CHAPTER 13
NUCLEUS

INTRODUCTION

Does the nucleus have a structure, just as the atom does? If so what are the constituents of the nucleus?

An atom is almost empty. If an atom is enlarged to the size of a classroom, the nucleus would be of the size of pinhead. Nevertheless, the nucleus contains most (more than 99.9%) of the mass of an atom.

ATOMIC MASSES

The mass of an atom is very small. Kilogram is not a very convenient unit to measure such small quantities. Therefore, a different mass unit is used for expressing atomic masses. This unit is the atomic mass unit (u).

Atomic Mass Unit (u)

Atomic mass unit (u) is defined as 1/12 th of the mass of the 'carbon -12' atom.

$$1u = \frac{\text{mass of one } ^{12}C \text{ atom}}{12} = \frac{1.992647 \, x \, 10^{-26}}{12}$$

=> $1u = 1.660539 \, x \, 10^{-27} \, kg$

NOTE: Accurate measurement of atomic masses is carried out with a **mass spectrometer.**

COMPOSITION OF NUCLEUS

Nucleus consists of positively charged protons and negatively charged neutrons. Neutron is discovered by James Chadwick .

Atomic number (Z)

It is the number of protons in the nucleus.

Mass number (A)

It is the total number of nucleons (no. of protons + number of neutrons)

Isotopes

Isotopes are the atoms of the same element having different mass numbers.

Eg: C_6^{12} , C_6^{14}

H_1^1 , H_1^2 , H_1^3

Isobars

Isobars are the atoms of different elements having same mass numbers.

Eg: C_6^{14} , N_7^{14}

H_1^3 ,, He_2^3

Isotones

Isotones are the atoms with same number of neutrons

H_1^3 and He_2^4 => No of neutrons= 2

Hg_{80}^{198} and Au_{79}^{197} => No of neutrons= 118

SIZE OF THE NUCLEUS

It has been found that a nucleus of mass number A has a radius

$$R = R_0 A^1/3$$

Where, $R_0 = 1.2 \, x \, 10^{-15} m$

Thus the volume of the nucleus is proportional to the mass number.

$$\frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A$$

Density of Nucleus

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

Let's assume $m_p = m_n$

Therefore

$$\text{density} = \frac{A \, m_p}{\frac{4}{3}\pi R_0^3 A} = 2.3 \, x \, 10^{17} \, kg/m^3$$

Note

1. Density of nucleus is independent of nuclear size
or density of all nuclei is the same.

2. The density of matter in neutron stars is comparable to this density. So neutron star resemble a big nucleus.

EINSTEIN'S MASS ENERGY RELATION

Einstein showed from his theory of special relativity that mass is an another form of energy

His famous mass-energy equivalence relation is $E = mc^2$

Here m – mass-energy

c – Velocity of light in vacuum = 3 x 10 ^{8} m/s

Example 13.2 NCERT

Calculate the energy equivalent of 1 g of substance.

Soln

$$E = mc^2 = 10^{-3} x (3 \, x \, 10^8)^2 = 9 \, x \, 10^{13} J$$

Thus, if one gram of matter is converted to energy, there is a release of enormous amount of energy.

Example 13.3 NCERT

Find the energy equivalent of one atomic mass unit,
first in Joules and then in MeV

Soln

$$1u = 1.6605 \times 10^{-27} kg$$

Therefore ,

$$E = 1.6605 \, x \, 10^{-27} x (3 \, x \, 10^8)^2 = 1.4924 \, x \, 10^{-10} J$$

$$1.4924 \, x \, 10^{-10} J = \frac{1.4924 \, x \, 10^{-10}}{1.6 \, x \, 10^{19}} eV$$

$$= 0.9315 \times 10^9 eV = 931.5 \, \text{MeV}$$

(Or) $1u = 931.5 \, \text{MeV}/c^2$

MASS DEFECT

Mass defect is the difference between total mass of the nucleons and actual mass of the nucleus

$$\Delta m = [Zm_p + (A - Z)m_n] - M$$

Z – atomic number
A – mass number
m_p – mass of proton
m_n – mass of neutron
M – Actual mass of nucleus

NUCLEAR BINDING ENERGY

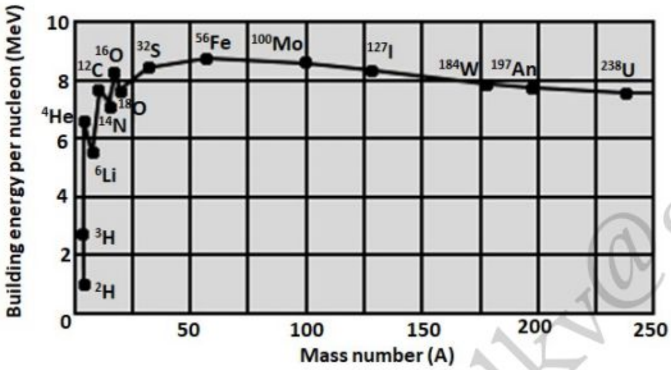
BE is the energy equivalent to mass defect. BE can also be defined as the average energy needed to separate a nucleus into its individual nucleons.

$$E_b = \Delta m c^2 = [[Zm_p + (A - Z)m_n] - M]c^2$$

BINDING ENERGY PER NUCLEON (E_{bn})

$$E_{bn} = \frac{\text{Binding energy}}{\text{mass number}} = \frac{E_b}{A}$$

The greater the binding energy per nucleon the more stable is the nucleus.



BINDING ENEGY PER NUCLEON V/S MASS NUMBER CURVE

Analysis of the graph

i) For nuclei of middle mass number (30<A<170), binding energy per nucleon is a constant (about 8MeV)

The constancy of the binding energy in the range 30 < A < 170 is a consequence of the fact that the nuclear force is short-ranged.

ii) Binding energy per nucleon is lower for both light nuclei (A<30) and heavy nuclei (A>170).

From the binding energy curve, it is obvious that the lighter nuclei have low binding energy per nucleon and hence low stability. Therefore they combine to form heavier nucleus, thereby increasing binding energy per nucleon and stability. This process is called **nuclear fusion.**

The heavier elements like uranium have low binding energy per nucleon and hence low stability. Therefore they split into lighter nuclei, thereby increasing the binding energy per nucleon and stability. This process is called **nuclear fission**.

iii) Binding energy per nucleon is maximum for A=56, about 8.75MeV.

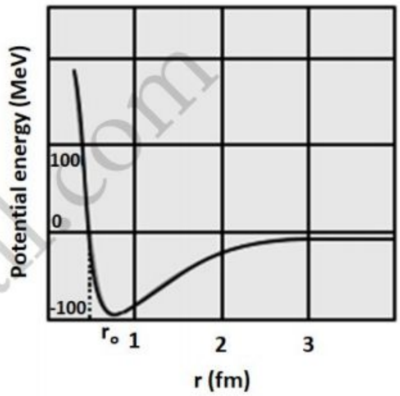
NUCLEAR FORCE

The strong force which binds the nucleons in a nucleus is called the nuclear force.

Characteristics of nuclear force

i) It is the strongest force existing in nature. It is 10^{38} times stronger than gravitational force.
ii) It is a short range force.
iii) Nuclear force is charge independent and mass independent. The force between two protons, two neutrons, a proton and a neutron are of equal strength.

Potential Energy of a pair of nucleons as a function of their separations between them



Analysis of the graph

i) If r > 3fm, PE is very small and force of attraction is negligible.
ii) If r is between r_0 fm and 3 fm, PE is negative and hence nuclear force is attractive.
iii) If r is less than r_0 fm, PE become positive and hence the force becomes repulsive.

RADIOACTIVITY

A. H. Becquerel discovered radioactivity in 1896

Radioactivity is the spontaneous disintegration of unstable nucleus by emitting radiations.

Three types of radioactive decay occur in nature :

(i) **α-decay :** in which a helium nucleus He_2^4 is emitted;
(ii) **β-decay :** in which electrons or positrons (particles with the same mass as electrons, but with a charge exactly opposite to that of electron) are emitted;
(iii) **ɣ -decay :** in which high energy photons are emitted.

NUCLEAR FISSION – ATOM BOMB

In nuclear fission a heavier nucleus when bombarded with neutron splits into two or more lighter nuclei, with the emission of large amount of energy.

Eg: $n_0^1 + U_{92}^{235} \rightarrow U_{92}^{236} \rightarrow Ba_{56}^{144} + Kr_{36}^{89} + 3\,n_0^1$

The same reaction can produce other pairs of intermediate mass fragments

$$n_0^1 + U_{92}^{235} \rightarrow U_{92}^{236} \rightarrow Sb_{51}^{133} + Nb_{41}^{99} + 4\,n_0^1$$

The energy released (the Q – value) in the fission reaction of nuclei like uranium is of the order of 200MeV per fissioning nucleus.

The disintegration energy in fission first appears as the kinetic energy of the fragments and neutrons. Then it is transferred to the surrounding matter appearing as heat.

NUCLEAR FUSION – ENERGY GENERATION IN STARS

When two light nuclei fuse to form a larger nucleus,
energy is released. This is nuclear fusion. Nuclear fusion occurs at very high temperatures (10^9 K) only. So it is called thermonuclear reaction.

Eg: $^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu + 0.42\,MeV$

Nuclear Fusion in The Sun

The fusion reaction in the sun is a multi-step process in which the hydrogen is burned into helium.

$^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu + 0.42\,MeV$ ---------(1)

$e^+ + e^+ \rightarrow \gamma + \gamma + 1.02\,MeV$ -------------(2)

$^2_1H + {}^1_1H \rightarrow {}^3_2He + \gamma + 5.49\,MeV$ --------------(3)

$^3_2He + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + {}^1_1H + 12.86\,MeV$ -(4)

For the forth reaction to occur the 1st three reactions must occur twice.

So we can conclude this cycle as follows
(1) x 2 + (2) x 2 + (3) x 2 + (4) =>

$$4\,{}^1_1H + 2e^- \rightarrow {}^4_2He + 2\,\nu + 6\,\gamma + 26.7\,MeV$$

Thus in p-p cycle, four hydrogen atoms combine to form a ^4_2He atom with a release of 26.7 MeV of energy.

CONTROLLED THERMONUCLEAR FUSION

Nuclear fusion cannot be controlled at present. Experiments are going on to make nuclear fusion controllable and use it to generate steady power. But the main challenge is to confine the fuel in the plasma state, since no container can with stand such a high temperature. If successful, fusion reactors will
hopefully supply almost unlimited power to humanity.