Nucleus.

(1) Different types of nuclei

The nuclei have been classified on the basis of the number of protons (atomic number) or the total number of nucleons (mass number) as follows

(i) Isotopes : The atoms of element having same atomic number but different mass number are called isotopes. All isotopes have the same chemical properties. The isotopes of some elements are the following

$$_1H^1,\ _1H^2,\ _1H^3\ \ _8O^{16},\ _8O^{17},\ _8O^{18}\ \ _2He^3,\ _2He^4\ \ _{17}Cl^{35},\ _{17}Cl^{37}\ \ _{92}U^{235},\ _{92}U^{238}$$

(ii) Isobars : The nuclei which have the same mass number (A) but different atomic number (Z) are called isobars. Isobars occupy different positions in periodic table so all isobars have different chemical properties. Some of the examples of isobars are

$$_1H^3 \text{ and } _2He^3,\quad _6C^{14} \text{ and } _7N^{14},\ _8O^{17} \text{ and } _9F^{17}$$

(iii) Isotones : The nuclei having equal number of neutrons are called isotones. For them both the atomic number (Z) and mass number (A) are different, but the value of (A – Z) is same. Some examples are

$$_4Be^9 \text{ and } _5B^{10},\ _6C^{13} \text{ and } _7N^{14},\ _8O^{18} \text{ and } _9F^{19},\ _3Li^7 \text{ and } _4Be^8,\ _1H^3 \text{ and } _2He^4$$

(iv) Mirror nuclei: Nuclei having the same mass number A but with the proton number (Z) and neutron number (A – Z) interchanged (or whose atomic number differ by 1) are called mirror nuclei for example.

$$_1H^3 \text{ and } _2He^3,\ _3Li^7 \text{ and } _4Be^7$$

(2) Size of nucleus

(i) Nuclear radius: Experimental results indicates that the nuclear radius is proportional to A1/3, where A is the mass number of nucleus i.e. $R \propto A^{1/3} \Rightarrow R = R_0 A^{1/3}$, where R0 = 1.2 × 10–15 m = 1.2 fm.

Note: Heavier nuclei are bigger in size than lighter nuclei.

(ii) Nuclear volume: The volume of nucleus is given by $V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A \Rightarrow V \propto A$

(iii) Nuclear density: Mass per unit volume of a nucleus is called nuclear density.

$$\text{Nuclear density}\,(\rho) = \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}} = \frac{mA}{\frac{4}{3}\pi (R_0 A^{1/3})^3}$$

Where m = Average of mass of a nucleon (= mass of proton + mass of neutron = 1.66 × 10–27 kg)

and mA = Mass of nucleus

$$\Rightarrow \rho = \frac{3m}{4\pi R_0^3} = 2.38 \times 10^{17}\, kg/m^3$$

Note: ρ is independent of A, it means ρ is same of all atoms.

Density of a nucleus is maximum at itscenter and decreases as we move outwards from the nucleus.

(3) Nuclear force

Forces that keep the nucleons bound in the nucleus are called nuclear forces.

(i) Nuclear forces are short range forces. These do not exist at large distances greater than 10–15 m.

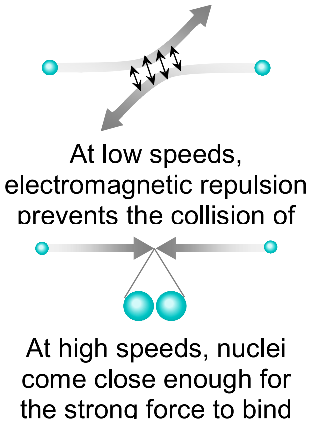
(ii) Nuclear forces are the strongest forces in nature.

(iii) These are attractive force and causes stability of the nucleus.

(iv) These forces are charge independent.

(v) Nuclear forces are non-central force.

Nuclear forces are exchange forces



According to scientist Yukawa the nuclear force between the two nucleons is the result of the exchange of particles called mesons between the nucleons.

π - mesons are of three types – Positive π meson (π+), negative π meson (π –), neutral π meson (π0)

The force between neutron and proton is due to exchange of charged meson between them i.e.

$$p \rightarrow \pi^{+} + n, \quad n \rightarrow p + \pi^{-}$$

The forces between a pair of neutrons or a pair of protons are the result of the exchange of neutral meson (πo) between them i.e. $p \rightarrow p' + \pi^{0}$ and $n \rightarrow n' + \pi^{0}$

Thus exchange of π meson between nucleons keeps the nucleons bound together. It is responsible for the nuclear forces.

Dog-Bone analogy

The above interactions can be explained with the dog bone analogy according to which we consider the two interacting nucleons to be two dogs having a common bone clenched in between their teeth very firmly. Each one of these dogs wants to take the bone and hence they cannot be separated easily. They seem to be bound to each other with a strong attractive force (which is the bone) though the dogs themselves are strong enemies. The meson plays the same role of the common bone in between two nucleons.

(4) Atomic mass unit (amu)

The unit in which atomic and nuclear masses are measured is called atomic mass unit (amu)

1 amu (or 1u) = $\frac{1}{12}th$ of mass of ${}_{6}C^{12}$ atom = 1.66 × 10–27 kg

Masses of electron, proton and neutrons

Mass of electron (me) = 9.1 × 10–31 kg = 0.0005486 amu, Mass of proton (mp) = 1.6726 × 10–27 kg = 1.007276 amu

Mass of neutron (mn) = 1.6750 × 10–27 kg = 1.00865 amu, Mass of hydrogen atom (me + mp) = 1.6729 × 10–27 kg = 1.0078 amu

Mass-energy equivalence

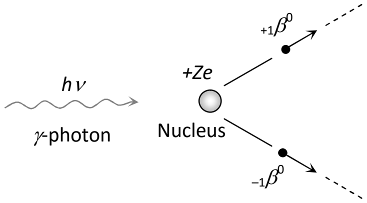
According to Einstein, mass and energy are inter convertible. The Einstein's mass energy relationship is given by $E = mc^{2}$

If m = 1 amu, c = 3 × 108 m/sec then E = 931 MeV i.e. 1 amu is equivalent to 931 MeV or 1 amu (or 1 u) = 931 MeV

(5) Pair production and pair-annihilation

When an energetic γ-ray photon falls on a heavy substance. It is absorbed by some nucleus of the substance and an electron and a positron are produced. This phenomenon is called pair production and may be represented by the following equation

$$\underset{(\gamma-\text{photon})}{h\nu} = \underset{(\text{Positron})}{{}_{1}\beta^{0}} + \underset{(\text{Electron})}{{}_{-1}\beta^{0}}$$



The rest-mass energy of each of positron and electron is

E0 = m0c2 = (9.1 × 10–31 kg) × (3.0 × 108 m/s) 2

= 8.2 × 10–14 J = 0.51 MeV

Hence, for pair-production it is essential that the energy of γ-photon must be at least 2 × 0.51 = 1.02 MeV. If the energy of γ-photon is less than this, it would cause photo-electric effect or Compton Effect on striking the matter.

The converse phenomenon pair-annihilation is also possible. Whenever an electron and a positron come very close to each other, they annihilate each other by combining together and two γ-photons (energy) are produced. This phenomenon is called pair annihilation and is represented by the following equation.

$$\underset{(\text{Positron})}{{}_{+1}\beta^{0}} + \underset{(\text{Electron})}{{}_{-1}\beta^{0}} = \underset{(\gamma\text{-photon})}{h\nu} + \underset{(\gamma\text{-photon})}{h\nu}$$

(6) Nuclear stability

Among about 1500 known nuclides, less than 260 are stable. The others are unstable that decay to form other nuclides by emittingα, β-particles and γ - EM waves. (This process is called radioactivity). The stability of nucleus is determined by many factors. Few such factors are given below:

(i) Neutron-proton ratio $\left(\frac{N}{Z}\text{Ratio}\right)$

The chemical properties of an atom are governed entirely by the number of protons (Z) in the nucleus, the stability of an atom appears to depend on both the number of protons and the number of neutrons.

For lighter nuclei, the greatest stability is achieved when the number of protons and neutrons are approximately equal (N ≈ Z) i.e. $\frac{N}{Z} = 1$

Heavy nuclei are stable only when they have more neutrons than protons. Thus heavy nuclei are neutron rich compared to lighter nuclei (for heavy nuclei, more is the number of protons in the nucleus, greater is the electrical repulsive force between them. Therefore more neutrons are added to provide the strong attractive forces necessary to keep the nucleus stable.)

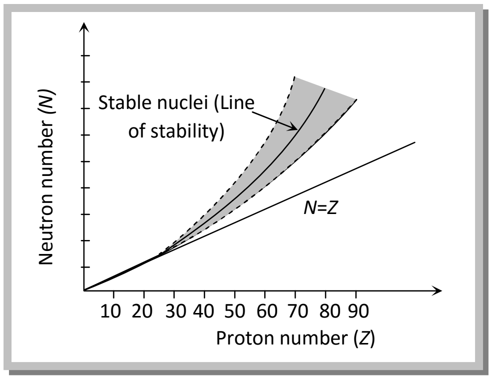
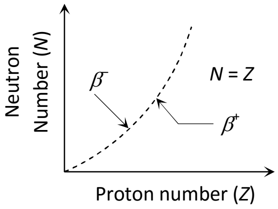


Figure shows a plot of N verses Z for the stable nuclei. For mass number up to about A = 40. For larger value of Z the nuclear force is unable to hold the nucleus together against the electrical repulsion of the protons unless the number of neutrons exceeds the number of protons. At Bi (Z = 83, A = 209), the neutron excess in N – Z = 43. There are no stable nuclides with Z > 83.

Note: The nuclide $_{83}Bi^{209}$ is the heaviest stable nucleus.

A nuclide above the line of stability i.e. having excess neutrons, decay through β^- emission (neutron changes into proton). Thus increasing atomic number Z and decreasing neutron number N. In β^- emission, $\frac{N}{Z}$ ratio decreases.



A nuclide below the line of stability have excess number of protons. It decays by β^+ emission, results in decreasing Z and increasing N. In β^+ emission, the $\frac{N}{Z}$ ratio increases.

(ii) Even or odd numbers of Z or N: The stability of a nuclide is also determined by the consideration whether it contains an even or odd number of protons and neutrons.

It is found that an even-even nucleus (even Z and even N) is more stable (60% of stable nuclide have even Z and even N).

An even-odd nucleus (even Z and odd N) or odd-even nuclide (odd Z and even N) is found to be lesser sable while the odd-odd nucleus is found to be less stable.

Only five stable odd-odd nuclides are known: ${}_1H^2,\ {}_3Li^6,\ {}_5Be^{10},\ {}_7N^{14}$ and ${}_{75}Ta^{180}$

(iii) Binding energy per nucleon: The stability of a nucleus is determined by value of its binding energy per nucleon. In general higher the value of binding energy per nucleon, more stable the nucleus is