Nucleus.

Nucleus is found to be a source of tremendous amount of energy, which has been utilized for the destructive as well as constructive purposes. Hence the study of nucleus of an atom has become so important that it is given a separate branch of chemistry under the heading of nuclear chemistry. According to an earlier hypothesis, the nucleus is considered as being composed of two building blocks, **proton's** and **neutron's**,which are collectively called **nucleons**.

(1) **Nuclear forces:** Since the radius of nucleus is very small ≈ 10^{-15} m, two protons lying in the nucleus are found to repel each other with an electrostatic force of about 6 tonnes. The forces, which hold the nucleons together means stronger proton – proton, neutron – neutron and even proton – neutron attractive forces, exist in the nucleus. These attractive forces are called nuclear forces. Unlike electrostatic forces which operate over long ranges, but the nuclear forces operate only within small distance of about $1\times10^{-15}\,m$ or 1 fermi (1 fermi = $10^{-13}\,cm$) and drops rapidly to zero at a distance of $1\times10^{-13}\,cm$. Hence these are referred to as short range forces. Nuclear forces are nearly 10^{21} times stronger than electrostatic forces.

(2) **Nuclear stability:** Nucleus of an atom contains all the protons and neutrons in it while all electrons are in the outer sphere. Nuclides can be grouped on the basis of nuclear stability, i.e. stable and unstable nucleus. The most acceptable theory about the atomic nuclear stability is based upon the fact that the observed atomic mass of all known isotopes (except hydrogen) is always less from the sum of the weights of protons and neutrons **(nucleons)** present in it. Other less important (or unusual) fundamental particles of the nucleus are electron, antiproton, positron, neutrino, photon, graviton, meson and γ - particles are

considered as created by stresses in which energy is converted into mass or vice versa, e.g. an electron (β- particle) from a radioactive nucleus may be regarded as derived from a neutron in the following way.

$$\boxed{\textbf{Neutron} \longrightarrow \textbf{Proton + Electron}}$$

Similarly, photons are produced from internal stresses within the nucleus.

A list of elementary particles is given below:

		Name of particle	Symbol	**Anti – particle symbol**	**Mass**	**Spin**	**Charge**
LEPTONS		Photon Electron Neutrino Muon Muon –neutrino Tauon	hν e^- Ve μ^- V_μ τ^-	– e^+ $\overline{Ve}$ μ^+ $\overline{V}_\mu$ τ^+	0 1 0 207 0 3500	1 1/2 1/2 1/2 1/2 1/2	0 –1 0 –1 0 –1
HARDONS	MEONS	Pions	π^0		264	0	0
			π^+	π^-	273	0	+1
		Kaons	k^+	k^-	966	0	+1
			k^0	$\overline{k}^0$	974	0	0
		Etameson	n^0	–	1074	0	0
	BARYONS	Proton	**p**	p^-	1836.6	1/2	+1
		Neutron	n	n^-	1836.6	1/2	0
		Lambda hyperon	λ^0	$\overline{\lambda}^0$	2183		
		Sigma hyperons	Σ^+ Σ^0 Σ^-	$\overline{\Sigma}^+$ $\overline{\Sigma}^0$ $\overline{\Sigma}^{-1}$	2328 2334 2343	1/2 1/2 1/2 1/2	0 +1 0 –1
		Xi hyperons Omega hyperons	1.1, 1.1 Ω^-	– $\overline{\Omega}^-$	2573 3273	1/2 3/2	0 –1

Some common important elementary particles are listed below:

Name	**Symbol**	**Mass**	**Charge**	**Discoverer**
Electron	e^-	$9.1 \times 10^{-31} kg$	$-1.602 \times 10^{-19} C$	J.J. Thomson (1896)
Proton	**p**	$1.673 \times 10^{-27} kg$	$+1.602 \times 10^{-19} C$	E. Goldstein (1886)

Neutron	n	$1.675\times10^{-27}kg$	Zero	J. Chadwick (1932)
Neutrino	V	$3.64\times10^{-32}kg$	Zero	Pauli
Mesons	μ	275 – 300 times mass of electron	$+ve, 0$ or $-ve$	Yukawa (1935)
Positron	e^{+}	$9.1\times10^{-31}kg$	$+ve$	Anderson (1932)

The stability of nucleus may be discussed in terms of any one of the following.

(i) **Nuclear Binding Energy and Mass defect:**The mass of hydrogen atom is equal to the sum of the masses of a proton and an electron. For other atoms, the atomic mass is less than the sum of the masses of protons, neutrons and electrons present. This difference in mass termed as, mass defect, is a measure of the binding energy of protons and neutrons in the nucleus. The mass energy relationship postulated by Einstein is expressed as:

$\boxed{\Delta E = \Delta mc^2}$, Where ΔE is the energy liberated, Δm the loss of mass and c is the speed of light.

Consider the helium nucleus, which contains 2 protons and 2 neutrons; the mass of helium nucleus on $^{12}C = 12m_u$, scale is $4.0017\ m_u$. The masses of individual isolated proton and neutron are 1.0073 and 1.0087 m_u respectively. The total mass of 2 protons and 2 neutrons is $(2\times1.0073)+(2\times1.0087) = 4.0320\ m_u$. The loss in mass or mass defect for helium nucleus is, $4.0320\ m_u - 4.0017\ m_u = 0.0303\ m_u$

$$\because 1m_u = 1.66057\times10^{-27}kg \text{ and } c = 2.998\times10^{8}ms^{-1}$$

$$\Delta E = 0.0303\times1.66057\times10^{-27}\times6.02\times10^{23}\times(2.998\times10^{8})^2\ kg\,m^2s^{-2}mol^{-1}$$

$$= 2.727\times10^{12}\ J\ mol^{-1}$$

Thus, the molar nuclear binding energy of helium nucleus, $_2He^4$, is $2.73\times10^{12}\ J\ mol^{-1}$. Binding energy of a nucleus is generally quoted as energy in million electron volts (MeV) per nucleon. One million electron volts are equivalent to $9.6\times10^{10}\ J\ mol^{-1}$. Thus, the formation of helium nucleus results in the release of $2.7\times10^{12}/9.6\times10^{10}$ MeV = 28 MeV (approximately). In comparing the binding energies of different nuclei, it is more useful to consider the binding energy per nucleon. For example, helium nucleus contains 4 nucleons (2 protons and 2 neutrons), the binding energy per nucleon in this case is 28/4 = 7 MeV.

Binding energies of the nuclei of other atoms can be calculated in a similar manner. When we plotted binding energies of the nuclei of atoms against their respective mass number. Three features may be noted. First, nuclei with mass number around 60 have the highest binding energy per nucleon. Second, species of mass numbers 4, 12, and 16 have high binding energy per nucleon implying that the nuclei ^4He, ^{12}C and ^{16}O, are particularly stable. Third the binding energy per nucleon decreases appreciably above mass number 100. The form of relationship between binding energy per nucleon and mass number indicates that heavy nuclei would release mass (and therefore energy) on division (or fission) into two nuclei of medium mass and that the light nuclei would release mass (and therefore energy) on fusion to form heavier nuclei. These processes called fission and fusion are described later in this Unit.

- The **average binding energy** for most of the nuclei is in the vicinity of 8 MeV. Nuclei having binding energy per nucleon very near to 8 MeV are more or less stable.
- Iron has the maximum average binding energy (8.79 MeV) and thus its nucleus is thermodynamically most stable.
- The isotopes with intermediate mass numbers 40 to 100 are most stable. The elements with Low Mass numbers or High Mass numbers tend to become stable by acquiring intermediate mass number. Evidently, nuclei of lighter elements combine together to form a heavier nucleus of intermediate mass number **(nuclear fusion)**; while the nuclei of heavy elements split into two lighter nuclei of intermediate mass numbers **(nuclear fission).** In either case, energy is released and hence the stability is enhanced.

Note: Relation between different units of energy $1cal = 4.2J$; 1 J = 10^7 ergs; 1eV = $1.622 \times 10^{-19} J$

(ii) **Relative stability of isotopes and binding energy:** Value of binding energy predicts the relative stability of the different isotopes of an element. If the value of binding energy is negative, the product nucleus or nuclei will be less stable than the reactant nucleus. Thus the relative stability of the different isotopes of an element can be predicted by the values of binding energy for each successive addition of one neutron to the nucleus.

$${}_2He^3 + {}_0n^1 \longrightarrow {}_2He^4 + 20.5MeV\,; \quad {}_2He^4 + {}_0n^1 \longrightarrow {}_2He^5 - 0.8MeV$$

Therefore, ${}_2He^4$ is more stable than ${}_2He^3$ and ${}_2He^5$.

(iii) **Packing fraction:** The difference of actual isotopic mass and the mass number in terms of packing fraction is defined as:

$$\boxed{\text{Packing fraction} = \frac{\text{Actual isotopic mass} - \text{Mass number}}{\text{Mass number}} \times 10^4}$$

The value of packing fraction depends upon the manner of packing of the nucleons with in the nucleus. Its value can be negative, positive or even zero.

Note: Actual isotopic mass is not a whole number whereas, mass number is a whole number.

(a) **Zero packing fraction:** $Carbon^{12}$ has zero packing fraction because it is taken as a reference on the atomic scale and its actual isotopic mass (12) is equal to itsmass number (12).

(b) **Negative packing fraction:**Negative value of the packing fraction means that the actual isotopic mass is less to the mass number. This term indicates that some mass has been transformed into energy (binding energy) during formation of nucleus. Such nuclei are, therefore more stable.

(c) **Positive packing fraction:**Positive packing fraction should imply the opposite, i.e., the nuclei of such isotopes should be unstable. However, this generalization is not strictly correct especially for elements of Low Mass numbers. For these elements, though packing fraction is positive, yet they are stable. This is explained on the basis that the actual masses of protons and neutrons (of which the nuclei are composed) are slightly greater than unity.

In general, lower the packing fraction, greater is the binding energy per nucleon and hence greater is the stability the relatively low packing fraction of He, C and O implies their exceptional stability packing fraction is least for Fe (negative) and highest for H (+78).

(iv) **Meson theory of nuclear forces:** Neutron is found to play a leading role in binding the nuclear particles. It has been established that neutron proton attractions are stronger than the proton-proton or neutron – neutron attraction. This is evident by the fact that the deutron, ${}_1H^2$ having one proton and one neutron, is quite stable.

Yukawa in 1935, put forward a postulate that neutrons and protons are held together by very rapid exchange of nuclear particles called Pi-mesons (π-mesons have mass equal to 275 times of the mass of an electron and a charge equal to +1, 0 or –1. There are designated as $\pi^+ \pi^0$ and π^- respectively). The nuclear force which is used in rapid exchange of Pi-mesons between nucleons are also called **exchange forces.**

- The binding forces between unlike nucleons (p and n) are explained by the oscillation of a charged π-meson (π^+ or π^-)

$$\boxed{\begin{array}{l} \text{(a)}\ \ p_1 + n_2 \rightleftharpoons n_1 + \pi^+ + n_2 \rightleftharpoons n_1 + p_2 \\ \text{(b)}\ \ p_1 + n_2 \rightleftharpoons n_1 + \pi^- + p_2 \rightleftharpoons n_1 + p_2 \end{array}}$$

- Binding forces between like nucleons (p - p or n - n) result from the exchange of neutral mesons (π^0) as represented below.

$$\boxed{\begin{array}{l}\text{(a)}\quad p_1 \rightleftharpoons p_2 + \pi^0 \text{ or } p_1 + \pi^0 \rightleftharpoons p_2 \\ \text{(b)}\quad n_1 \rightleftharpoons n_2 + \pi^0 \text{ or } n_1 + \pi^0 \rightleftharpoons n_2\end{array}}$$

(v) **Nuclear shell model:** According to this theory, nucleus of atom, like extra-nuclear electrons, also has definite energy levels (shells). The shell structure is supported by the existence of periodicity in the nuclear properties. For example, elements with even number of protons and neutrons are more abundant, more stable and richer in isotopes. Nuclides with odd number of protons and neutrons are least abundant in nature (only 5 are known ${}_1H^2$, ${}_5B^{10}$, ${}_7N^{14}$ and ${}_{73}Ta^{180}$).

Thus elements have a tendency to have even number of both protons and neutrons. This suggests that like electrons, nucleon particles in the nucleus are paired. Magnetic fields of the two paired protons spinning in opposite direction cancel each other and develop attractive forces, which are sufficient to stabilize the nucleus. Further nuclei with 2, 8, 20, 28, 50, 82 or 126 protons or neutrons have been found to be particularly stable with a large number of isotopes. These numbers, commonly known as **Magic numbers** are defined as the number of nucleons required for completion of the energy levels of the nucleus. Nucleons are arranged in shells as two protons or two neutrons (with paired spins) just like electrons arranged in the extra-nuclear part. Thus the following nuclei ${}_2He^4$, ${}_8O^{16}$, ${}_{20}Ca^{40}$ and ${}_{82}Pb^{208}$ containing protons 2, 8, 20 and 82 respectively (all magic numbers) and neutrons 2, 8, 20 and 126 respectively (all magic numbers) are the most stable.

Magic numbers for **protons**: 2, 8, 20, 28, 50, 82, 114

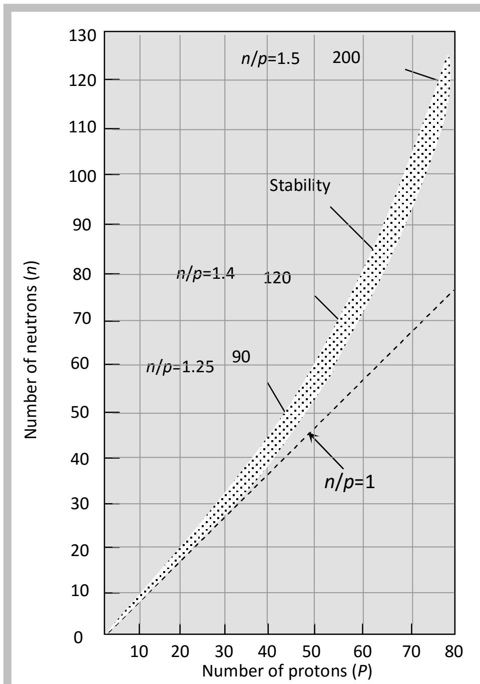
Magic numbers for **neutrons**: 2, 8, 20, 28, 50, 126, 184, 196

When both the number of protons and number of neutrons are magic numbers, the nucleus is very stable. That is why most of the radioactive disintegration series terminate into stable isotope of lead (magic number for proton = 82, magic number for neutron = 126). Nuclei with nucleons just above the magic numbers are less stable and hence these may emit some particles to attain magic numbers.

(vi) **Nuclear fluid theory:** According to this theory the nucleus is considered to resemble a liquid drop. Nucleons are believed to be present in the nucleus as nuclear fluid of very high density equal to 130 trillion tonnes/m^3, which is about 100 trillion times the density of water. The density is uniform and does not vary from atom to atom. Along with its almost unbelievable high density nuclear fluid possesses a correspondingly high surface tension ($= 9.3 \times 10^{19}\ Nm^{-1}$, i.e., 1.24×10^{18} times the surface tension of water). A nuclear film attached to a wire one centimeter long would support the mass of one billion tonnes. This force of nuclear surface tension is, in fact, responsible for keeping the nucleons bound together against the forces of repulsion. This is known as the **nuclear fluid theory** of the stability of the nuclei. Thus according to this theory the nucleons are free to move within the nucleus whereas according to the nuclear shell structure theory the nucleons exist in definite energy levels.

(vii) **Neutron-proton ratio and nuclear stability or causes of radioactivity:** The nuclear stability is found to be related to the neutron/proton (n/p) ratio. If for different elements the number of neutrons is plotted against the number of protons, it is found that the elements with stable nuclei (non-radioactive elements) lie within a region (belt) known as **zone** or **belt of stability**.

(a) For elements with low atomic number (less than 20), n/p ratio is 1, i.e., the number of protons is equal to the number of neutrons. Remember that n/p ratio of ${}_1H^1$ is zero as it has no neutron. Nuclide with highest n/p ratio is ${}_1H^3$ (n/p = 2.0)



Nuclei lying above or below the stability belt are unstable

(b) With the increase in atomic number although the number of protons increases but the number of neutrons increases much more than the number of protons with the result the n/p ratio goes on increasing from 1 till it becomes nearly equal to 1.5 at the upper end of the belt.

(c) When the n/p ratio exceeds 1.52 as in elements with atomic number 84 or higher, the element becomes radioactive and undergoes disintegration spontaneously. Note that these elements lie outside the zone of stability.

The way an unstable nucleus disintegrates is decided by its position with respect to the actual n/p plot of stable nuclei (the zone of stability)

•**Neutrons to proton (n/p) ratio too high.** If the n/p ratio is too high, i.e., when the nucleus contains too many neutrons, it falls above the zone of stability. The isotope would be unstable and would tend to come within the stability zone by the emission of a β-ray (electron). Electron, is produced in the nucleus probably by the following type of decay of a neutron.

$$\boxed{{}_0n^1 \rightarrow {}_1H^1 + {}_{-1}e^0} \text{ (Beta particle)}$$

The electron thus produced is emitted as a β-particle and thus the neutron decay ultimately increases the number of protons, with the result the n/p ratio decreases and comes to the stable belt. Consider the example of C^{12} and C^{14}. In C^{12}, the n/p ratio (6/6) is 1, hence its nucleus is quite stable. On the other hand, in C^{14}, the n/p ratio (8/6) is 1.3, hence it should be unstable. In practice also it is found to be so and C^{14} decays in the following way to give N^{14} (n/p ratio = 1)

$$\underset{\left(\frac{n}{p}=\frac{8}{6}=1.33\right)}{{}_6C^{14}} \longrightarrow \underset{\left(\frac{n}{p}=\frac{7}{7}=1.0\right)}{{}_7N^{14}} + {}_{-1}e^0 \; ; \quad \underset{\left(\frac{n}{p}=\frac{146}{92}=1.587\right)}{{}_{92}U^{238}} \longrightarrow \underset{\left(\frac{n}{p}=\frac{144}{90}=1.6\right)}{{}_{90}Th^{234}} + {}_2He^4$$

•**Neutron to proton ratio (n/p) too low**, (i.e., when the nucleus contains excess protons): There are no naturally occurring nuclides with n/p ratio less than 1, however there are many artificially nuclides in such cases, the nucleus lies below the zone of stability, it would again be unstable and would tend to come within the zone of stability by losing a positron.

$$\underset{\left(\frac{n}{p}=\frac{5}{6}=0.83\right)}{{}_6C^{11}} \longrightarrow \underset{\left(\frac{n}{p}=\frac{6}{5}=1.2\right)}{{}_5B^{11}} + {}_{+1}e^0 ; \quad \underset{\left(\frac{n}{p}=\frac{5}{6}=0.83\right)}{{}_7N^{13}} \longrightarrow \underset{\left(\frac{n}{p}=\frac{7}{6}=1.16\right)}{{}_6C^{13}} + {}_{+1}e^0$$

Such nuclides can increase n/p ratio by adopting any one of the following three ways:

By emission of an alpha particle: $\underset{\left(\frac{n}{p}=\frac{146}{92}=1.58\right)}{{}_{92}U^{238}} \rightarrow \underset{\left(\frac{n}{p}=\frac{144}{90}=1.60\right)}{{}_{90}Th^{234}} + {}_2He^4$

By emission of a positron: $\underset{\left(\frac{n}{p}=\frac{6}{7}\right)}{{}^{13}_{7}N} \rightarrow \underset{\left(\frac{n}{p}=\frac{7}{6}\right)}{{}^{13}_{6}C} + {}_{+1}e^0$

By K-electron capture: $\underset{\left(\frac{n}{p}=\frac{115}{79}\right)}{{}^{194}_{79}Au} + {}_{-1}e^0 \rightarrow \underset{\left(\frac{n}{p}=\frac{116}{78}\right)}{{}^{194}_{78}Pt}$

α-emission is usually observed in natural radioactive isotopes while emission of positron or K-electron capture is observed in artificial radioactive isotopes. The unstable nuclei continue to emit α or β-particles. Until stable nuclei comes into existence.

(3) **Nuclear reactions:**In a chemical reaction, only electrons (extra-nuclear particle) of the atom take part while the nucleus of the atom remains unaffected. However, the reverse reactions (i.e., where only nuclei of atoms take part in reactions) are also possible. Such reactions in which nucleus of an atom itself undergoes spontaneous change or interact with other nuclei of lighter particles resulting new nuclei and one or more lighter particles are called nuclear reactions.

(i) **Some characteristics of nuclear reactions:**

(a) Nuclear reactions are written like a chemical reaction: As in a chemical reaction, reactants in a nuclear reaction are written on the left hand side and products on the right hand side with an arrow in between them.

(b) Mass number and atomic number of the elements are written in a nuclear reactions: Mass number and atomic number of the element involved in a nuclear reaction are inserted as superscripts and subscripts respectively on the symbol of the element. For example $^{27}_{13}Al\ or\ Al^{27}_{13}$ or $_{13}Al^{27}$ stands for an atom of aluminum with mass number 27 and atomic number 13.

(c) Mass number and atomic number are conserved: In a nuclear reaction the total mass numbers and total atomic numbers are balanced on the two sides of the reaction (recall that in an ordinary reaction the total number of atoms of the various elements are balanced on the two sides)

(d) Energy involved in the nuclear reactions is indicated in the product as +Q or –Q of reactions accompanied by release or absorption of energy respectively.

(e) Important projectiles are α-particles$({}_2He^4)$, Proton$({}_1H^1 \text{ or } p)$, deutron $({}_1H^2 \text{ or } {}_1D^2)$, neutron$({}_0n^1)$, electron ($\beta$-particle or ${}_{-1}e^0$ or e^-) and positron$({}_{+1}e^0)$.

(f) Representation of nuclear reactions: For example, ${}_7N^{14} + {}_2He^4 \rightarrow {}_8O^{17} + {}_1H^1 + Q$. Sometimes a short hand notation is used, e.g., the above reaction can be represented as below. ${}_7N^{14}(\alpha, p)_8O^{17}$

(ii) **Nuclear reactions Vs chemical reactions:**

(a) As per definition, chemical reactions depend upon the number of extra nuclear electrons while nuclear reactions are independent upon the electrons but depend upon the nature of the nucleus.

(b) Chemical reactions involve some loss, gain or overlap of outer orbital electrons of the two-reactant atoms. On the other hand, nuclear reactions involve emission of some light particles (α, β, positron, etc.) from the nucleus of the atom to form another element.

(c) The chemical reactivity of the element is dependent on the nature of the bond present in the concerned compound. On the other hand, the nuclear reactivity of the element is independent of its

state of chemical combination, e.g., radium, whether present as such or in the form of its compound, shows similar radioactivity.

(d) The energy change occurring in nuclear reactions is very high as compared to that in chemical reactions. Again in chemical reactions the energy is expressed in kcal per mole while in nuclear reactions the energy is expressed in MeV per nucleus. Nuclear reactions, which liberate energy are called **exoergic reactions** and which absorb energy are called **endoergic.**

(e) A chemical reaction is balanced in terms of mass only while a nuclear reaction must be balanced in terms of both mass and energy. In endoergic reactions, the mass of products is more than the mass of reactants. While in exoergic reaction the mass of products is less than the mass of reactants.

(f) The chemical reactions are dependent on temperature and pressure while the nuclear reactions are independent of external conditions.

(iii) **Types of nuclear reactions:**Nuclear reactions may broadly be divided into two types:

(a) **Natural nuclear reactions:**In these reactions, nucleus of a single atom undergoes a spontaneous change itself.

(b) **Artificial nuclear reactions:**In these reactions, two nuclei of different elements are brought to interact artificially. Bombarding a relatively heavier nucleus (non-radioactive) with a lighter nucleus, viz. proton, deutron and helium, does this. Artificial nuclear reactions are divided as follows:

- **Projectile capture reactions:**The bombarding particle is absorbed with or without the emission of γ-radiations.

$${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239} + \gamma\,; \quad {}_{13}Al^{27} + {}_{0}n^{1} \rightarrow {}_{13}Al^{28} + \gamma$$

- **Particle-particle reactions:**Majority of nuclear reactions come under this category. In addition to the product nucleus, an elementary particle is also emitted.

$$_{11}Na^{23} + {}_1H^1 \rightarrow {}_{12}Mg^{23} + {}_0n^1;\quad {}_{11}Na^{23} + {}_1H^2 \rightarrow {}_{11}Na^{24} + {}_1H^1$$

$$_{11}Na^{23} + {}_2He^4 \rightarrow {}_{12}Mg^{26} + {}_1H^1;\quad {}_7N^{14} + {}_0n^1 \rightarrow {}_6C^{14} + {}_1H^1$$

- **Spallation reactions:**High speed projectiles with energies approximately 40 MeV may chip fragments from a heavy nucleus, leaving a smaller nucleus.

$$_{29}Cu^{63} + {}_2He^4 + 400\ MeV \rightarrow {}_{17}Cl^{37} + 14\ {}_1H^1 + 16\,{}_0n^1$$

- **Fission reactions:**A reaction in which a heavy nucleus is broken down into two or more medium heavy fragments. The process is usually accompanied with emission of neutrons and large amount of energy.

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

- **Fusion reactions:** Light nuclei fuse together to reproduce comparatively heavier nuclei. A fusion reactions is the source of tremendous amount of energy.

$$_1H^2 + {}_1H^3 \rightarrow {}_2He^4 + {}_0n^1 + 17.6\ MeV$$