same is 3.80×10^{26} W. Determine the change in mass of the sun and calculate the rate at which the mass of the sun diminishes.

Solution

From the mass energy relation we have,

$$E = (\Delta m) c^2.$$

where Δm is the change in mass.

Hence, we have :

$$\Lambda m = \frac{E}{c^2} = \frac{3.80 \times 10^{26} J}{(3 \times 10^8 m/s)^2}$$

or
$$\Delta m = \frac{3.80 \times 10^{26} J}{9 \times 10^{16} m^2/s^2} = 4.20 \times 10^{9} kgs^{-1}$$

Now, one year consists of 365 × 60 × 60 × 24 s

i.e 3.16×10^{7} s/ year

∴ The rate of loss of Sun's mass will be given by:

$(\Delta m)\ (3.16 \times 10^{7}\ s/yr) = 1.32 \times 10^{17}\ kg/yr.$

19.10. Mass Defect and Binding Energy

According to the accepted model of the nucleus, it consist of protons and neutrons. But the electrostatic repulsive force between two protons with in the nucleus $(\sim 10^{-15}$ m) is so strong that nucleus should be blown apart. But we observe that nucleus of elements with atomic number as high as 82 are stable. The gravitational force of attraction is far too weak to hold the nucleus together. There ought to exist a force strong enough to over power the repulsive electrostatic force. This is called strong nuclear force. Experiments using protons and neutrons as bombarding particles have shown that the strong nuclear force is independent of the charge. This nuclear force is stronger than the electric force, but is effective only at extremely short range.

Another interesting feature emerges, when we measure the nuclear masses and compare them with the masses of the constituent nucleus in free states. The mass of the nucleus is always less that the mass of the constituent nucleons. This difference in mass, Δm is known as the MASS DEFECT. As shown earlier, Δm is equivalent to an energy $(\Delta m)\ c^2$. This difference in energy between the stable nucleus and the free constituents nucleon, is called the BINDING ENERGY of the nucleus.

We can illustrate the case by the following example. For deuteron $_1H^2$ which consist of one proton and one neutron we have :

Mass of proton $_1H^1 = 1.6724 \times 10^{-27}$ kg

Mass of neutron $_0n^1 = 1.6748 \times 10^{-27}$ kg

i.e the sum of the proton and neutron mass will be 3.3472×10^{-27} kg.

But, mass of deuteron $_1H^2 = 3.343 \times 10^{-27}$ kg.

∴ The mass defect Δm will be given by:

$$\Delta m = (3.3472 - 3.3431) \times 10^{-27} \text{ kg} = 0.0041 \times 10^{-27} \text{ kg}$$

The mass defect must appear as the binding energy can be calculated :

$$E = (\Delta m)\, c^2 = (0.0041 \times 10^{-27} \text{ kg})\,(3 \times 10^8 \text{ m/s})^2$$

or, $E = 3.69 \times 10^{-13}$ J

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

The binding energy of deuteron will be:

$$(B.E)_{\text{Deuteron}} = \frac{3.69 \times 10^{-13} \text{ J}}{1.60 \times 10^{-19} \text{ J/eV}} = 2.3 \times 10^{-6} \text{ eV}$$

$$= 2.3 \text{ MeV}$$

Another useful quantity for a nucleus is the binding energy per nucleon or the PACKING FRACTION. The value of packing fraction fordeuteron is 1.1MeV, a large value consistent with the observation that the combination of two protons and two neutrons is very stable. Packing fraction for various nuclei has been plotted against graph - Fig. (19.5):

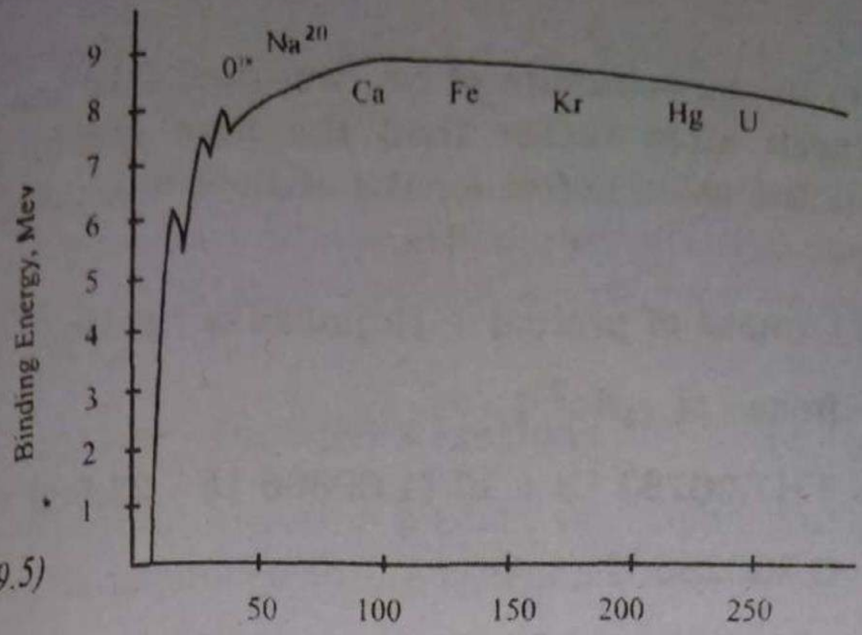


Fig.(19.5)

It can be noted from the graph that the binding energy per nucleon increases rapidly at first and then slowly decreases as the number of nucleous increases beyond about 60. Apparently the nuclei with largest binding energy per nucleon and hence most tightly bound are those in the middle region of the periodic table of elements - iron, cobalt and nickel. These nuclei have considerably less mass than the sun of the masses of their constituent nucleons. It would take a large amount of energy to pull the nucleous apart. For these elements the amount of binding energy per nucleon is over 8 MeV. The graph can also be interpreted as a rough graph of nuclear stability.

Example 19.6.

Sodium ($_{11}Na^{23}$) has a atomic mass of 22.989 u. Find the total binding energy of the sodium nucleus and estimate the binding energy per nucleon.

Solution

The atomic number of sodium is $Z= 11$

The mass number of sodium is $A = 23$

$\therefore$ The neutron number $N = A - Z$

$= 23-11 = 12.$

Because the atomic mass includes the mass of 11 electrons in the structure of Na, we must take the mass of hydrogen atom rather than the bare proton mass. Therefore the mass defect for the sodium nucleus will be given by:

$$11 \text{ (mass of proton)} + 12 \text{ (mass of neutron)}$$

$$- (\text{mass of } {}_{11}Na^{23})$$

$$= 11(1.00782 \text{ U}) + 12\ (1.00866 \text{ U}) - 22.989 \text{ U}$$

$$= 0.200285 \text{ U}$$

$$\therefore \text{B.E} = (0.200285 \text{ U})\ (931.5 \text{ MeV/U}) = 186.6\text{MeV}$$

$$\text{and B.E per Nucleon} = \frac{\text{B.E}}{A} = \frac{186.6 \text{ MeV}}{23} = 8.11\text{MeV}$$

19.11. Nuclear Reactions:

Nuclear reactions in which alpha and beta particles are emitted by unstable nuclei were introduced earlier. These nuclear reactions are however spontaneous and uncontrollable. But they provided the first rich source of nuclear particles, which may be used to bombard other nuclei and initiate new nuclear reactions. One of the first nuclear reaction (artificially induced) was observed by Rutherford in 1919. He used alpha particles (obtained from radioactive nuclei) to bombard Nitrogen nuclei to produce an Oxygen isotope and energetic protons. This reaction is as follows:

$${}_7N^{14} + {}_2He^4 \text{ (α-particle)} \longrightarrow \underset{\text{Oxygen Isotope}}{{}_8O^{17}} + {}_1H^1 \text{ (proton)}$$

In nuclear physics this reaction is commonly abbreviated in the form ${}_7N^{14}(\alpha,p)\,{}_8O^{17}$. Just like the balancing of a chemical reaction equation, here the nuclear reaction equation is also balanced. The charge number Z on both the sides of the equation is the same i.e $Z = 7+2 = 9$ on the left hand side and $8 + 1 = 9$ on the right hand side. Similarly, the nucleon number A is the same on both sides of the equation i.e A = 14+4 = 18 and 17+1 = 18.

The discovery of this nuclear reaction was a land mark in physics and opened a new era for producing other types of nuclear reaction which may be summarized as below:

1. **Protons - Induced Reactions**

If lithium absorb a proton, two alpha particles are found to be produced in the reaction.

$${}_3Li^7 + {}_1H^1 \text{ (proton)} \xrightarrow{\qquad} {}_2He^4 + {}_2He^4$$

Two alpha particles.

This reaction is of great historical importance because it provided the earliest experimental verification of the Einstein's mass - energy relationship.

2. **Deutron – Induced Reactions**

High energy deuterons may be absorbed by ${}_3L_1^6$ to produce two alpha particles i.e

$${}_3Li^6 + {}_1H^2 \text{ (deuteron)} \xrightarrow{\qquad} {}_2He^4 + {}_2He^4$$

3. **Gamma – Induced Reactions**

High energy gamma rays also have been found to induce nuclear reactions by a process which is usually known as photo disintegration. Examples of such reactions are :

$${}_{13}AL^{27} + {}_1H^2 + \gamma \text{ (50 Mev)} \xrightarrow{\qquad} {}_{11}Na^{25} + 2\,{}_1H^1$$

Soduim isotope   Two protons

19.12. Nuclear Fission

A remarkable nuclear reaction was discovered in 1934 when Fermi, Segre, and Co-workers bombarded Uranium by neutrons and noticed the production of several beta activities with different half lives. Four years later in the year 1938 two German scientists Hahn and Strassman showed that one of the radioactive elements produced when uranium is bombarded by neutrons is the Barium isotope ${}_{56}Ba^{141}$. Soon after in the year 1939 Frisch and Meitner suggested that in the above neutron bombardment experiment the uranium nucleus undergoes a nuclear fission process producing two fragments ${}_{56}Ba^{141}$ and ${}_{36}Kr^{92}$ of roughly equal size. Such a process of splitting of a heavy nucleus into smaller fragments is called Nuclear Fission. Each fission process also involves the production of some smaller particles also in addition to the bigger fragments. Typical nuclear fission reactions are the following:

$$ {}_0n^1 + {}_{92}U^{235} \rightarrow ({}_{92}U^{236})^* \rightarrow {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3\,{}_0n^1 + Q $$

Excited Compound nucleus. Barium. Krypton. Neutrons. Energy

where, Q is the energy released in the reaction. Thus the general scheme of the nuclear fission reaction is of the following form :

$$ {}_0n^1 + {}_{92}U^{235} \rightarrow ({}_{92}U^{236})^* \rightarrow X + Y + \text{Neutrons} + \text{Energy } (\gamma\text{-Ray}) $$

where, $({}_{92}U^{236})^*$ is the excited nucleus after the capture of neutron. X and Y are the fission fragments. The fission process may be schematically represented as shown in Fig - (19.6) below:

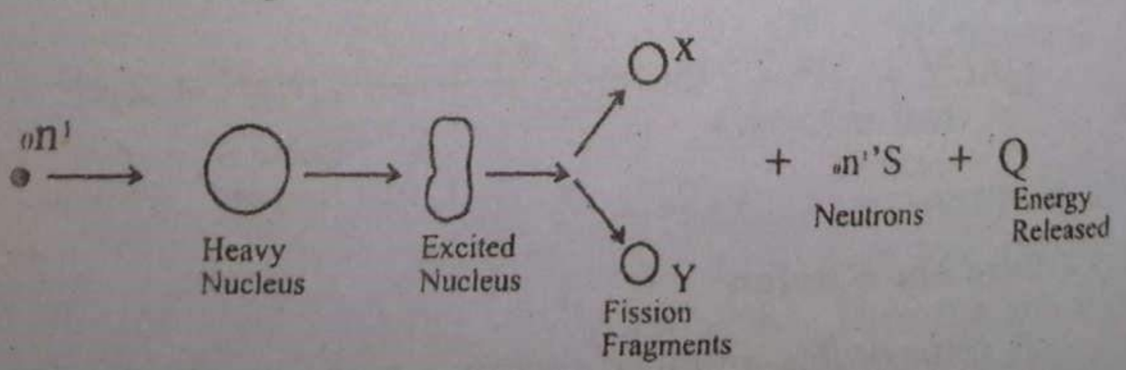


Fig.(19.6)

The most important aspect in the above reaction is the liberation of atleast one or more energetic neutrons. Which may further induce fission in the additional heavy nuclei in the form of a chain reaction resulting in the sudden release of a huge amount of energy (a nuclear bomb). The energy release in the fission process is due to the conversion of mass defect between the mass of the heavy nucleus and the resulting fragments, into energy.

The nuclear chain reaction may be schematically represented as shown in Fig.(19.7) below :

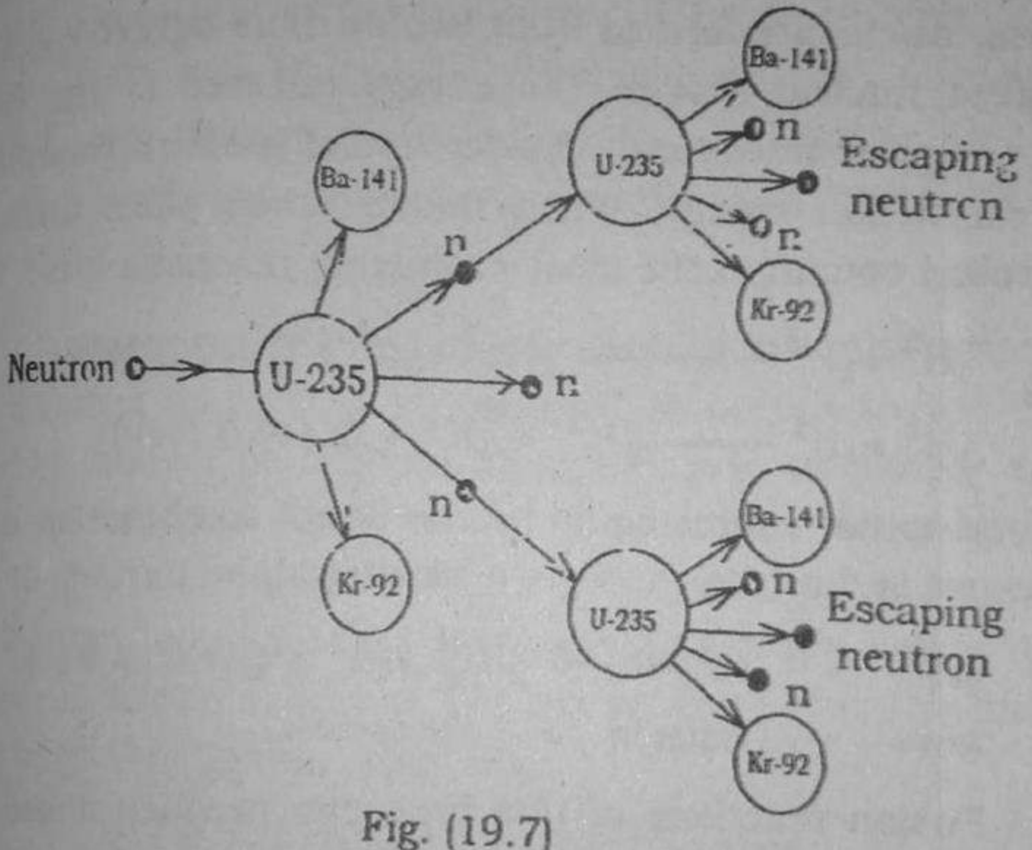


Fig. (19.7)

The chain reaction described above is a self-sustaining reaction. If such a reaction is allowed to proceed rapidly it would lead to a huge explosion because of the unchecked release of energy. The uncontrolled chain reaction may be checked if some device is used to absorb some of the neutrons produced in fissions. A suitable device is the use of some material as a moderator to slow down the reaction. Commonly used materials as good moderation are graphite, and cadmium. Which may keep the chain reaction well below the self-sustaining level. Moderators are used in the form. numerous rods inserted into the reaction chamber.

19.13. Nuclear Fusion

From the binding energy curve Fig.(19.5) of Section 19.10 we may note that nuclei with mass number A less then 30 or 40 have smaller binding energies per nucleon than havier nuclei. For example, the binding energy per nucleon of Hydrogen is 1.12 MeV, whereas it has a value of 7.07 MeV for Helium. This suggests that, in principle, a process inverse to fission is energetically possible for lighter nuclei. Hence, the process in which heavier nuclei are formed from two or more lighter nuclei is called nuclear fusion. The energy released in the fusion of lighter nuclei into heavier nuclei is called thermonuclear fusion energy. When fusion taken place under controlled condition the most promising reactions are :

$${}_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + {}_0n^1 + Q \ (=3.3 \text{ MeV})$$

and, $${}_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + Q \ (=4.0 \text{ MeV})$$

Another source could be the direct combination of a deutron and a triton to form a heavier alpha particle i:e

$$\underset{\text{Triton}}{{}_1H^3} + \underset{\text{Deuteron}}{{}_1H^2} \longrightarrow \underset{\text{Alpha particle}}{{}_2He^4} + {}_0n^1 + Q(=17.6 \text{ Mev})$$

Fusion reactions of this type can produce abundant energy. The raw material for the reaction is deuteron which is found in abundance in world oceans as heavy water. Fusion reactions are also, the basic source of energy in stars including the sun. One such chain reaction of fusion process is as follows:

$${}_1H^1 + {}_1H^1 \longrightarrow {}_1H^2 + \beta^+ + \nu \text{ (neutrino)}$$

$${}_1H^1 + {}_1H^2 \longrightarrow {}_2He^3 + \gamma \text{ (gamma ray photon)}$$

$${}_1H^1 + {}_2He^3 \longrightarrow {}_2He^4 + \beta^+ + \nu$$

In the first and the third reaction above, neutrino (ν) is a electrically neutral particle of very small mass (very small as compared with that of electron or may be even zero) that carries away the missing energy in the concerned nuclear reaction, and fulfills the requirements of the conservation laws of momentum and energy. This means that in a processes involving beta decay the disintegration energy is shared between the beta particle, the neutrino, and the recoil nucleus with the division of energy among three particles.

The above fusion reactions means that the net effect of the proton-proton cycle of three fusion reactions is the conversion of four protons ($_1H^1$) into an alpha particle ($_2He^4$), two positrons (β^+), two neutrinos (υ) and a gamma ray photon. In this fussion process the amount of energy released have been calculated to be of the order of 25 MeV.

Fusion of Hydrogen into Helium can also proceed in another way. This is assumed to occurs in the Sun and is known as carbon -Nitrogen cycle or simply Carbon Cycle. This cycle of fusion reactions was proposed by Bethe in the year 1938. In this cycle four protons are converted into an alpha particle with Carbon acting as a catalyst in the reaction. The sequence of reaction taking place in the Carbon cycle are :

$$_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13} + \gamma \text{ (gamma Ray)}$$

$$_7N^{13} \rightarrow {}_6C^{13} + \beta^+ + \upsilon \text{ (neutrino)}$$

$$_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} + \gamma \text{ (gamma Ray)}$$

$$_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15} + \gamma \text{ (gamma Ray)}$$

$$_8O^{15} \rightarrow {}_7N^{15} + \beta^+ + \upsilon \text{ (neutrino)}$$

$$_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4 \text{ (alpha particle)}$$

Carbon Reappears

(I.e it acts as a catalyst)

The energy released after a complete

which four protons ($_1H^1$) combine to form a nucleus of Helium (an alpha particle, $_2He^4$) and two positrons (β^+) have found to be more than 26.7 MeV. There has been a concentrated effort to produce controlled thermonuclear fusion in the laboratory on earth and some progress toward it has been made since 1948. There seems to be a promise of Virtually unlimited useful source of energy through the development of controlled fusion reactors in future.

19.14. Nuclear Reactors

A seemingly in exhaustible source of energy is locked up inside the atomic nucleus. A nuclear fission reaction produces on the average 10^9 times more energy compared to the energy released when a carbon atom in the conventional coal furnace combine with oxygen in the air to form carbon dioxide.

Thus, a great energy resource may be opened up by the possibility of developing easier means to extract the hidden energy from the nucleus. Reactors are the possible devices for achieving this objective. Different kinds of nuclear reactors have been developed in our present day world. Inspite of a number of possible variation in the design and components of nuclear reactors there are quite a few general features which are to almost all types of reactors. These features may be summarized as under:

1. Nuclear Fuel

A material consisting of the fissionable (or fissile) isotope is called the reactor fuel. The fuels that may be used in a reactor are Uranium U^{235} in its natural abundance of 0.715% or in an enriched proportion i.e. U^{235} and U^{239} etc.

2. Moderators

In the nuclear fission process at least one or more energetic neutrons are produced per fission. To reduce the energy of neutrons some suitable materials are required which are known as moderators. The good moderating materials possess usually low mass number and large slowing down power. The ordinary water (light water) is an attractive moderator material because of its easy supply at low cost. Heavy water is supposed to be the best suited material for neutron moderation inspite of its greater cost as compared with light water. Other moderators which may be used in a reactor are graphite. Beryllium and its oxide and certain organic compounds.

3. Coolants

A huge amount of heat is generated in the reactor core as a result of fission taking place in the nuclear fuel. To remove this large quantity of heat materials are required which are called coolants. These materials are usually circulated through the core in order to absorb heat and transfer it to the outside core. The properties of a good coolant are :

(a) It should have as little effect on neutrons as possible i.e. it should not absorb nor moderate the neutrons.

(b) It should not induce any chemical effect with other materials in contact with system.

(c) The coolant should not breakup under the effect of radiations.

(d) The coolant material should be capable of acquiring long lived radio activity during its circulation through the reactor.

(e) It should have low vapour pressure at the operating temperature of the reactor.

(f) The material should be able to remove large quantities of heat for a small input of pumping power.

In fact, no single coolant possess all the above properties simultaneously, and the choice of a coolant depends upon the type of reactor. The materials commonly used as coolants are light water, heavy water, liquid metals such as sodium or sodium potassium alloy or mercury. Certain organic liquids and gases are also used as coolants.

4. Control Materials

In order to control the nuclear fission in a reactor suitable neutron absorbing materials are required to be placed in the core region. The control material should be such that it does not become radioactive by the neutron capture. Cadmium has been found to be a good control material. Because of its low melting point cadmium can be used as a control material at low temperature. For higher temperature an alloy of silver with 15% indium and 5% cadmium is more suitable because of its higher melting point. Boron is also a very good control material due to its very high melting point and large neutron absorbing capability. Some times Boron is mixed with stainless steel, aluminium or carbon is successfully used as a control material for some reactors.

5. Shielding

With the exception of reactors operating at very low powers all reactors are sources of intense neutron and gamma ray radiations. These radiations are hazardous in the vicinity of the reactor. Hence proper shielding material is always required to protect the persons working in the reactor area. A shielding material used for such a protection is called the biological shielding because its purpose is to protect health. Generally a layer of concrete, about six to eight feet thickness has been found to absorb both neutrons and gamma rays and acts as a good biological shield. For reactors operating at high powers another type of protection known as thermal shield is required to eliminate excessive heat produced in the immediate neighbourhood or contact of the core of the reactor. For the purpose of thermal shielding of this type special cooling arrangements are required to prevent the shield in contact with the core from cracking or suffering from any other heat damage. A few centimeters of iron or steel very close to the core of the reactor provides the required thermal shield.

19.15 Breeder Reactor

235 In the natural occurrence of uranium, the isotope $_{92}U^{238}$ makes up only 0.72% whereas the rest 99.28% is the other isotope $_{92}U^{238}$. The least abundant isotope $_{92}U^{235}$ is used as the fuel for conventional reactors. If some how we could make use of $_{92}U^{238}$ as a fuel as a nuclear reactor, we could be better off in increasing the life span of the existing uranium fuel supplies of the world deposits of uranium ore. Due to this reason our interest in breeder type of reactors has increased significantly. The far more available isotope, $_{92}U^{238}$ has been found more likely to undergo the following reaction:

$$\begin{tikzcd}[column sep=small] {}_{92}U^{238} + {}_0n^1 \arrow[r] & {}_{93}Np^{239} + \beta^- + \upsilon^- \text{ (anti neutrino)} \arrow[d, phantom] \\ & {}_{94}Pu^{239} + \beta^- + \upsilon^- \arrow[from=1-1, to=2-2, rounded corners, to path={|- (\tikztotarget)}] \end{tikzcd}$$

In this nuclear reaction $_{94}Pu^{239}$ is an alpha emitter with a half life of 2.4×10^4 yr. It is responsive to undergo fission by slow neutrons. In a breeder reactor some of the neutrons from the fission of $_{92}U^{235}$ are used to transmute $_{92}U^{238}$ into $_{94}Pu^{239}$ as indicated in the above reaction. We see that the breeder reactor does not create material capable of undergoing fission, but it simply converts the unuseable most abundant isotope $_{92}U^{238}$ into fissionable isotope $_{94}Pu^{239}$ with a very long half life of 2.44 x 10^4 year. The isotope $_{94}Pu^{239}$ is also radio active and can decay into $_{92}U^{235}$ with the emission of alpha particle, but due to its long half life large quantities of $_{94}Pu^{239}$ can be collected and used for power reactors where it fissions under neutron bombardment with the release of huge amounts of energy through the following nuclear reaction:

$$_0n^1 + {_{94}Pu^{239}} \longrightarrow 2\,{_0n^1} + X + Y + 200\text{ MeV}$$

Where, X and Y are fission products consisting of a variety of isotope near the middle of periodic table. The term breeder is used to signify that, starting with a nonfissile abundant isotope $_{92}U^{238}$, we are able to breed a fissile nucleus $_{94}Pu^{239}$, which can be used in a reactor to produce almost the same amount of energy as is available from the fission reaction of $_{92}U^{235}$

There are however, still some problems of technical nature with operating a breeder reactor, which may be resolved in due course of time. Another serious problem is that $_{94}Pu^{239}$ is highly toxic and is also a potent material for producing fission bombs. This is of course, a matter of great anxiety and concern for many nations of the world.

In a Fast Breeder Reaction (FBR) more fissionable material is produced than consumed by the capture of fast neutrons from fertile material. In such reactors the energy of the neutrons should not be lowered to decrease otherwise the neutrons will be absorbed as slow neutrons in the structured materials. Thus, use of lighter elements should be avoided in these reactors eg. water used as coolant in thermal reactors is not a suitable coolant in FBR, because of its high slowing power. In fast breeder reactors sodium is widely used as coolant and reactors so designed are called Liquid Metal Fast Breeder Reactors (LMFBR). A schematic diagram of a LMFBR is shown in Fig. (19.8)

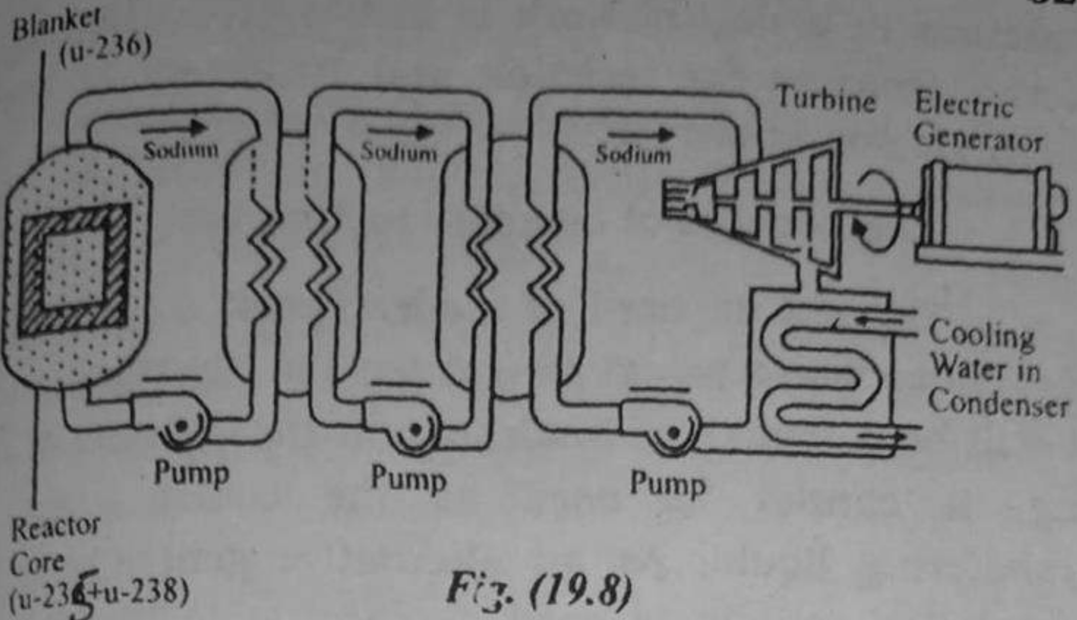


Fig. (19.8)

From the above diagram it may be seen that this type of reactor is just like a conventional reactor except that the reactor core is made up of 15 to 30% $_{92}U^{235}$ surrounded by a blanket of $_{92}U^{238}$. Since the fast neutrons are more efficient in converting $_{92}U^{238}$ to $_{94}Pu^{239}$ there is no need to use a moderator in this reactor to slow down the liberated neutrons. Reactions in a fast breeder reactor are shown in Fig. (19.9).

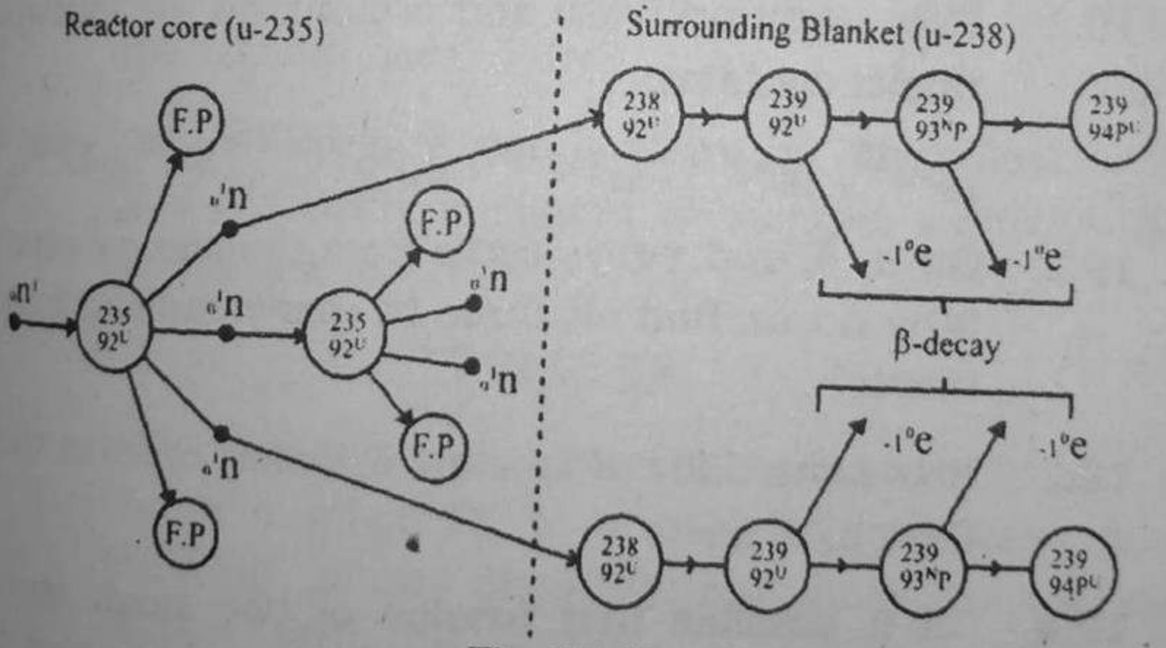


Fig. (19.9)

Nuclear reactors are not only used as useful sources of power generation, but also they are sources of useful neutrons which acts as research tools in physics, biochemistry, biology, medicine and many other related deciplines.A very useful and important utilization of Nuclear topes (Ans: 52.2% and 49.8%).

19.4 The half life of $_{104}Po^{210}$ is 140 days. By what per-cent does its activity will decrease per week? (Ans: 3.46%).

19.5. If a neutron would be entirely converted into energy, how much energy would be produced? Express your answer in Joules as well as electron volts. (Ans: 1.50×10^{-10} J: 942.0 Mev).

19.6. Find the binding energy of $_{52}Te^{126}$. Given:

$m_p = 1.0078\,u, m_n = 1.0086\,u,$

$m_{Te} = 125.9033$ u and 14 = 931.5 MeV

(Ans: 1.066×10^3 MeV

19.7. If the number of atoms per gramme of $_{88}Ra^{226}$ is 2.666×10^{21} and it decays with a half life of 1622 years. Find the decay constant and the activity of the sample.

(Ans: 1.355×10^{-11} S^{-1}: 3.612×10^{10} disintegrations/S).

19.8 What will be the maximum energy of the electron in the beta decay of $_1H^3$ through the reaction.

$_1H^3$ - - - - - - - $_2He^3 + \beta^- + \gamma$

(Ans: - 0.0186 Mev)

19.9 Find the Q-value for the nuclear reaction.

$_{20}Ca^{42}$ (P.d) $_{20}Ca^{41}$

(Ans:- 9.25 MeV)

19.10. Find the energy released when two deuterium ($_1H^2$) nuclei fuse together to form an alpha particle ($_2He^4$).

(Ans:- 23.80 MeV