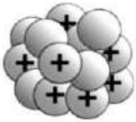
13. Nuclei



Atomic Masses -

The unit in which atomic and nuclear masses are measured is called atomic mass unit (a.m.u.)

One 'a.m.u.' is defined as $\frac{1}{12}$th of the mass of an atom of $_6C^{12}$. It is denoted by 'u'.

As Avogadro's number $= 6.023 \times 10^{23}$

$\therefore$ Mass of one atom of $C^{12} = \frac{12}{6.023 \times 10^{23}}$ g

By definition $1 \text{ a.m.u.} = \frac{1}{12} \times$ mass of one atom of C^{12}

$$\therefore \quad 1 \text{ amu} = \frac{1}{12} \times \frac{12}{6.023 \times 10^{23}} = 1.66 \times 10^{-24} g.$$

$$\boxed{1 \text{ a.m.u.} = 1.66 \times 10^{-27} \text{ Kg.}}$$

In terms of a.m.u.,

mass of an electron $m_e = 0.00055$ u.
mass of a Proton $m_p = 1.0073$ u.
mass of a neutron $m_n = 1.0086$ u.

Electron Volt (ev) -

It is the small unit of energy. One electron volt is the energy gained by an electron, when accelerated through a potential difference of one volt.

Energy = Work done = Charge $\times$ Potential

$1 \text{ ev} = 1.602 \times 10^{-19} \times 1$

or $1 \text{ ev} = 1.602 \times 10^{-19}$ J

According to the Einstein Mass-energy equivalence -

$$E = mc^2$$

taking $m = 1 \text{ a.m.u} = 1.66 \times 10^{-27}$ Kg and $c = 3 \times 10^8$ m/s

$$E = (1.66\times10^{-27})(3\times10^{8})^2 = 1.49\times10^{-10} J$$

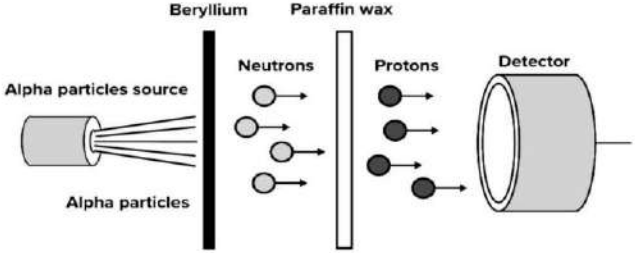
Hence $E = \dfrac{1.49\times10^{-10}}{1.6\times10^{-19}} = 931.15\times10^{6}\ eV$

$\therefore$ $\boxed{1\ a.m.u. = 931.15\ MeV}$

Discovery of Neutron -

A neutron is a neutral particle carrying no charge and having mass equal roughly to the mass of a proton.

The neutron was discovered experimentally by chadwik.

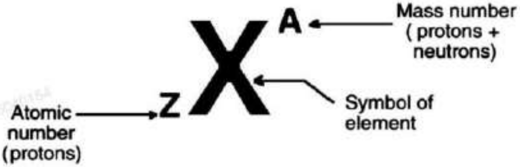


Chadwik observed that when beryllium was bombered with alpha particles, some neutral particles were emitted, whose mass is roughly equal to the mass of a proton. A Free neutron is unstable and has a mean life time of 1000 s. Neutron is stable inside the nucleus.

Atomic Number (Z) -

It is the number of protons present inside the nucleus of an atom of the element. It is represented by Z.

$$Z = \text{Number of Protons} = \text{Number of electrons}$$



Mass Number (A) -

It is the total number of protons and neutrons Present inside the atomic nucleus of the element. It is represented by A.

$$A = \text{Number of nucleons (neutron + Proton)}$$

$$A - Z = \text{number of neutrons}$$

A nuclide is represented as ${}_ZX^A$, where x is the chemical Symbol of the element.

Examples - ${}_6C^{12}$, ${}_{79}Au^{197}$, ${}_{92}U^{235}$ etc.

Nuclear Size -

Experimental measurement shows that the volume of a nucleus is proportional to its mass number A.

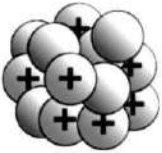
If R is the radius of the nucleus, then its volume $\propto$ A

$$\frac{4}{3}\pi R^3 \propto A$$

or $$R \propto A^{1/3}$$

or $$\boxed{R = R_0 A^{1/3}}$$

$$R_0 = 1.2 \times 10^{-15} m$$



* As A is different for different elements, therefore atomic nuclei of different elements have different sizes.

Nuclear Density -

Density of a nucleus is the ratio of mass of nucleus to its volume.

If m is average mass of a nucleon and R is the nuclear radius, then mass of nucleus $= mA$

where A is the mass number of the element.

$$\text{Volume of Nucleus} = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi (R_0^3 A)$$

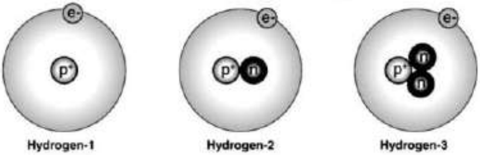
$$\text{Density of Nucleus} = \frac{mA}{\frac{4}{3}\pi R_0^3 A} = \frac{3m}{4\pi R_0^3}$$

or $$\rho = \frac{3 \times 1.66 \times 10^{-27}}{4 \times 3.14 \times (1.2 \times 10^{-15})^3} = 2.29 \times 10^{17} kg/m^3$$

* Hence density of nucleus is same for all the elements, which is very large as compared to density of ordinary matter.

Isotopes -

Isotopes of an element are that atoms which have the same atomic number but different atomic weights.



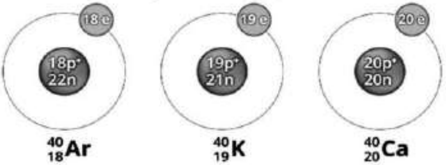
Example - $_1H^1$, $_1H^2$, $_1H^3$ are isotopes of hydrogen,

$_6C^{10}$, $_6C^{11}$, $_6C^{12}$, $_6C^{13}$, $_6C^{14}$ are the isotopes of carbon.

As isotopes of an element have the same atomic number, hence these have identical chemical properties, but due to different atomic weight their physical properties are different.

Isobars -

Isobars are the atoms of different elements which have the same atomic weight but different atomic number.

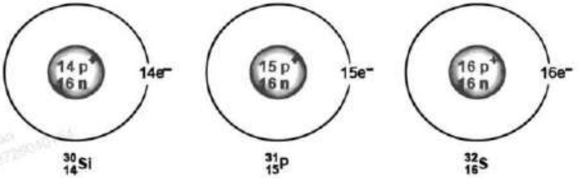


Example: $_{11}Na^{22}$ and $_{10}Ne^{22}$ are isobars, $_{20}Ca^{40}$ and $_{18}Ar^{40}$ are isobars etc.

The chemical properties of isobars are different due to different atomic number but their physical properties may be identical due to same atomic weight.

Isotones -

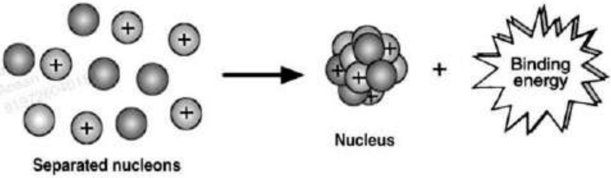
Isotones are the atoms of different elements which contain the same number of neutrons, hence in their case, $(A-Z) = N$ is the same.



Examples - $_{17}Cl^{37}$ and $_{19}K^{39}$ are isotones, similarly $_{1}H^{3}$ and $_{2}He^{4}$ are isotones.

Nuclear Binding Energy -

Binding energy of a nucleus is the energy with which nucleons are bound in the nucleus. It is measured by the work required to separaate the nucleons at infinite distance apart from the nucleus, so that they may not interact each other.



Mass Defect -

The difference between the sum of the masses of neutrons and protons forming a nucleus and mass of the nucleus is called mass defect.

This mass defect appears in the form of binding energy, which is responsible for binding the nucleon together in the nucleus.

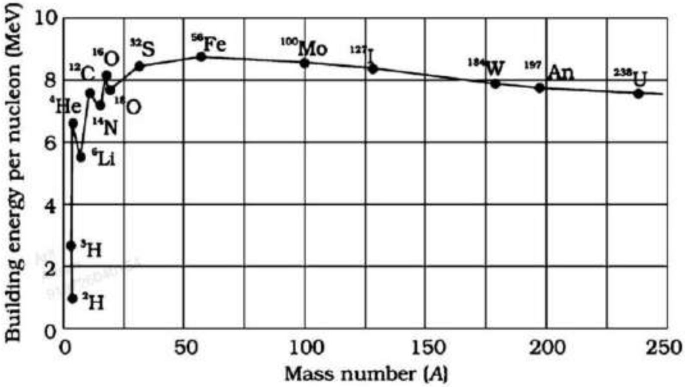
Nuclear Binding energy = Mass defect × (Velocity of Light)^2

$$\boxed{B.E. = [Z m_p + (A-Z) m_n - m_N] \times c^2}$$

B.E. (in Mev) = [Mass defect in a.m.u.] × 931

Average Binding Energy per nucleon of a Nucleus

It is the average energy we have to spend to remove a nucleon from the nucleus to infinite distance. It is given by the total binding energy devided by the mass number of the nucleus.



The graph between binding energy per nucleon and mass number (A) shows the following facts:

(i) Average binding energy of light nuclie like $_1H^1$, $_1H^2$, $_1H^3$ is small.

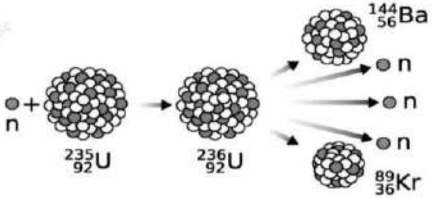
(ii) There are sharply defined peaks corresponding to $_2He^4$, $_6C^{12}$, $_8O^{16}$ which represents that these nuclie are relatively more stable than the other nuclie in their neighbourhood.

(iii) The B.E. curve has a maximum value in the range A = 30 to A = 140 corresponding to average binding energy per nucleon = 8.5 Mev. The peak value of the maximum is 8.8 Mev/N for $_{26}Fe^{56}$. Hence iron is the most stable element on the earth.

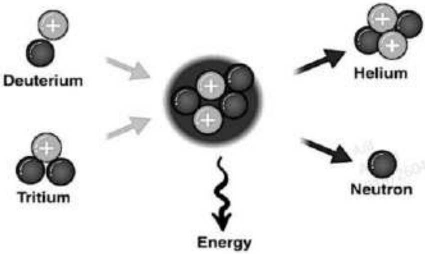
(iv) As the mass number increases the B.E./nucleon decreases and gradually falling to about 7.6 Mev per nucleon for $_{92}U^{238}$. Hence heavy nuclei are relatively less stable.

Importance of Binding energy Curve -

(i) When we move from the heavy nuclei region to the middle region of the graph, there will be an increment in the overall binding energy and hence release of energy. This indicates that energy can be released when a heavy nucleus ($A \approx 240$) breaks into two roughly equal parts. This process is called nuclear fission.



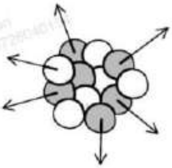
(ii) When we move from lighter nuclei to heavier nuclei we find that there is an increment in the overall binding energy and hence release of energy. This indicates that energy can be released when two or more lighter nuclei fuse (mix) together to form a heavy nucleus. This process is called nuclear fusion.



Nuclear Forces-

Nuclear forces are the strong forces of attraction which hold together the nucleons (neutrons and protons) in the tiny nucleus of an atom, inspite of strong electrostatic force of repulsion between protons.

REPULSION FORCE BETWEEN THE PROTONS



THE STRONG NUCLEAR FORCE HOLDS ALL PROTONS AND NEUTRONS TOGETHER

Important characteristics of Nuclear forces-

(i) Nuclear forces act between a pair of neutrons, a pair of protons and also between a neutron, proton pair with the same strength. This shows that nuclear forces are independent of charge.

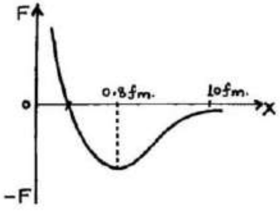
(ii) Nuclear forces are the strongest forces in nature. The nuclear forces is 100 times and 10^{38} time stronger than the electrostatic and gravitational forces respectively.

(iii) The nuclear forces are very short range forces. They are operative upto distance of a few fermi.

(iv) Nuclear forces are non central forces. This shows that the distribution of nuclons in a nucleus is not spherically symmetric.

(V) The variation of nuclear forces with the distance between nucleons is shown in figure:

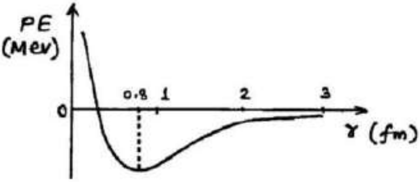
(a) Nuclear forces are negligible, when distance between nucleons is more than 10 fermi.



(b) When nucleons are brought closer, nuclear force of attraction develops, which increase rapidly with decreasing distance. At distance 0.8 fermi forces becomes strongly attractive.

(c) When distance between nucleons becomes less than 0.8 fm, the nuclear forces becomes strongly repulsive.

(vi) The variation of potential energy of a pair of nucleons as a function of their separation. It shows that nuclear force is of attractive nature for separation between the nuclei greater than 1 fm and repulsive when separation is less than 1 fm.



* P.E. is positive for repulsive forces and is negative for attractive forces.

Nuclear Stability -

Nuclear stability depends on following factors :

(i) The stability of a nucleus is determined by the value of its binding energy per nucleon. Higher the B.E./nucleon more stable is the nucleus.

(ii) The stability of a nucleus is also determined by its neutron to proton ratio. More is the number of protons in the nucleus, greater is the electrical repulsive force between them. Therefore more neutrons are needed to provide the strong attractive forces necessary to Keep the nucleus stable.

(iii) The stability of a nucleus is also determined by the consideration, that it contains an even or odd number of protons and neutrons. A detailed study shows that stable nuclei often contains even number of protons or neutrons or both.

Nuclear Reaction -

A nuclear reaction represents the transformation of one stable nucleus into another nucleus by bombaring with suitable high energy particles.

Nuclear reaction can be represented as -

$$_{Z}X^{A} + {}_{2}He^{4} \longrightarrow {}_{Z+2}C^{A+4} \longrightarrow {}_{Z+1}Y^{A+3} + {}_{1}H^{1} + Q$$

The reaction is named (α, P) reaction after the name of the bombared particle (α) and product particle (P). In the nuclear reaction Q is the total energy change in the reaction.

Examples :-

(i) $_{3}Li^{7} + {}_{1}H^{1} \longrightarrow {}_{4}Be^{8*} \longrightarrow {}_{2}He^{4} + {}_{2}He^{4}$ (P, α reaction)

(ii) $_{5}B^{11} + {}_{1}H^{1} \longrightarrow {}_{6}C^{12*} \longrightarrow {}_{6}C^{12} + {}_{0}n^{1}$ (P, n reaction)

(iii) $_{6}C^{12} + {}_{1}H^{1} \longrightarrow {}_{7}N^{13*} \longrightarrow {}_{7}N^{13} + \gamma$ (P, γ reaction)

(iv) $_{1}H^{2} + \gamma \longrightarrow {}_{1}H^{1} + {}_{0}n^{1}$ (Photo disintegration)

Note :-

The Q value of nuclear reaction is calculated from Einstein's mass energy equivalence relation $E = (\Delta m)c^2$. It may be positive or negative.

* A nuclear reaction in which Q value is positive, energy is released. Such a reaction is called exoergic.
* A nuclear reaction in which Q value is negative, energy has to be supplied before the reaction occurs. Such a reaction is called endoergic.

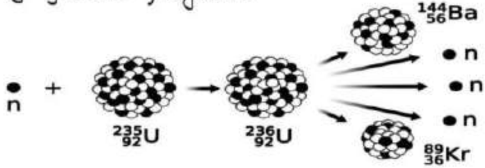
Nuclear Fission -

Nuclear fission is the phenomenon of splitting of a heavy nucleus ($A > 230$) into two or more lighter nuclei.

In this process, certain mass disappears i.e. sum of the masses of final product is found to be slightly less than the sum of the masses of the reactant components. This difference in masses is called mass defect (Δm).

Energy released in nuclear fission $(E) = \Delta m \times c^2$

This energy appears in the form of γ-rays and Kinetic energy of fission fragment.



Example - $\quad {}_{92}U^{235} + {}_0n^1 \longrightarrow {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3\,{}_0n^1 + Q$

* The disintegration energy (Q) in fission, first appears as the Kinetic energy of fragments. After that it is transferred to the surrounding matter in the form of heat.

Nuclear Chain Reaction -

Nuclear chain reaction refers to a process in which neutron released in fission produces an additional fission in at least one furthe nucleus. This nucleus in turn produces neutrons and the process repeats.

The process may be controlled (nuclear power) or uncontrolled (nuclear bomb).

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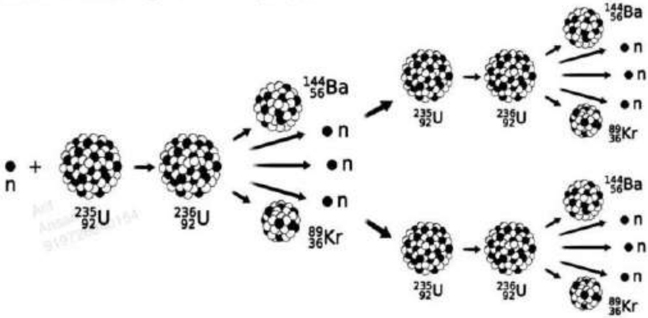


The following points should be considered for a self propagating nuclear chain reaction :

(1) Leakage of neutrons from the system.

(2) Absorption of neutrons by impurity.

(3) Absorption of neutrons by Uranium-238.

(4) Critical size of the fissionable sample.

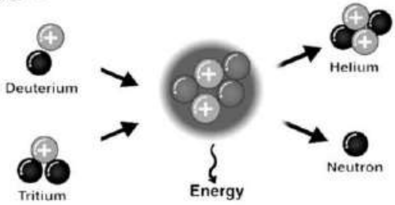
(5) Reproduction factor (K) = $\dfrac{\text{rate of Production of neutrons}}{\text{rate of Loss of neutrons}}$

* If K = 1, the chain reaction will be steady and Continuous.
* If K > 1, the chain reaction accelerates resulting in explosion.
* If K < 1, the chain reaction gradually stops.

Nuclear Fusion -

Nuclear Fusion is the phenomenon of fusing two or more lighter nuclei to form a single heavy nucleus.

The mass of the product nucleus is slightly less than the sum of the masses of the lighter nuclei fusing together. This difference in masses (Δm) results in the release of tremendous amount of energy, in accordance with Einstein's mass energy relation $E = (\Delta m) c^2$.



Examples :- $_1H^1 + {_1H^1} \longrightarrow {_1H^2} + {_{+1}e^0} + \nu + 0.42\,\text{Mev}$

$$_1H^2 + {_1H^2} \longrightarrow {_2He^3} + {_0n^1} + 3.27\,\text{Mev}$$

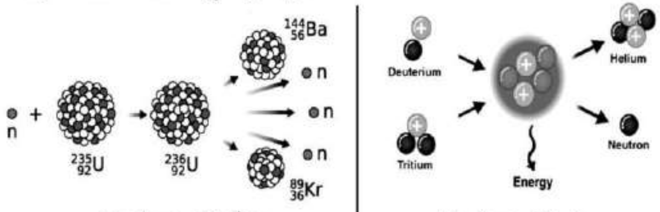
In nuclear reactions, the coulomb repulsion between the nucleus prohibits them to come close enough to be within the range of their attractive nuclear forces and fuse. The height of Coulomb barrier depends on the charges and the radius of the interacting nuclei.

The essential condition for carrying out nuclear fusion is to raise the temperature of the material so that particles have enough energy due to their thermal motions alone and they can penetrate the Coulomb barrier. This process is called Thermonuclear fusion.

Difference between Nuclear Fission & Nuclear Fusion

(1) In fission a heavy nucleus splits into two or more lighter nuclei. In fusion, two or more lighter nuclei fuse together to form a heavier nucleus.

(2) For nuclear fission a fast moving neutron is needed. For carrying out nuclear fusion the lighter nuclei have to be brought very close to eachother against Coulomb repulsion. For this suitable energy is to be made available, often by raising the temperature of the order of 10^7 K.



Nuclear Fission　　　　Nuclear Fusion

(3) In a nuclear fusion reaction, energy liberated per unit mass of their nuclei is many times larger than the energy liberated per unit mass in nuclear fission reaction. Therefore for a given weight, hydrogen bomb (based on nuclear fusion) is far more dangerous than an atom bomb (based on nuclear fission).

(4) The product of nuclear fission are radioactive. They produce environmental pollution and hence require very careful disposal. However the products of nuclear fusion are not radioactive. They are harmless and can disposed off easily.