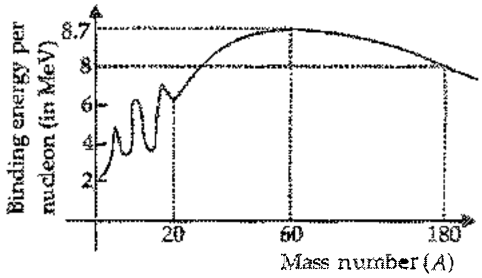
$\Rightarrow$ B.E. $= \Delta m (931)$ MeV

There is another quantity which is very useful in predicting the stability of a nucleus called as binding energy per nucleon.

$$\text{B.E. per nucleon} = \frac{\Delta m(931)}{A} \text{MeV.}$$

- **Plot of B.E. Per Nucleon Vs Mass Number (A)**



  - B.E. per nucleon increases on an average and reaches a maximum of about 8.7 MeV for A ° 50-80.
  - For heavier nuclei, B.E. per nucleon decreases slowly as A increases. For the heaviest natural element ${}_{92}U^{238}$ it drops to about 7.5 MeV.
  - From above observation, it follows that nuclei in the region of atomic masses 50-80 are most stable.

NUCLEAR FORCES

- The protons and neutrons are held together by the strong attractive forces inside the nucleus. These forces are called as nuclear forces.

Properties of the Nuclear Force

- Nuclear force is short ranged. It exists in small region (of diameter 10^{-15} m = 1 fm). The nuclear force between two nucleons decreases rapidly as the separation between them increases and becomes negligible at separation more than 10 fm.
- Nuclear force is much stronger than electromagnetic force and gravitational force.
- Nuclear force is independent of charge. The nuclear force between two protons is same as that between two neutrons or between a neutron and proton. This is known as charge independent character of nuclear force.

Nuclear Reaction

- In nuclear reaction, sum of masses before reaction is greater than the sum of masses after the reaction. The difference in masses appears in the form of energy following the law of inter-conversion of mass and energy. The energy released in a nuclear reaction is called as Q value of a reaction and is given as follows :
- If difference in mass before and after the reaction is Δm u

  Δm = mass of reactants minus mass of products, then Q value $= \Delta m(931)$ MeV
- Law of conservation of momentum is also followed.
- Total number of protons and neutrons should also remain same on both sides of a nuclear reaction.

Nuclear Fission

- The breaking of a heavy nucleus into two or more fragments of comparable masses, with the release of tremendous amount of energy is called as nuclear fission. The most typical fission reaction occurs when slow moving neutrons strike ${}_{92}U^{235}$. The following nuclear reaction takes place.

$${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_0n^1 + 200 \text{ MeV}$$

- If more than one of the neutrons produced in the above fission reaction are capable of inducing a fission reaction (provided U^{235} is available), then the number of fissions taking place at successive stages goes increasing at a very brisk rate and this generates a series of fission reactions. This is known as chain reaction. If mass of U^{235} sample greater than a certain size called the critical size then it is capable of continuous fission by itself.
- If the number of fissions in a given interval of time goes on increasing continuously, then a condition of explosion is created. In such cases, the chain reaction is known as uncontrolled chain reaction. This forms the basis of atomic bomb.
- In a chain reaction, the fast moving neutrons are absorbed by certain substances known as moderators (like heavy water), then the number of fissions can be controlled and the chain reaction in such case is known as controlled chain reaction. This forms the basis of a nuclear reactor.

Nuclear Fusion

- The process in which two or more light nuclei are combined into a single nucleus with the release of tremendous amount of energy is called as nuclear fusion. Like a fission reaction, the sum of masses before the fusion (*i.e.* of light nuclei) is more than the sum of masses after the fusion (*i.e.* of bigger nucleus) and this difference appears as the fusion energy. The most typical fusion reaction is the fusion of two deuterium nuclei into helium.

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + 24 \text{ MeV}$$

- For the fusion reaction to occur, the light nuclei are brought closer to each other (with a distance of 10^{-14} m). This is possible only at very high temperature to counter the repulsive force between nuclei. Due to this reason, the fusion reaction is very difficult to perform. The inner core of sun is at very high temperature, and is suitable for fusion, in fact the source of energy in sun and other stars is the nuclear fusion reaction.

Illustration 10

It is proposed to use the nuclear fusion reaction, ${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4$ in a nuclear reactor, of 200 MW rating. If the energy from above reaction is used with a 25% efficiency in the reactor, how many grams of deuterium will be needed per day?

(The masses of ${}_1H^2$ and ${}_2He^4$ are 2.0141 u and 4.0026 u respectively.)

Solution : Let us first calculate the Q value of nuclear reaction.

$Q = \Delta mc^2 = \Delta m(931)$ MeV

$\Rightarrow \quad Q = (2 \times 2.0141 - 4.0026) \times 931$ MeV

$= 23.834 \text{MeV} = 23.834 \times 10^6$ eV.

Now efficiency of reactor is 25%.

So effective energy used

$$= \frac{25}{100} \times 23.834 \times 10^6 \times 1.6 \times 10^{-19} \text{ J} = 9.534 \times 10^{-13} \text{ J}$$

Now 9.534×10^{-13} J energy is released by fusion of 2 deuterium.

$$\Rightarrow \quad \frac{(9.534 \times 10^{-13})}{2} \text{ J/deuterium is released.}$$

Requirement is 200 MW = 200×10^6 J/s × 86400 for 1 day.

No. of deuterium nuclei required

$$= \frac{200 \times 10^6 \times 86400}{\frac{9.534}{2} \times 10^{-13}} = 3.624 \times 10^{25}$$

$$\text{Number of deuterium nuclei} = \frac{m}{M} \times 6 \times 10^{23}$$

$$3.624 \times 10^{25} = \frac{m}{2} \times 6 \times 10^{23}$$

$$\Rightarrow \quad m = \frac{2 \times 3.624 \times 10^{25}}{6 \times 10^{23}} = 120.83 \text{ g/day.}$$