GENESIS TUTORIALS

Institute for CSIR-UGC-NET/JRF, GATE & IIT-JAM

Nuclear Chemistry

Atomic Nucleus

The central part of atom in which total positive charge anf the total mass of atom is concentrated is called Nucleus. All protons and neutrons are present in Nucleus. The radius of atomic nucleus is of the order of $10^{-13} - 10^{-12}$. All the atomic nuclei do not have same radius. The radius of nucleus can be calculated by the following formula:

$$r = 1.33 \times 10^{-13} [A]^{1/3}\ cm$$

Where, A = mass number of element

The distance between proton and neutron in the nucleus is approximately 2–3 fermi (f) and 1f = 10^{-13} cm

Atomic Number and Mass number

An atom is characterised by its atomic number, Z and its mass number, A. The atomic number written as a subscript to the left of element symbol, gives the number of protons in the nucleus. The mass number, written as a superscript to the left of the element symbol, gives the total number of nucleons, a general term for the both protons (p) and neutrons (n) i.e. mass number = nucleons = P + N

Mass Number $\rightarrow$ A

$$^{A}_{Z}X$$

Atomic Number $\rightarrow$ Z

For example, the most common isotope of carbon has 12 nucleons:6 protons and 6 neutrons.

Mass Number $\rightarrow$ 12

$$^{12}_{6}C$$

Atomic Number $\rightarrow$ 6

6 proton
6 Neutrons
12 Nucleons

Mass Number (A) = Z + N

or

A = P + N

Isotopes

Atoms with identical atomic numbers but different mass number are called isotopes and the nucleus of a specific isotope is called a nuclide.

Example:

(1) Isotopes of hyrdogen : Three isotopes of hydrogen are known.

^1_1H	^2_1H	^3_1H
Protium	Duterium	Tritium

(2) Isotopes of chlorine: Two isotopes are known

$$^{35}_{17}Cl \text{ and } ^{37}_{17}Cl$$

(3) Isotopes of Carbon: Three isotopes are known.

$$^{12}_{6}C, ^{13}_{6}C \text{ , and } ^{14}_{6}C$$

(4) Isotopes of Oxygen: The isotopes are known.

$$^{16}_{8}O, ^{17}_{8}O \text{ , and } ^{18}_{8}O$$

Types of Isotopes

(1) Non Radioactive Isotopes or stable Isotopes

The isotopes which have stable nuclei and do not decompose spontaneously. *For* example: Carban has three isotopes: $^{12}_{6}C, ^{13}_{6}C$, and $^{14}_{6}C$. $^{12}_{6}C$ and $^{13}_{6}C$ are nonradioactive isotopes and $^{14}_{6}C$ is a radioactive isotope.

(2) Radioactive Isotopes

The isotopes which have unstable nuclei and these nuclei decompose spontaneously. For example $^{14}_{6}C$ and $^{3}_{1}H$ isotopes of carbon and hydrogen respectively, are the radioactive isotopes.

Properties of Isotopes

1. The atomic number of all isotopes of an element is same because no. of protons in their nuclei is same.

2. No. of protons is same but no. of neutrons is different in all the isotopes of an element.

3. Chemical properties of all the isotopes of an element are same because electronic configuration of isotopes are same.

4. The isotopes of an element have different physical properties because they have different atomic masses.

5. Radioactive properties of istopes of an element are different because tthey have different nuclear structure

6. All the isotopes of an element are placed in one place in periodic table because their atomic numbers are same

Seperation of Isotopes.

The isotopes have similar chemical properties, so their separation by chemical methods is difficult. Because their atomic mass and hence physical properties are different so these are sperated by physical mehods like diffusion, fractional distillation, mass spectrograph, chemical exchange method, fractional electrolysis etc.

Isobars

The atoms of different elements having the same mass number but different atomic numbers are called isobars.

Examles:

1. ${}^{40}_{18}Ar$, ${}^{40}_{19}K$, and ${}^{40}_{20}Ca$ are isobars
2. ${}^{3}_{1}H$ and ${}^{3}_{2}He$ are isobars.
3. ${}^{14}_{6}C$ and ${}^{14}_{7}N$ are isobars.
4. ${}^{58}_{26}Fe$ and ${}^{58}_{28}Ni$ are isobars.

Properties of Isobars

1. Number of protons in the nuclei of the isobars are different so their atomic number are also different and therefore, these are of different elements. Number of nucleons in the nuclei of isobars is same so their mass number are also same. Their electonic configurations are also different

2. Isobars have different chemical properties because their electronic configuration are different.

3. Since isobars are of different elements so these are placed in different spaces in periodic table.

4. Their physical properties are also different because they have different no. of eletrons, protons and neutrons

<u>Istopic Mass</u>

The mass of an isotope of an element with respect to the carbon-12 (one twelfth the mass of a carbon-12 atom) is called isotopic mass.

For example: Isotopic mass of $_{35}Cl$ is 34.96 and that of $_{37}Cl$ is 36.95.

Mass number and isotopic mass of an isotope are same

Isotones

The atoms of different elements having same number of neutrons but different mass number are called isotones. For example, $^{30}_{14}Si$, $^{31}_{15}P$ and $^{32}_{16}S$ are isotones. Similarly $^{3}_{1}H$ and $^{4}_{2}He$ are isotones. $^{13}_{6}C$ and $^{14}_{7}N$ are isotones

Nuclear Isomers

The radioactive element having the same mass number and the same atomic number but different radioactive properties are called nuclear isomer. They have different rate of disintegration, disintegration constant and the half lives.

Example ^{60}Co and $^{60}Co^*$, $^{80}Br^*$ and $^{80}Br^*$, ^{69}Zn $^{69}Zn^*$

* = Metastable state

Mass Defect

Mass defect is the difference between the mass of nuclear particles (proton and neutron) and the real mass of nucleus

Mass defect (Δm) = Mass of (proton + neutrons) present in the nucleus – Actual mass of nucleus

When a stable nucleus is formed by the combination of protons and neutrons, some amount of mass is disappeared in the form of energy ($E = mc^2$), so the actual mass of the nucleus is smaller than the no. of proton and the no. of neutrons present in the nucleus

Binding Energy of Nucleus

The energy released when a nuicleus is formed by the combination of protons and neutrons, is called nuclear binding energy

OR

The energy required to disrupt the nucleus into its constituent particels (protons and neutrons) is called nuclear binding energy.

The mass defect caused by the combination of protons and neutrons to form the nucleus is convered into energy according to Eintein equation ($E = mc^2$). This energy is equivalent to binding energy of nucleus.

Binding energy (B) = Δmc^2

where Δm = mass defects in a.m.u

$c = 3 \times 10^8 m/s$

$B = \Delta m \times 1.66 \times 10^{-27}\ kg \times (3 \times 10^8)^2 \quad (\because\ 1\ a.m.u. = 1.66 \times 10^{-27} kg)$

$B = \Delta m \times 1.49 \times 10^{-12}\ J$

$B = \Delta m \times \frac{1.49 \times 10^{-12}}{1.6 \times 10^{-14}}\ MeV \quad (\because\ 1\ MeV = 1.6 \times 10^{-13} J)$

$$\boxed{B = \Delta m \times 931.5\ MeV}$$

B = Binding energy of nucleus

Δm = mass defect in a.m.u.

Atomic mass unit (a.m.u):

1 amu = $\frac{1}{12}$th of the mass of an atom of ${}^{12}_{6}C$ isotope

N_o (Avogadro number) = 6.023×10^{23}

Mass of 6.023×10^{23} atoms of ${}^{12}_{6}C = 12g$

Mass of one atom of ${}^{12}_{6}C = \frac{12}{6.023 \times 10^{23}} g$

$1\ amu = \frac{1}{12} \times \frac{12}{6.023 \times 10^{23}} = 1.66 \times 10^{-27}\ kg$

Binding energy per Nucleon ($\bar{B}$)

$(\bar{B}) = \frac{\text{Binding Energy}}{\text{Number of Nucleons}}$

$= \frac{B.E}{P + N}$

P + N = Number of Nucleons

Note: Binding energy of a radioactive element is higher whereas the binding energy pernucleon is smaller. But for stable nuclei B.E per nucleon is larger.

Example 1. Binding energy of ${}^{4}_{2}He$ is 28.57 MeV. Calculate binding energy per nucleon

Solution B.E/Nucleon = $\frac{28.57}{4} = 7.14$ MeV

Example 2: Calculate binding energy per nucleon of ${}^{4}_{2}He$ nucleus.

$$2\,{}^{1}_{1}H + 2\,{}^{1}_{0}n \rightarrow {}^{4}_{2}He$$

Given- Mass of one proton = 1.00728 amu.

Mass of one Neutron = 1.00866 amu

Mass of one electron = 0.0005486 amu

mass of ${}^{4}_{2}$He atom = 4.00260 amu

Solution :

Mass of 2 protons = 2 × 1.00728 = 2.01456 amu

Mass of 2 neutrons = 2 × 1.00866 = 2.01732 amu

Total mass of 2n + 2p = 4.03188 amu

Mass of ${}^{4}_{2}$He nucleus = mass of ${}^{4}_{2}$He atom – Mass of 2 electrons

= 4.00260 – 2 × 0.0005486

4.00260 – 0.00110

= 4.00150 amu

Mass defect = Mass of (2p + 2N) – Mass of ${}^{4}_{2}$He nucleus

= 4.03188 – 4.00150 = 0.03038 amu

B.E/Nucleon = $\frac{\text{B.E}}{\text{Nucleons}}$

$= \frac{0.03038 \times 931.5}{4} = 7.08$ MeV

Stability of Nucleus

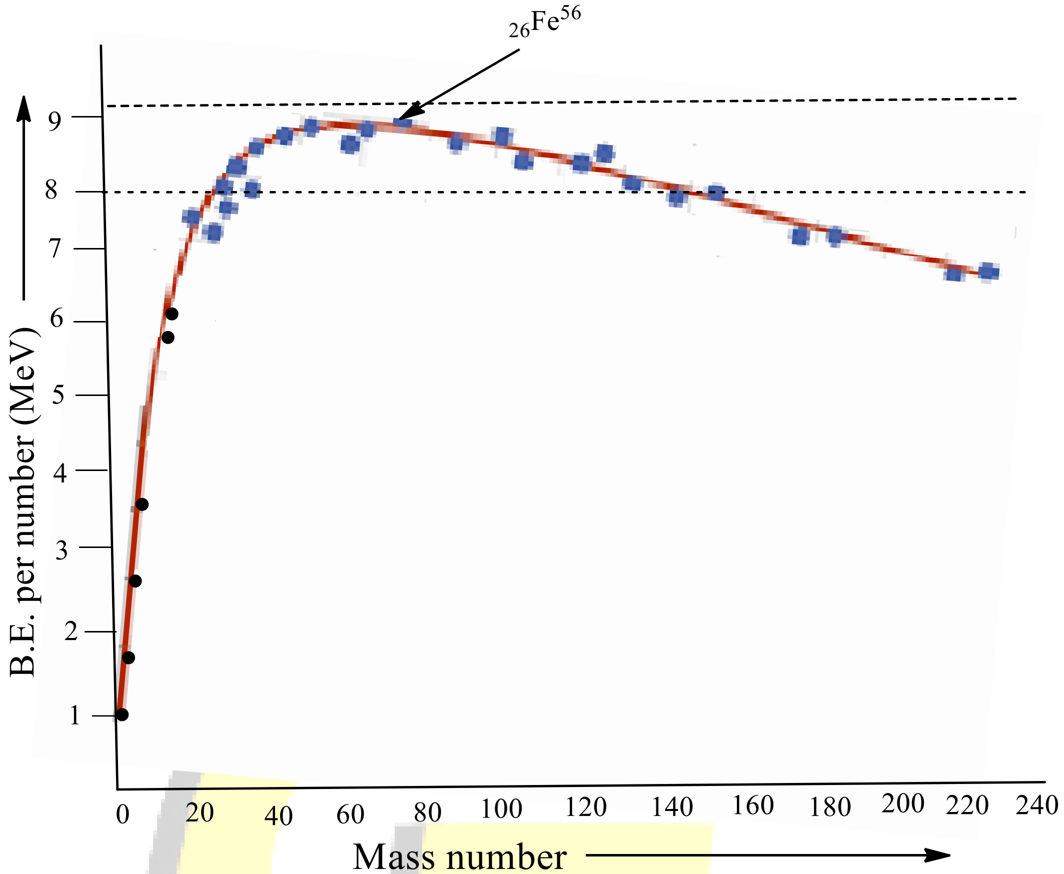
Stability of nucleus can be explained on the basis of following theories

(1) Binding Energy and B.E. per Nucleon

Binding energy of nucleus is the measure of stability of nucleus. The stability of nuclei of same mass number can be explained on the basis of binding energy but the stability of elements of different mass number can not be expaind on the basis of binding energy. The nuclei of same mass number having the larger binding energy are more stable. Binding energy increases with increase in mass number but for higher mass number, the rate of increase in binding energy becomes slow, because nuclei having higher number of nucleons have larger binding energy.

The stability of nuclei of different mass number and the same mass number can be explained on the basis of B.E. per nucleon ($\overline{\text{B}}$).

The nucleus with large B.E. per nucleon is more stable. When a graph is plotted between B.E. per nucleon and mass number of different nuclei, the following curve is obtained. This curve is called nuclear energy curve.



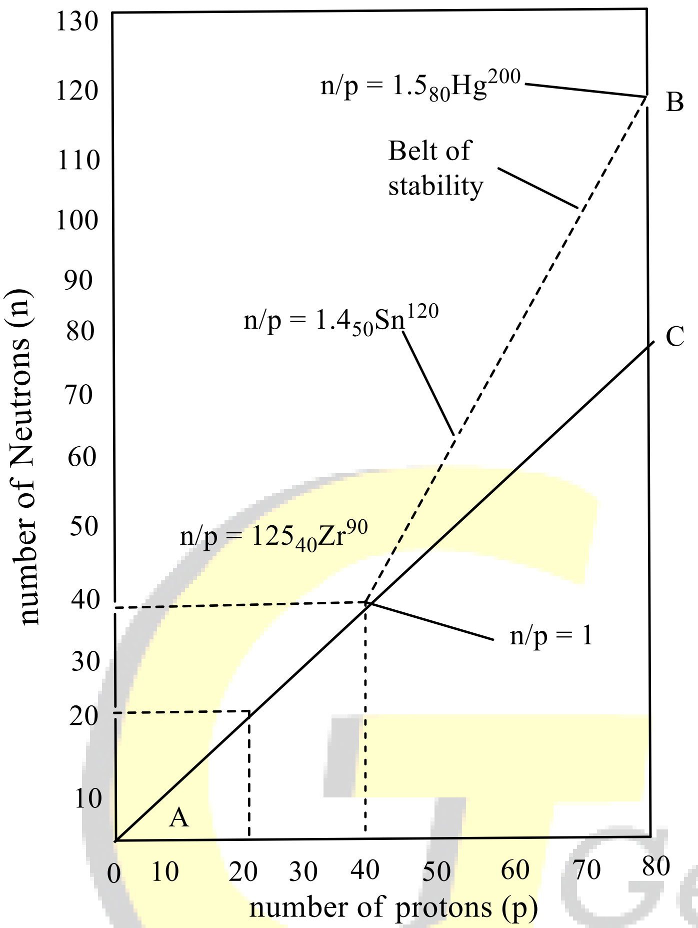
Except $^4_2$He, $^{12}_6$C and $^{16}_8$O, all the elements lie on this curve, B.E, per nucleon of heavy elements is small, so these elements are radioactive. The heavy elements are disintegrated and after disintegration stable nuclei are formed because these stable nuclei have larger value of B.E per nucleon.

The maximum B.E, per nucleon (8.7 MeV) is of iron so iron is found in nature in abundance

Maximum stable nuclei have $\bar{B}$ near 8 MeV

(2) Ratio of Neutons and protons (n/p Ratio)

The stability of nucleus can also be explained on the basis of n/p ratio. The nuclei of elements for which the value of n/p is in the range 1 to 1.52 are stable. The value of n/p for hydrogen ($^1_1$H) is zero and the this ($^1_1$H) nucleus is stable because it has only one proton and no electron and no force of repulsion works in this nucleus. The most abundant stable isotopes of other elements upto $_{20}$Ca (including $_{20}$Ca also) usually have the same number of protons and neutrons ($^4_2$He, $^{12}_6$C, $^{28}_{14}$Se, etc for example) or have only one more neutron than proton ($^{11}_5$B, $^{19}_9$F, and $^{23}_{11}$Na, for example) i.e. these element have value of n/p ~ 1. If number of neutrons is plotted against the number of protons, the following curve is obtained which shown by dots. This curve is called nuclear stability belt. The nuclei with atomic number upto 20 have n/p ratio close to 1 i.e., plot is linear. With increase in atomic number, the graph becames curved whose slope increases gradually. The nuclei with n/p ratio lying above or below the stability belt are unstable. They undergo position (β^+) emission or K-capture or lose of α or β-particles so that their n/p ratio falls within the stability belt.



1. The elements lying below the stability belt, have lesser number of neutrons. These elements decay by positron emission or K-capture so that n/p ratio increase to (n + 1) / (p - 1) so a to go up into stability belt. In these processes proton is converted to neutron

(a) Positron Emission

$$ {}^{1}_{1}\mathrm{P} \rightarrow {}^{1}_{0}\mathrm{n} + \underset{Positron}{{}^{0}_{+1}\mathrm{e}} $$

$$ {}^{13}_{7}\mathrm{Na} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}\mathrm{e} + \mathrm{v} $$

$$ {}^{30}_{15}\mathrm{P} \rightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\mathrm{e} $$

(b) K-capture: in this process nucleus capture K-shell electron.

$$ {}^{1}_{1}\mathrm{P} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{1}_{0}\mathrm{n} $$

$$ {}^{81}_{37}\mathrm{Rb} + \underset{\mathrm{Electron}}{{}^{0}_{-1}\mathrm{e}} \rightarrow {}^{81}_{36}\mathrm{Kr} $$

In both the process (a) and (b), no. of neutrons increases so n/p ratio also increases and the new element formed goes to the stability region.

2. The elements lying above the stability belt, have larger no. of neutrons. These elements emit $\beta -$ particles so that n/p ratio decreases to (n-1)/ (p + 1) so as to come down into the stability belt. In this process, one neutrons is converted to β-particle and proton.

$$\underset{\text{Neutron}}{{}_0^1n} \rightarrow \underset{\text{Proton}}{{}_1^1p} + \underset{\beta - \text{particle}}{{}_{-1}^{0}e} + \underset{\text{Antinutrino}}{\bar{\upsilon}}$$

$${}_1^3H \longrightarrow {}_2^3He + {}_{-1}^{0}e$$

$${}_6^{14}C \longrightarrow {}_7^{14}N + {}_{-1}^{0}e$$

3. The elements having mass number larger than 209 and atomic number larger than 83, have n/p ratio greater than 1.5 and these elements are radio active.

For example:

$${}_{92}^{235}U,\ n/p = \frac{143}{92} = 1.55$$

$${}_{90}^{234}Th,\ \ n/p = \frac{144}{90} = 1.6$$

These elements emit α-particles and form a stable nucleus.

In this process no. of protons and neutrons decreases equally and the n/p ratio also decreases.

$${}_{92}^{238}U \longrightarrow {}_{90}^{234}Th + \underset{\alpha\text{-particle}}{{}_2^4He}$$

Note: There are several elements which have n/p ratio smaller than 1.5 and are radio active.

For example—

$${}_6^{14}C,\ n/p = \frac{8}{6} = 1.33$$

$${}_{15}^{30}P,\ \ n/p = \frac{15}{15} = 1$$

$${}_7^{13}N,\ n/p = \frac{6}{7} = 0.86$$

(3) Nuclear Forces

Nuclear force is explained by Yukawa by discovery of new fundamental particles called π-meson in 1935. Mass of π-meson is 273 times more than the mass of the electron and it may have have positive or negative charge or may be eletrically neutral represented by π^+, π^- and π^0 respectively.

The force which hold the nucleons together within the small nucleus are called nuclear forces. These forces are stronger than the force of repulsion. Nuclear forces are force of attraction. These forces exist among protons-protons, protons-neutrons and neutron-neutrons. Thses forces are not electrostatic forces because protons are positively charged particles and neutrons are neutral particles. The nuclear forces are operated for distance of 2*f* to 3*f*.

According to Yukawa, Nuclear forces result by the exchange of π-meson between proton and neutron. The mesons keep of echanging among nucleons very rapidly (about 10^{24} transfer per second) and hold the nucleus together.

Proton is converted into a neutron with the liberation of positive meson (π^+) which in turn taken up by a neutron which is coverted into a proton.

Also, Neutron is converted into a proton with liberation of negative meson (π^-) which is taken up by a proton which is converted into a neutron.

$$p \longrightarrow n + \pi^+$$

$$n + \pi^- \longrightarrow p$$

$$p + \pi^+ \longrightarrow n$$

$$n \longrightarrow p + \pi^-$$

There is exchange of neutral meson between two protons and between two neutrons.

$$p \underset{+\pi^0}{\overset{+\pi^0}{\rightleftharpoons}} p$$

$$n \underset{+\pi^0}{\overset{+\pi^0}{\rightleftharpoons}} n$$

Thus by the exchange of meson, force of attraction is produced and hold the nucleons together into the nucleus and nucleus remains stable. These forces of attraction are also called as exchange forces

(4) Stability Number or Magic Numbers

The nuclei having the number of protons or neutrons equal to 2, 8, 20, 28, 50, 82 or 126 are more stable than the others. These numbers are called magic numbers.

The nuclei in which both protons and neutrons are magic numbers, are highly stable.

e.g. $^{4}_{2}He$, $^{16}_{8}O$, $^{40}_{20}Ca$

Follow Up :

Particle	Symbol	Mass (amu)	Charge	Discovered by
Electron	$_{-1}e^0$	0.000548	-1	Thomson (1897)
Proton	p, $^{1}_{1}H$	1.00757	+1	Goldstein (1886)
Neutron	$^{1}_{0}n$	1.00893	0	Chadwick (1932)
Positron	$^{0}_{+1}e$	equal to electron	+1	Anderson (1932)
Neutrino	υ	0	0	Reins and cown (1953)
Antinutrino	$\overline{\upsilon}$	0	0	Powell
Meson	$\left.\begin{matrix}\pi^+\\ \pi^0\\ \pi^-\end{matrix}\right\}$	0.156	$\left.\begin{matrix}+1\\ 0\\ -1\end{matrix}\right\}$	Yukawa
Antiproton	$^{1}_{-1}p$		-1	Sieger, Wieland (1955)

Radiactivity

Discovered by Henry Becquerel in 1896. The phenomenon of spontaneous emission of certain kinds of invisible and penetrating rays (radiations) is called as radoactivity and the elements and their salts emitting such type of radiations are called radioctive substances. The invisible and penetrating rays are called radioactive rays or becquerrel rays.

Nature or radioactive Rays

Rutherford (1899) and Villard had proved that the radioactive rays are of three types

(a) $\alpha -$ rays (b) $\beta -$ rays (c) $\gamma -$ rays

When the radioactive rays (obained from radioactive substances) are passed through the magnetic filed or static electric field. These are divided into three parts.

(a) $\alpha -$ rays consist of a stream of particles that are repelled by a positively charged electrode and are attracted by a negatively charged electrode and have a mass to charge ratio identifying them as helium nuclei, $^{4}_{2}He^{2+}$. This indicates that $\alpha -$ rays have positive charge

(b) $\beta -$ rays consist of a stream of particles that are attracted to a positive electrode and are repelled by negatively electrode and have a mass to charge ratio identifying them as $\beta -$ particles, $^{0}_{-1}e$ or β^- .This indicates that $\beta -$ rays have negative charge

(c) $\gamma -$ rays are unaffected by elettric field. These have no charge and no mass and are simply electromagnetic radiations of very high energy

$\beta -$ rays are more deviated than the $\alpha -$ rays beause e/m of $\beta -$ rays is very high

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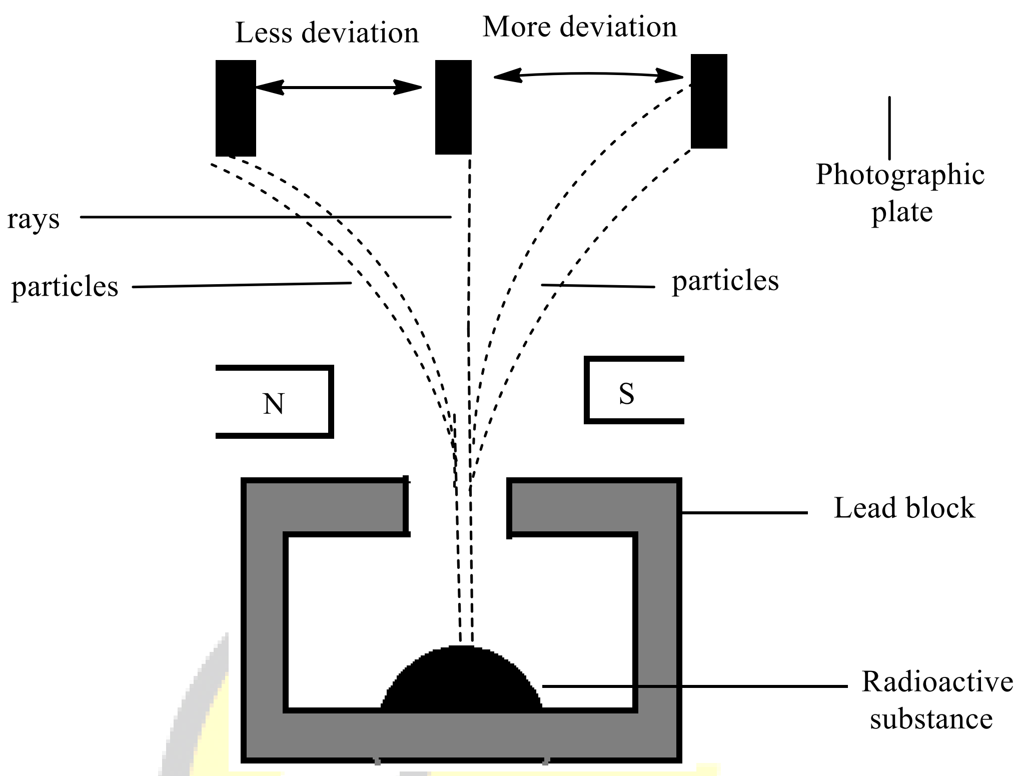
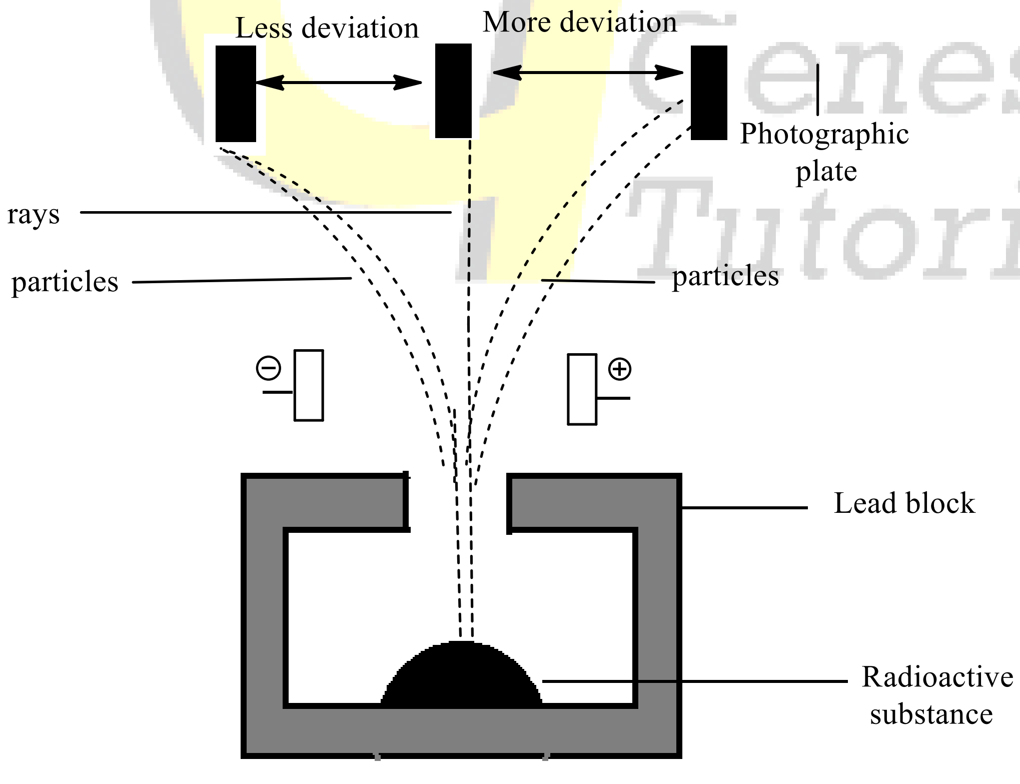


(a)



(b)

Properties of $\alpha-$, $\beta-$, and $\gamma-$ rays

properties of $\alpha-$, $\beta-$, and $\gamma-$ rays is given in the following table.

Property	$\alpha-$ rays	$\beta-$ rays	$\gamma-$ rays
1. Nature	These carry positive charge. Each α-particle carries two unit positive charge and four unit mass i.e., they are simply helium nuclei.	They carry negative charge. Each β - particles carries same charge and mass as that of an electron. Hence β - particle are same as electrons.	They carry no charge and have no mass. So they can not be considered as made up of particles. They are simply electomagnetic radiations like x-rays
2. Velocity	Their velocity is $\frac{1}{10}$ th of velocity of light, i.e., their velocity is 3×10^9 cm/sec.	Their velocity is 2.79×10^{10} cm/second.	Their velocity is same as that of velocity of light
3. Penetrating power	Being heavy particles, their penetrating power is smaller than β - and γ - rays, these penetrate the Al foil of the thickness of 0.002 cm	Because of smaller mass and higher velocity, their penertating power is nearly 100 times more than that of $\alpha-$ rays . These penetrate the Al foil of thickness of 0.2 cm.	Their penetrating power is even 100 times higher than $\beta-$ rays. These penetrate Al foil of thickness of 100 cm
4. Ionizing power	Being heavy particle, they have momentum and linetic energy and hence high ionizing power	Being much lighter particle than $\alpha-$ particles. They posses low momentum and kinetic energy and hence their ionizing power $\frac{1}{100}$th is of the $\alpha-$particles	Because of no mass their ionizing power is very poor
5. Effect of Magnetic field	These are deflected towards negative plate	These are deflected towards positive plate $\beta-$ rays are deflected to a much extent than$\alpha-$ rays because $\beta-$	Being neutral these are not affected by magnetic field.

		particles are much lighter than α – particles	
6. Effect on photographic plate	Blackend the photo-graphic plate.	Blackened the photographic plate.	Blackened the photo-graphic plate.
7. Effect on ZnS screen	Produce flurescence on ZnS screen.	Produce fluore-scence on ZnS screen	Produces fluorescence on ZnS screen.

Origin of α-, β-, and γ- rays

α-, β-, and γ- rays are produced by nuclear decay.

(1) Emission of α-rays: When an α –particle emits from the nucleus, atomic number and mass number of an element decreases by 2 and 4 units respectively.

$$^{213}_{83}\text{Bi} \longrightarrow {}^{209}_{81}\text{Tl} + \underset{\alpha\text{-particle}}{^{4}_{2}\text{He}}$$

An α –particle is composed of two protons and two neutrons

$$2\,{}^{1}_{1}\text{p} + 2\,{}^{1}_{0}\text{n} \longrightarrow {}^{4}_{2}\text{He}$$

Thus atomic number and mass number of an element decreases by 2 and 4 units respectively of an element.

(2) Emission of β-rays: β-particles are nuclear electrons. When a β-particles emits from the nucleus, mass number of an element does not charge but the atomic number is increased by one unit

$$^{213}_{83}\text{Bi} \longrightarrow {}^{213}_{84}\text{Po} + \underset{\beta\text{-particle}}{^{0}_{-1}\text{e}}$$

It is considered that, when one neutron decays, one electron (β-particle), one proton and antineutrino is produced.

$$\underset{\text{Neutron}}{^{1}_{0}\text{n}} \rightarrow \underset{\text{Proton}}{^{1}_{1}\text{p}} + \underset{\beta-\text{particle}}{^{0}_{-1}\text{e}} + \underset{\text{Antinutrino}}{\bar{\nu}}$$

Thus due to emission of β-particle, atomic number of an element increases by one unit but mass number remains as such.

(3) Emission of γ-rays: γ-rays are electromagnetic radiations like X-rays. γ-rays are produced from nucleus during nucleus decay. After emission of α − or β-particles, the element is in excited state. The element in the excited state emits γ-radiations and comes to the ground state. There is no effect of γ-emission on atomic number and mass number of an element

Group Displacement Law

Soddy, Fajans and **Russell** (1911-1913) observed that when an α-particle is lost (called α − decay), a new element with atomic number less by 2 and mass number less by 4 is formed. Similarly when β-particle is lost (called β-decay), a new element with atomic number greater by 1 is obtained. The element emitting the α or β particle is called parent element and the new element formed is called daughter element. The above results have been summarized as **'Group Displacement Laws'** as follows:

(1) When an α-particle is emitted, the new element formed is displaced two positions to the left in the periodic table than that of the parent element (because the atomic number decreases by 2)

For example, When $^{238}_{92}U$ nucleus emits an α-particle, thorium nucleus $^{234}_{90}Th$ is obtained.

$$^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He \qquad \text{------- (1)}$$

(ii) When a β-particle is emited, the new element formed is displaced one position to the right in the perodic table than that of the parent element (because atomic number increases by 1)

For example, the emission of β-particle by $^{234}_{90}Th$ and $^{14}_{6}C$ may be represented as follows.

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e \qquad \text{--------(2)}$$

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e \qquad \text{----------(3)}$$

Chemical equations such as (1), (2) and (3) respresenting nuclear changes are called **nuclear reactions.**

Explanation: The results of the group displacement laws may be explanied as follows:

Since an α-particle is simply a helium nucleus (containing two protons and two neutrons), therefore, loss of α-particle means loss of two protons and two neutrons. Thus the new element formed has atomic number less by 2 and mass number less by 4.

It is believed that for the emission of β-particle to occur, a neutron changes to a proton and the an electon i.e.

$$\text{Neutron} \longrightarrow \text{Proton + Electron (β-particle)}$$

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As a result, the number of protons in the nucleus increases by 1 and so does the atomic number.

Increase or decrease in the number of protons in the nucleus (due to loss of α and β particle) is accompanied simulaneously by the loss or gain of electons in the extranuclear part (from the surroundings) so that the electrical neutrality is maintained in the new atom formed.

Further, it is important to mention here that in addition to α, β and γ emissions, two more decay processes that have been observed are positron (β^+) emission and K-electron capture. These are briefly explained below:

(i) Positron (β^+) emission: A positron is a positively charged β-particle, represented by β^+ or ${}_{+1}^{0}e$. The emission of a positron, therefore, results in the decrease of atomic number by one unit. It is believed that the positron emission takes placed due to change of a proton into neutron in the nucleus

$$\text{Proton} \longrightarrow \text{Neutron} + \beta^+ \text{ or } {}_{+1}^{0}e \text{ (positron)}$$

i.e.
$$p^+ \longrightarrow n + \beta^+$$

An example of a reaction involving β^+ emission is

$$^{13}_{7}N \longrightarrow {}^{13}_{6}C + \beta^+ \text{ (or } {}_{+1}^{0}e)$$

(ii) K-electron capture: In certain nuclides, the nucleus captures an electron from the K-shell (being nearest to the nucleus). The vacancy created is filled up with the electron from the higher shells (thereby emitting X-rays). A result of K-electron capture, a proton in the nucleus is coverted into a neutron ($p^+ + e^- \longrightarrow n$).

Hence atomic number decrease by one unit. An example of a reaction involving K-capture is given below:

$$^{133}_{56}Ba + {}_{-1}^{0}e \longrightarrow {}^{133}_{55}Cs + \text{X-rays}$$

$$^{A}_{Z}X \xrightarrow{-\alpha \text{ particle}} {}^{A-4}_{Z-2}Y$$

$$^{A}_{Z}X \xrightarrow{-\beta \text{ particle}} {}_{Z+1}^{A}Y$$

$$^{A}_{Z}X \xrightarrow{-\beta^+ \text{ (positron)}} {}_{Z-1}^{A}Y$$

$$^{A}_{Z}X \xrightarrow[\text{(K-capture)}]{+e^-} {}^{A}_{Z-1}Y$$

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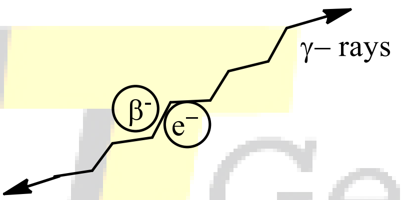
Emission of neutrino and antineutrino: On the basis of law of conservation of mass and energy, It has been postulated that when a β-particle is emitted, it is accompanied by the emission of chargeless, massless particle, called **neutrino** e.g,

$$^{14}_{6}C \longrightarrow\ ^{14}_{7}N +\ ^{0}_{-1}e + \upsilon \text{ (neutrino)}$$

Similarly, when a positron emission takes place, it is accompanied by emission of a chargeless, massless particle called antineutrino (which is identical to the neutrino but has opposite spin) eg.

$$^{15}_{8}O \longrightarrow\ ^{15}_{7}N +\ ^{0}_{+1}e + \bar{\upsilon} \text{ (anti neutrino)}$$

Annihilation of a positron and an electron: Positron was the first antiparticle to be discovered. It is similar to the electron in all respects expect charge. When a positron and an electron collide, they annihilate each other, γ-radiation equivalent to the masses of the two particles is produced.



Why is electron capture accompanied by production of X-rays? The capture of the orbitals electron leaves a vacancy in the K or L-shell and when an outer electron falls into this vacancy, X-rays emission follows.

Radioactive Disintegration

Spontaneous disintegration of a nucleus is called radioactive disintegration or decay.

Example

$$^{226}_{88}Ra \xrightarrow{\text{disintegration}}\ ^{222}_{86}Rn +\ ^{4}_{2}He$$

$$^{238}_{92}U \xrightarrow{\text{disintegration}}\ ^{234}_{90}Th +\ ^{4}_{2}He$$

$$^{234}_{90}Th \xrightarrow{\text{disintegration}}\ ^{234}_{91}Pa + \underset{\beta\text{-particle}}{^{0}_{-1}e}$$

$$^{213}_{83}Bi \xrightarrow{\text{disintegration}}\ ^{213}_{84}Po + \underset{\beta\text{-particle}}{^{0}_{-1}e}$$

Rate of Radioactive Disintegration or Decay

Radioactive sunstances spontaneously disintegrated regularly. Rate of disintegration decrease with increase in time. The rate of disintegration depends only upon the nature of radioactive substance and is independent of the external conditions such as pressure, temperature catalyst etc. Radioactive decay follows first order kinetics.

Suppose a radioactive element A decays to form an element B.

$$A \longrightarrow B$$

initial no. of element N_0

No. of element after time N_t

The rate of disintegration at time t is given by

$$-\frac{dN_t}{dt} \propto N_1$$

$$\text{or} \quad -\frac{dN_t}{dt} = kN_1$$

where k is the disintegration constant or decay constant.

$$\text{or} \quad \frac{dN_t}{N_t} = kdt \qquad \text{----------} \ (1)$$

if dt = 1 sec, then

$$k = \frac{dN_t}{N_t} \qquad \text{-----------} \ (2)$$

Thus distegration constant may be defined as the fraction of the torial no. of atoms of a substance present any time which disintegrates in one second.

Integrating equation (1)

$$-\int \frac{dN_t}{N_t} = k\int dt$$

$$\text{or} - \ln N_t = kt + C \qquad \text{---------} \ (3)$$

where C is the integration constant.

when t = 0

Putting these values in equation (3)

$$- \ln N_0 = C$$

Now put the value of C in equation (3)

$$-\ln N_t = kt - \ln N_0 \qquad \text{---------- (4)}$$

or $$\ln N_0 - \ln N_t = kt$$

or $$\ln \frac{N_0}{N_t} = kt \qquad \text{----------- (5)}$$

or $$k = \frac{1}{t} \ln \frac{N_0}{N_t} \qquad \text{------------ (6)}$$

or $$k = \frac{2.303}{t} \log \frac{N_0}{N_t} \qquad \text{--------- (7)}$$

$(\because \ln x = 2.303 \log x)$

Equation (7) can also be written as

$$k = \frac{2.303}{t} \log \frac{a}{a-x} \qquad \text{--------- (8)}$$

Where a = Initial amount of radioactive substance

a-x = Amount of radioactive substance present at time t.

x = Amount of radiactive substance disintegrated

Equation (6) can also be written as

or $$\frac{N_0}{N_t} = e^{kt} \qquad \text{----------- (9)}$$

or $$\frac{N_t}{N_0} = e^{-kt} \qquad \text{---------- (10)}$$

or $$\boxed{N_t = N_0 e^{-kt}}$$

Half life ($t_{1/2}$)

The half life of a radioactive substance is the time in which half of the original substance disintegrates. Half life of a substance is independent of the amount of the radioactive substance present initially. It is a characteristic constant of a radioactive isotope.

Now. when $t = t_{1/2}$, $N_t = \frac{N_0}{2}$

put these values in equation (7)

$$k = \frac{2.303}{t_{1/2}} \log \frac{N_0}{N_0/2}$$

or $$k = \frac{2.303}{t_{1/2}} \times 0.3010$$

or $$\boxed{k = \frac{0.693}{t_{1/2}}} \qquad \text{---------------- (11)}$$

or $$\boxed{t_{1/2} = \frac{0.693}{k}}$$ - -------------- (12)

Equation (12) show that half life of radioactive substance depends upon the disintegration constant. and independent to the amount of the radioactive substance

Relationship between Amount of Radioactive Substance and Time

Amount of substance left after one half life = $\frac{N_0}{2} = \left(\frac{1}{2}\right)^1 N_0$

Amount of substance left after two half lives = $\frac{(N_0/2)}{2}$

$$\frac{N_0}{4} = \left(\frac{1}{2}\right)^2 N_0$$

Amount of sunstance left after three half lives = $\frac{(N_0/4)}{2} = \frac{N_0}{8} = \left(\frac{1}{2}\right)^3 N_0$

Thus

Amount of the substance left after n half lives = $\left(\frac{1}{2}\right)^n N_0$

$$\boxed{N_t = N_0\left(\frac{1}{2}\right)^n}$$

where N_0 = Initial amount

N_t = Amount of the substance left after n half lives

n = no. of half lives = $\frac{\text{Total time (t)}}{\text{Half life } (t_{1/2})}$

Activity of a Radioactive Substance

Number ot atoms (or no. of disintegration) disintegrated in unit time is called activity . It is also the rate of disintegration.

$\because$ Activity = Rate of disintegration = $-\frac{dN_t}{dt}$

$$-\frac{dN_t}{dt} = kN_t$$

But $k = \frac{0.693}{t_{1/2}}$

$$\text{Activity} = -\frac{dN_t}{dt} = \frac{0.693}{t_{1/2}} \times N_t$$

Specific Activity

The activity of a radioactive substance per gram or rate of disintegration per gram of the substance is called specific activity

Average Life (τ)

It is the reciprocal of decay constant (k)

$$\tau = \frac{1}{k} = \frac{1}{0.693/t_{1/2}}$$

or $$\tau = \frac{t_{1/2}}{0.693} = 1.44\, t_{1/2}$$

Units of Radioactivity

The rate of decay is expressed in terms of number of disintegrations per second i.e. the no. of atoms disintegrated in one second.

(1) The becquerel: The becquerel (Bq) is the Sl unit for measuring the number of radioactive disintegrations per second in a sample.

1Bq = 1 disintegration/second

(2) Rutherford (rd): It is the amount of radioactive aubstance which decay rate is 10^6 disintegration per second.

1rd = 10^6 disintegration per second

1 milli rutherford (1m rd) = 10^3 disintegration per second

1 micro rutherford (1 μ rd) = 1 disintegration per second

(3) Curie (Ci): A curie is the amount of a sunstance which undergoes 3.7×10^{10} disintegration per second. One curie is the decay rate of 1g of radium, equal to 3.7×10^{10} disintegration per second

1 Ci = 3.7×10^{10} disintegration per second

= 3.7×10^{10} Bq

1 milli curie (1m Ci) = 3.7×10^{7} disintegration per second

1 micro curie (1 μ Ci) = 3.7×10^{4} disintegration per second

Radioactive Equilibrium

In a disintegration series, these are some intermediates between starting element and the last stable isotope. A stage is reached when the rate of disintegration of the intermediates becomes equal.

Consider the following disintegration series:

$$\ldots A \longrightarrow B \longrightarrow C \ldots$$

A, B and C are intermediates between starting element and stable isotope

$$-\frac{dN_A}{dt} = -\frac{dN_B}{dt} = -\frac{dN_C}{dt}$$

$$-\frac{dN_A}{dt} = k_A N_A, \qquad -\frac{dN_B}{dt} = k_B N_B, \qquad -\frac{dN_C}{dt} = k_C N_C$$

Hence $k_A N_A = k_B N_B = k_C N_C$

Hence $\frac{N_A}{N_B} = \frac{k_B}{k_A} = \frac{(t_{1/2})_A}{(t_{1/2})_B} = \frac{\tau_A}{\tau_B}$

Where N_A, N_B and N_C are the number of atoms of A, B and C

k_A, k_B and k_C are the decay constant of A, B and C

$(t_{1/2})_A$, and $(t_{1/2})_B$ are half lives of A and B respectively.

τ_A and τ_B are the average llives of A and B.

Example. 1. after 24 hours, only 0.125 g out of the initial quantity of 1g of a radioisotopie remains behind. What is its half-life period?

Solution $N_0 = 1g, N_t = 0.125g$

$$N_t = \frac{N_o}{2^n}$$

$$0.125 = \frac{1}{2^n} \text{ or } 2^n = 8 = 2^3$$

$$n = 3. \text{ But } n = \frac{\text{Total time}}{t_{1/2}}$$

$$t_{1/2} = \frac{\text{Total time}}{n} = \frac{24}{3} = 8 \text{ hrs}$$

Example (2) The half-life period of $_{53}I^{125}$ is 60 days. What percentage of the original radioactivity would be present after 180 days?

Solution

$t_{1/2} = 60$ days, $\quad$ t = 180 days

$$n = \frac{\text{Total time (t)}}{\text{Half} - \text{life period } (t_{1/2})} = \frac{180}{60} = 3$$

$N_t = \frac{N_0}{2^n}$

$$N_t = \frac{N_0}{2^3} = \frac{1}{8} N_0 = \frac{1}{8} \times 100\%$$

= 12.5 %

Example (3): Half-life period of a radioactive element is 100 seconds. Calculate the disintegration constant and average life period. How much time it take for 90% decay?

Solution: $t_{1/2} = 100\ s$

$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{100\ s}\ 0.00693\ s^{-1}$

Average-life period, $\tau = \frac{1}{k} = \frac{1}{0.00693\ s^{-1}} = 144.3$ s

For 90% decay, $\frac{N_0}{N_t} = \frac{100}{100-90} = \frac{100}{10} = 10$

$t = \frac{2.303}{k} \log \frac{N_0}{N_t} = \frac{2.303}{0.00693\ s^{-1}} \log 10$

= 332.3 s

Example (4): The half-life of cobalt-60 is 5.26 years. Calculate the percentage activity remaining after 4 years.

Solution: $t_{1/2} = 5.26$ years

$k = \frac{0.693}{5.26}\ \text{years}^{-1}$

t = 4 years

$$k = \frac{2.303}{t} \log \frac{a}{a - x}$$

We get, $\frac{0.693}{5.26}\ \text{yr}^{-1} = \frac{2.303}{4\ \text{yr}} \log \frac{a}{a-x}$

or $\quad \log \frac{a}{a-x} = 0.2288$

$\frac{a}{a-x}$ = Antilog 0.2288 = 1.693

or $\frac{a-x}{a} = \frac{1}{1.693} = 0.59$

∴ % age activity = 0.59 × 100= 59%

Example (5) The activity of 1 gram of radium is found to be 0.5 curie. Claculate the half-life period of radium and the time required for the decay of 2 gram of radium (atomic mass of radium = 226)

Solution No of atoms present in 1g of ^{226}Ra = $\frac{6.02 \times 10^{23}}{226}$

Activity i.e $-\frac{dN}{dt}$ = 0.5 curie

= 0.5 × 3.7 × 10^{10} disinteg/sec

= 1.85 × 10^{10} disinteg/sec

$$\boxed{-\frac{dN}{dt} = kN}$$

= 1.85 × 10^{10} = k × $\frac{6.02 \times 10^{23}}{226}$

= k = 6.945 × 10^{-12} s^{-1}

$$t_{1/2} = \frac{0.693}{k} = \frac{0.693}{6.945 \times 10^{-12}\ s^{-1}}$$

= 9.978 × 10^{10} s

$$= \frac{9.978 \times 10^{10}}{3600 \times 24 \times 365} \text{ year}$$

= 3164 years

Time required for decay of 2 g of Ra to 0.25g = three half-lives = 3 × 3164 = 9492 years

Example (6) It is found that 3.125 × 10^{-8} gram-atom of Rn exists in equilibrium with 1 g of radium at 0°C and 1 atm pressure. The disintegration constant of Ra 1.48 × 10^{-11} sec^{-1}. Calculate the disintegration constant of Rn

Solution No. of g atom of ^{226}Ra in 1 g of ^{226}Ra = $\frac{1}{226}$ = 4.425 × 10^{-3}

At equilibrium, $k_A N_A = k_B N_B$

$$k_{Rn} \times N_{Rn} = k_{Ra} \times N_{Ra}$$

$$\frac{k_{Rn}}{k_{Ra}} = \frac{N_{Ra}}{N_{Rn}}$$

$$k_{Rn} = \frac{N_{Ra}}{N_{Rn}} \times k_{Ra}$$

$$\frac{4.425 \times 10^{-3}}{3.125 \times 10^{-8}} \times 1.48 \times 10^{-11}\ s^{-1}$$

$$= 2.095 \times 10^{-6}\ s^{-1}$$

Radioactive Disintegration Series

When a radioactive element emits an α or β-particle a new element is formed. The element emitting α- or β- particle is called parent element and the new element formed is called daughter element. If the daughter element is radioactive, it again disintegrates by emitting α or β-particle formig a new element. Thus, a daughter element becomes a parent element and a new element is formed. This process of disintegration goes on till the end product is a stable element (an isotope of lead or bismuth).

The series of spontaneous changes that take place starting from the parent element upto the formation of stable isotope is called radioactive series

There are four radioactive series:

(1) 4n series (Thorium series)

(2) (4n + 1) series (Neptunium series)

(3) (4n + 2) series (Uranium series)

(4) (4n + 3) series (Actinium series)

Series	Name of the series	Starting Element	Stable and product	Value of n for the starting element	Value of n for the sable and product
4n	Thorium series	Th–232	Pb–208	58	52
4n + 1	Naptunium series	NP–237	Bi–209	59	52
4n + 2	Uranium series	U–238	Pb–206	59	51
4n + 3	Actinium series	U–235	Pb–207	58	51

Nuclear Transmutation

Nuclear transmutation is the change of one element into another

Types of Nuclear Transmutation

(1) Natural Transmutation

(2) Artifical Transmutaion

(1) Natural Transmutation

The radioactive element emit α or β -particle and a new element is formed. This process is called natural transmutation. This process is spontaneous.

(2) Artifical Transmutaion

The process of converting one element into the other by artificial means, i.e., by bombarding the atom with high speed (or high energy) particle such as proton, neutron or α-particle is called artifical Transmutaion

The first nuclear transmutation was accomplished in 1917 by Rutherford, who bombarded ^{14}N nuclei with α-particles and found that ^{17}O was produced

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$$

Synthesis of new Elements

Other nuclear transmutations can lead to the synthesis of entirely new elements never before seen on earth. Infact, all transuranium element—Those elements with atomic number greater than 92 have been produced by bombardment reactions. Plutonium, for example, can be made by bombardment of uranium–238 with α-particles.

$$^{238}_{92}U + ^{4}_{2}He \longrightarrow ^{241}_{94}Pu + ^{1}_{0}n$$

The plutonium-241 that results form uranium–238 bombarment is itself radioactive with half life of 14.4 days, decaying by β-emission to yield americiam-241. Americiam-241 is also radioactive, decaying by α-emission with a half life of 432 years.

$$^{241}_{94}Pu \longrightarrow ^{241}_{95}Am + ^{0}_{-1}e$$

$$^{241}_{95}Am \longrightarrow ^{237}_{93}Np + ^{4}_{2}He$$

Other Example

(a) Synthesis of Curium:

$$^{239}_{94}Pu + ^{4}_{2}He \longrightarrow ^{242}_{96}Cm + ^{1}_{0}n$$

(b) Sunthesis of Cf:

$$^{242}_{96}Cm + ^{4}_{2}He \longrightarrow ^{244}_{98}Cf + 2^{1}_{0}n$$

(c) Synthesis of ^{60}Co:

$$^{58}_{26}Fe + 2^{1}_{0}n \longrightarrow ^{60}_{27}Co + ^{0}_{-1}e$$

Nuclear Reactions

When a bombarding particle (projectile) comes in close with the nucleus being hit, the incident particle and the target nucleus form a composite system and after a short while reaction takes place. Since in such a reaction nucleus of the target is changed into new nucleus, hence it is called a nuclear reaction. These reactions follow laws of converation as given below.

(i) Law of conservation of mass and energy: The total energy (rest energy and kinetic energy) of a particle before and after the reaction remains the same.

Since mass changes into energy ($E = mc^2$), hence during nuclear reactions, energy and mass are interconvertible quantities inside

(ii) Law of conservation of mass number: The total number of nucleons (mass number) before and after the reaction is conserved.

(iii) Law of conservation of atomic number: The total charge (atomic number) before and after the reaction is conserved.

Such reaction are usually represented by the following notation (called **Bethe's notation**).

Target nucleus (bombarding particle i.e. projectile, particle emitted) product nucleus.

For Example:

$$_7N^{14}\ (\alpha, p)\ _8O^{17}$$

Similary, Al^{27} (α, p) Si^{30} denotes that aluminium-27 is a target, α-particle is a projectile, proton is the ejectile (i.e.particle emitted) and silicon-30 is the product.

Differrent Types of Nuclear Reactions

(i) α-particle induced reactions:

Two types of reactions are observed, one involving the ejection of a proton and the other that of a neutron e.g.

(a) $_2He^4 + {}_7N^{14} \longrightarrow {}_8O^{17} + {}_1H^1$ ....(α, p)

(b) $_2He^4 + {}_4Be^9 \longrightarrow {}_6C^{12} + {}_0n^1$ ....(α, n)

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(ii) Neutron induced reaction: Four types of reactions are observed. One example of each type is given below.

(a) $^{1}_{0}n + ^{27}_{13}Al \longrightarrow ^{27}_{12}Mg + ^{1}_{1}H$ ....(n, p)

(b) $^{1}_{0}n + ^{16}_{8}O \longrightarrow ^{13}_{6}C + ^{4}_{2}He$ ....(n, α)

(c) $^{1}_{0}n + ^{23}_{11}Na \longrightarrow ^{24}_{11}Na + \gamma$ ....(n, γ)

(d) $^{1}_{0}n + ^{39}_{19}K \longrightarrow ^{38}_{19}K + 2^{1}_{0}n$ ....(n, 2n)

(iii) Proton induced reaction: Four types of disintegrations take place as follows:

(a) $_1H^1 + _4Be^9 \longrightarrow _3Li^6 + _2He^4$ ....(p, α)
α–Particle

(b) $_1H^1 + _4Be^9 \longrightarrow _4Be^8 + _1D^2$ ....(p, d)
(deutron)

(c) $_1H^1 + _4Be^9 \longrightarrow _5B^{10} + \gamma$ ....(p, γ)
γ–radiation

(d) $_1H^1 + _{20}Ca^{44} \longrightarrow _{21}Sc^{44} + _0n^1$ ....(p, n)
neutron

(iv) Deuterium induced reactions: A few example of this types are as follows:

(a) $^{2}_{1}D + ^{209}_{83}Bi \longrightarrow ^{210}_{83}Bi + ^{1}_{1}H$ (proton) ....(d, p)

(b) $^{2}_{1}D + ^{27}_{13}Al \longrightarrow ^{25}_{12}Mg + ^{4}_{2}He$ (α-paticle) ....(d, α)

(c) $^{2}_{1}D + ^{27}_{13}Al \longrightarrow ^{28}_{14}Si + ^{1}_{0}n$ (neutron) ....(d, n)

A few examples of artificail disintegration by high energy γ-radiations have also been reported

for example

$^{2}_{1}H + \gamma \longrightarrow ^{1}_{1}H + ^{1}_{0}n$ ....(γ, n)

$^{9}_{4}Be + \gamma \longrightarrow ^{8}_{4}Be + ^{1}_{0}n$ .... (γ, n)

The reactions as given above are either capture reactions or particle –particle reactions. capture reations are those reactions in which the bombarding particle is absorbed by the nucleus and no massive particle is emitted except the product nucleus and γ-radiation e.g (n, γ) and (p. γ) given above belong to this catagory.Particle-particle reactions are those reactions in which in addition to product nucleus, a massive particle is also liberated. These are the most common types of nuclear reactions. Besides these, we also have **fission reactions, spallation reactions and fusion reaction**

Artificial Radioactivity

The process of converting of a stable nucleus by bombarding it with projectile such as α-particle, neutron proton, deutron etc, into radioactive nucleus is called artifical radioactivity or induced radioactivity.

Examples.

(1) When aluminium is bombarded with α-particle, radioactive isotope ($^{30}_{15}P$) is formed which decays spontaneously with the emission of positron, $^{0}_{+1}e$

$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow \underset{\text{Radioactive isotope}}{^{30}_{15}P} + ^{1}_{0}n$$

$$^{30}_{15}P \longrightarrow ^{30}_{14}Si + \underset{\text{Positron}}{^{0}_{+1}e}$$

(2) When $^{10}_{5}B$ is bombarded with α-particle, $^{13}_{7}N$ is formed which is radioactive. $^{13}_{7}N$ decays spontaneously with the emission of positron.

$$^{10}_{5}B + ^{4}_{2}He \longrightarrow \underset{\text{Radioactive}}{^{13}_{7}N} + ^{1}_{0}n$$

$$^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{+1}e$$

(3) When $^{27}_{13}Al$ is bombarded with neutron, radioactive $^{24}_{11}Na$ is formed. $^{24}_{11}N$ decays spontaneously with the emission of β-particle.

$$^{27}_{13}Al + ^{1}_{0}n \longrightarrow \underset{\text{Radioactive}}{^{24}_{11}Na} + ^{4}_{2}He$$

$$^{24}_{11}Na \longrightarrow ^{24}_{12}Mg + \underset{\text{β-particle}}{^{0}_{-1}e}$$

A few example of the bombardment reactions leading to the formation of radioactive isotope are given below:-

(i) Those involving bombardment with α-particles, e.g.,

$${}_{2}^{4}He + {}_{12}^{24}Mg \longrightarrow {}_{14}^{27}Si + {}_{0}^{1}n$$

Radioactive

$${}_{14}^{27}Si \longrightarrow {}_{13}^{27}Al + {}_{+1}^{0}e$$

stable positron

$${}_{2}^{4}He + {}_{5}^{10}B \longrightarrow {}_{7}^{13}N + {}_{0}^{1}n$$

Radioactive

$${}_{7}^{13}N \longrightarrow {}_{6}^{13}C + {}_{+1}^{0}e$$

stable positron

(ii) Those involving bombardment with protons,e.g.,

$${}_{1}^{1}H + {}_{6}^{12}C \longrightarrow {}_{7}^{13}N$$

Radioactive

$${}_{7}^{13}Na \longrightarrow {}_{6}^{13}C + {}_{+1}^{0}e$$

stable positron

(iii) Those involving bombarding with deuterons, e.g.,

$${}_{1}^{2}D + {}_{11}^{23}Na \longrightarrow {}_{11}^{24}Na + {}_{1}^{1}H$$

Radioactive

$${}_{11}^{24}Na \longrightarrow {}_{12}^{24}Mg + {}_{+1}^{0}e$$

stable positron

(iv) Those involving bombarding with neutrons, e.g.,

$${}_{0}^{1}n + {}_{13}^{27}Al \longrightarrow {}_{11}^{24}Na + {}_{2}^{4}He$$

Radioactive

$${}_{11}^{24}Na \longrightarrow {}_{12}^{24}Mg + {}_{+1}^{0}e$$

stable positron

Nuclear Fission

Nuclear fission was discoverd by **Otto Hahn** and **Strassmann** in 1939

The splitting of a heavier nucleus into two smaller fragments with the bombardment of slow moving neutrons is called Nuclear fission.

Energy released in this process is called nuclear energy.

The fission of a nucleus does not occur in exactly the same way each time: more than 100 different fission pathways have been identified for uranium-235, yielding more than 200 different fission products. One of the more frequently occurring pathways generates barium-142 and krypton-91, along with two additional neutrons plus the one neutron that initiated the fission:

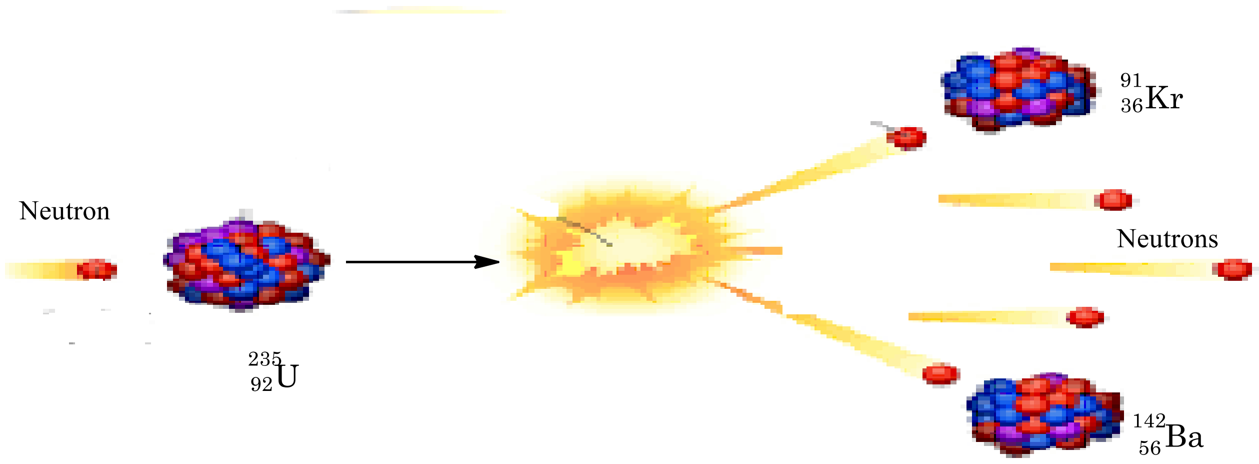
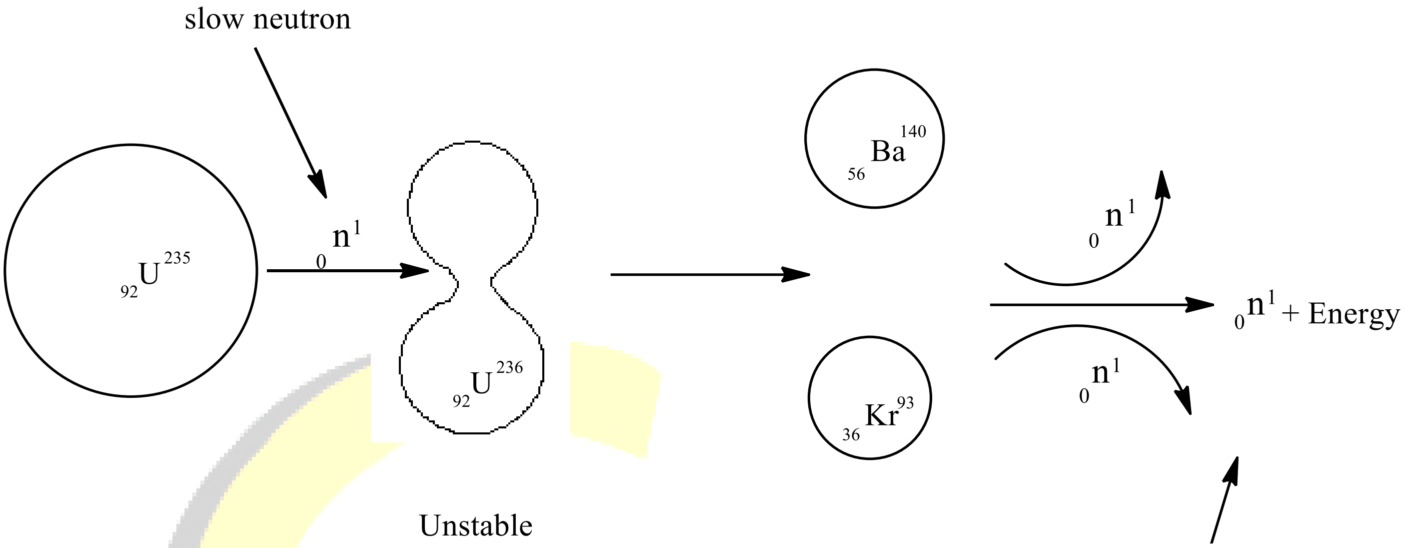


Figure: representation of nuclear fission. A uranium-235 nucleus fragments when struck by a neutron, yielding two smaller nuclei and realeasing a large amount of energy

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3\,^{1}_{0}e$$

The three neutrons released by fission of ^{235}U nucleus can induce three more fissions yielding nine neutrons, which can induce nine more fissions yielding 27 neutrons, and so on indefinitely. The result is a **Chain reaction** that continues to occur even, if the supply of neutrons from outside is cut off. If the sample size is small, many of the neutrons escape before initiating additional fission events, and the chain reaction soon stops. If there is a sufficient amount of ^{235}U, though-an amount called the **critical mass-**enough neutrons remain in the sample for the chain reaction to become self-sustaining. At some point, the chain reaction may even occur so rapidly that a nuclear explosion result. For ^{235}U, the critical mass is about 56 kg, altthough the amount can be reduced to 15 kg by placing a coating of ^{238}U around the ^{235}U to reflect back some of the escaping neutrons.



An aspect which is extremely important for a chain reaction to continue is that the fissionable material (uranium-235) must have a minimum size. If the size is smaller than this minimum size, the neutrons escape from the sample without hitting the nucleus and causing fission and thus the chain reaction stops.

The minimum mass which the fissionable material must have so that one of the neutrons released in every fission hits another nucleus and causes fission so that the chain reaction continues at a constant rate is called **critical mass**. If the mass is less than the critical mass, it is called **sub-critical**. If the mass is more than the critical mass, it is called **super-critical**. In this case many of the neutrons released in every fission are able to hit the other nuclei and thus the number of fission multiply in the chain reaction.

A difficulty that arises with the use of U-235 is that the naturally occurring uranium contains mostly U-238 isotope (about 99.3%) which is not fissionable with the slow neutrons an the separation of U-235 from U-238 is extremely difficult.

The tremendous amount of energy relesed, if uncontrolled, can be used for destructive purposes e.g., in the formation of an atomic bomb. However, if the chain reaction is controlled, the energy released can be used for constructive purposes, e.g., in the **nuclear reactor**. The principle of each of these devices is briefly explained below:

Example How much energy (in kJ/mol) is released by the fission of uranium-235 to form barium-142 and krypton-91? The fragment masses ^{235}U (235.0439 amu), ^{142}Ba(141.9164) ^{91}Kr (90.9234 amu), and n*(1.00866 amu)

Solution First calculate the mass change by subtracting the masses of the products from the mass of the ^{235}U reactant.

Mass of ^{235}U	= 235.0439 amu
Mass of ^{142}Ba	=-141.9164 amu
Mass of ^{91}Kr	=-90.9234
Mass of 2 n = - (2) (1.00866 amu)	= 02.0173
Mass change	= 0.1868amu (or 0.1868g/mol)

$$\Delta E = \Delta mc^2$$

$$= \left(0.1868\ \frac{g}{mol}\right)\left(1 \times 10^{-3}\frac{kg}{g}\right)\left(3.00 \times 10^{8}\ \frac{m}{s}\right)^2$$

$$= 1.68 \times 10^{13} kg.m^2/(s^2.mol) = 1.68 \times 10^{10} kJ/mol$$

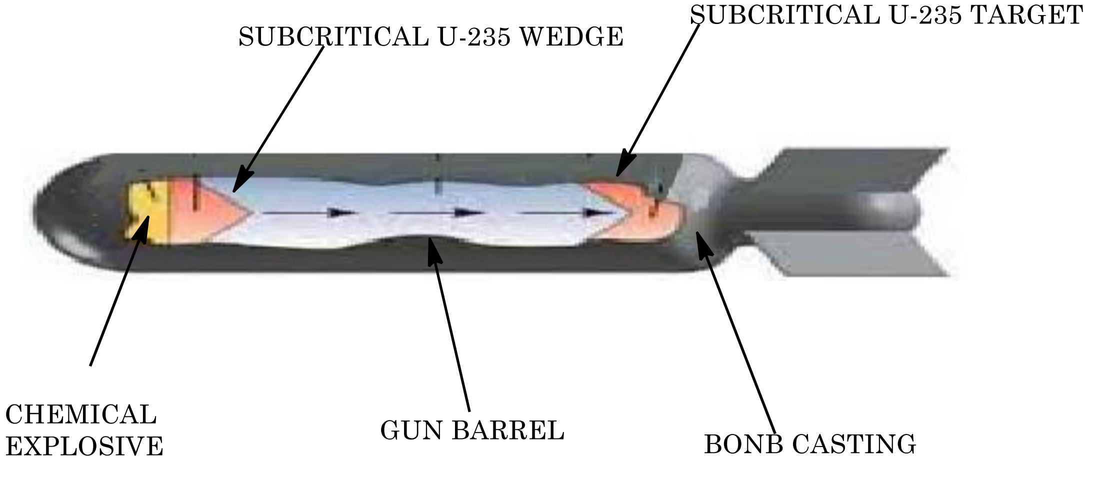
Nuclear fission of 1 mol of ^{235}U realeases 1.68×10^{10}kJ

Problem: An alternate pathway for the nuclear fission of ^{235}U produces tellurium-137 and zirconium-97. How much energy (in kJ/mol) is released in this fission pathway?

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{137}_{52}Te + ^{97}_{40}Zr + 2^{1}_{0}n$$

The masses are ^{235}U (235.0439 amu), ^{137}Te(136.9254 amu), ^{97}Zr(96.9110amu) and n (1.00866 amu)

1. <u>Atomic Bomb</u>: A simple design of an atomic bomb is shown in following fig.



Pricipally, it contains two pieces of U-235 (or plutonium 239) each of sub-critical mass, one called the wedge and the other the target. A chemical explosive is packed at the back of the wedge which can push the wedge to the target and the two join together to form super-critical mass. The reaction is started by a slow neutron.

2. <u>Nuclear Reactor:</u> A nuclear reactor is an arrangement in which the energy produced (in the form of heat) in a nuclear fission can be used in a controlled manner to produce steam which can run the turbine and produce electricity.

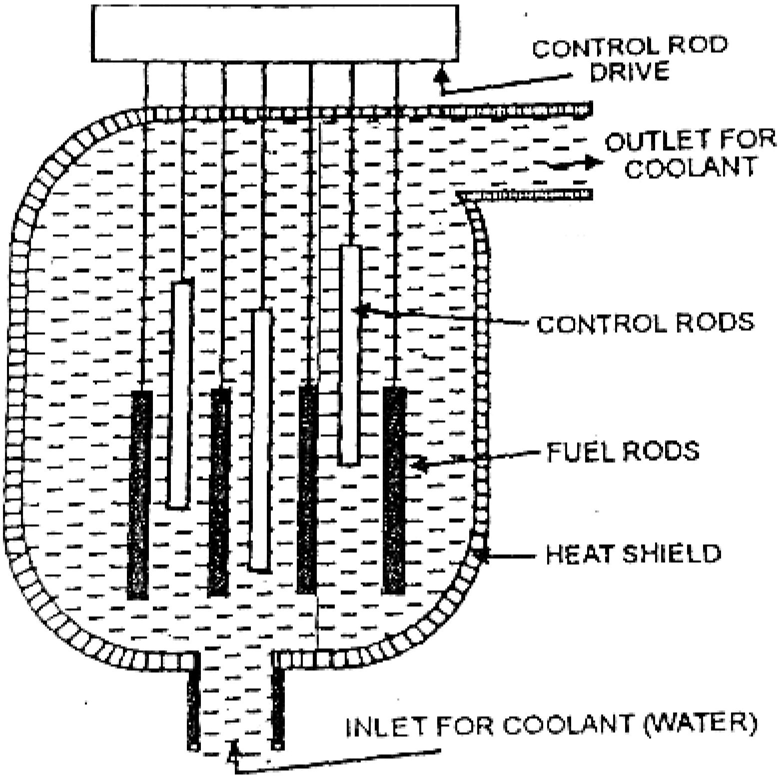
The energy can be controlled by controlling the nuclear fussion which, in turn, can be controlled by controlling the number of neutrons released during the fission.

To control the number of neutrons, advantage is taken of the fact that cadmium and boron can absorb neutrons to form the corresponding isotopes which are not radioactive i.e

$$_{48}Cd^{113} + {}_0n^1 \longrightarrow {}_{48}Cd^{114} + \gamma$$

$$_5B^{10} + {}_0n^1 \longrightarrow {}_5B^{11} + \gamma$$

The main part of the nuclear reactor is the reactor core.



It consists essentially of following parts

(1) <u>Fuel rods:</u>

The fissile (fissionable) material used in the reactor is called **Fuel**. The fuel used is *enriched* Uranium-235 (in the form of U_3O_8). This is obtained from the naturally-occurring U–235 (containing about 0.7% of U–235) by raising the percentage of U–235 to about 2–3%. The solid fuel is made into the form of rods or pellets, shielded by placing them in stanless steel tubes.

(2) Control rods:

To control the fission process, rods made of cadmium or boron are suspended between the fuel rods. These rods can be raised or lowered and control the fission process by absorbing neutrons. That is why they are called 'control rods'.

(3) Moderator:

The neutrons produced in the fission have to be slowed down to speeds at which they are easily captured by the fuel so that the fission process can take place most efficiently. This is done by surrounding the fuel rods with heavy water (D_2O). The meterial thus used to slow down the neutrons (without absorbing them) is called a 'moderator'. Graphite is also a good moderator.

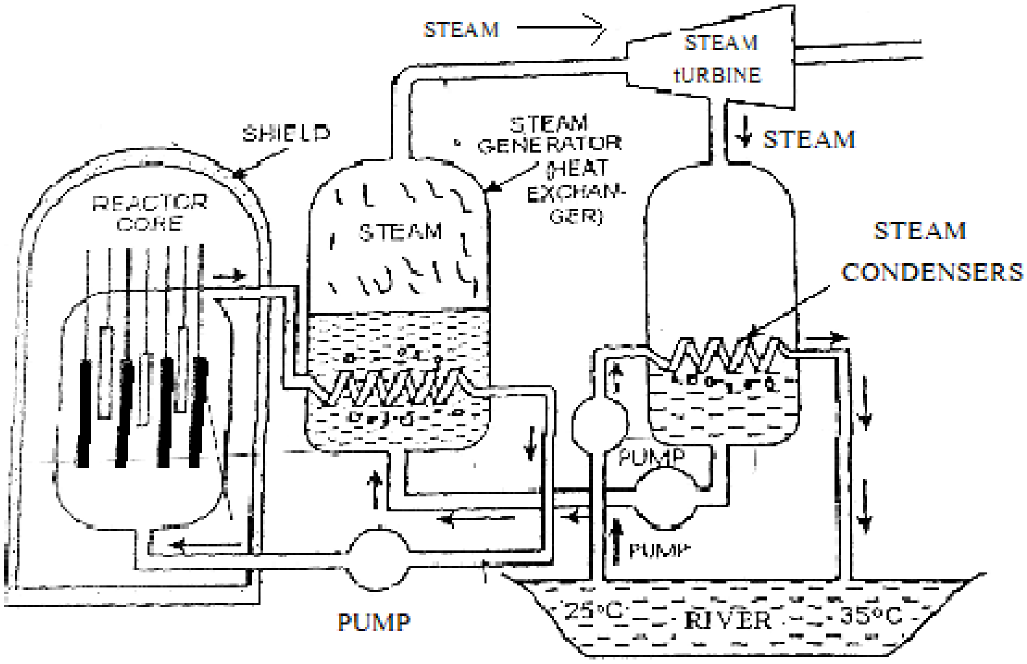
(4) Coolant:

To carry away the heat produced during fission, a liquid is circulated in the reactor core. This liquid enters the base of the reactor core and leaves at the top. The heat carried by the outgoing liquid is used for producing steam. As a result, the liquid cools down and the is pumped back to the base of the reactor core. The liquid thus used is called a ''coolant''. Usually the coolant used is heavy water so that is also acts as a moderator.

(5) Shield

To prevent the losses of heat and to protect the persons operating the reactor from the radiation and heat, the entire reactor core is enclosed in a heavy steel or concrete dome, called the 'Sheild'.

The complete design of a power plant is shown in following fig.



The steam after driving the turbine has to be condensed. For this purpose additional cooling water is needed. This is usually obtained from a large source such as river or lake which has flowing water. This is essential because it is evident that after condensing the steam, the water is returned to the source at a higher temperature. Thus a complete nuclear power plant consists essentially of the following four parts.

(i) Reactor core

(ii) Steam generator (Heat exchange)

(iii) Steam turbine

(iv) Steam condensing system

The desing of a thermal power plant is exactly similar except that in place of reactor core there is arrangement for producing heat by burning coal.

Breeder Reactor:

It may be mentioned that the rate at which U–235 is being used up to produce power, the stocks are likely to exchaust very soon. Scientist have, therefore been actively engaged in investigating other fissionable material. They have found plutonium-239 and uranium–233 to be quit suitable. These are produced by bombardment of more abundantly available U-238 and Th-232 with neutrons. Scientists have been, therefore, trying to build reactors in which the neutrons produced from fission of U-235 are partly used up carrying on the fission U–235 and partly to produce Pu–239 or U-233. Such reactors would produce more fissionable material (as Pu–239 or U–233) than they consume (as U–235). These reactors have been named as **Breeder reactors**. The first such reactor began operation in 1972 in Russia

The sequence of reactions that take places when $_{92}U^{238}$ is bombarded with fast neutrons producing the fissionable nuclei of plutonium–239 may be represented as follows:

$$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} \longrightarrow {}_{93}Np^{239} + {}_{-1}e^{0}$$

$$_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + {}_{-1}e^{0}$$

$$_{94}Pu^{239} + {}_{0}n^{1} \longrightarrow \text{Fission products} + 2 \text{ or } 3\ {}_{0}n^{1} + \text{Energy}$$

Similarly, the fissionable isotope of uranium $^{233}_{92}U$ is produced form the naturally occurring abundant isotope of thorium, $^{232}_{90}Th$ as follows:

$$^{232}_{90}Th + {}^{1}_{0}n \longrightarrow {}^{233}_{90}Th \xrightarrow{-\beta} {}^{233}_{91}Pa \xrightarrow{-\beta} {}^{233}_{92}U$$

In breeder reactors, the coolant used is an alloy of sodium and potassium which is in the moten state and transfers heat to water in the steam generator (heat exchange)

India is the first country in the Asian region to use uranium-233, a man made fissionable material derived from thorium, as a fuel in the 30 MW Kalpakkam mini reactor, Kamini (On Oct 29, 1996)

The nuclides such as U–238 and Th–232 which can be converted into fissioable nuclides are called **Fertile nuclides** whereas nuclides such as U–235, Pu–239 which are fissionable are called **Fissile nuclides.**

Spallation Reactions

There is another category of nuclear reactions, called **spallation reactions** which are similar to fission reactions. They differ in the fact that they are brought about by high energy bombarding particles or photons. Due to high energy, a large number of particle are emitted from the target nucleus and the product nucleus has mass number and atomic number much less than the target nucleus. For example, When U^{238} is bombarded with α-particles having energy equal to 400 MeV, it releases 6 protons and 13 neutrons, forming $^{225}_{88}Ra$ as the product nucleus i.e. the reaction is

$$^{238}_{92}U\ (\alpha, 6p, 13n)\,^{225}_{88}Ra$$

Nuclear Fusion

This is opposite to nuclear fission.

Nuclear fusion is a process in which lighter nuclei fuse together to form a heavier nucleus.

Since the nuclei coming together experience strong forces of repulsion, the process of fusion can take place at extremely hogh temperature (>10^6 K). Such reactions are therefore, called thermonuclear reactions

In fact it's just such a fusion reaction of hydrogen nuclei to produce helium that powers our sun and other stars, Among the processes thought to occur in the sun are those in the following sequence leading to helium–4

$${}_1^1\text{H} + {}_1^1\text{H} \longrightarrow {}_1^2\text{H} + {}_1^0\text{e}$$

$${}_1^1\text{H} + {}_1^2\text{H} \longrightarrow {}_2^3\text{He}$$

$${}_2^3\text{He} + {}_2^3\text{He} \longrightarrow {}_2^4\text{He} + 2{}_1^1\text{H}$$

$${}_2^3\text{He} + {}_1^1\text{H} \longrightarrow {}_2^4\text{He} + {}_1^0\text{e}$$

The main appeal of nuclear fusion as a power souce is that the hydrogen isotopes used as fuel are cheap and plentiful and the fusion products are nonradioactive and nonpolluting. The technical problems that must be solved before achieving a practical and controllable fusion method are staggering, however. Not the least of the problems is that a temperature of approximately 40 million kelvins is needed to initiate the fusion process.

Hydrogen Bomb

It is based on nuclear fusion reaction. Deuterium and tritium are used in the construction of hydrogen bomb. A very high temperture (> 10^6 K) is required to start the nuclear fusion reaction. This high temperature is provided by nuclear fission reactions. In this bomb any amount of the reactant can be used,

Following reactions occurs in hydrogen bomb.

$${}_1^2\text{H} + {}_1^2\text{H} \longrightarrow {}_1^3\text{H} + {}_1^1\text{H} + 4\text{ MeV}$$

$${}_1^2\text{H} + {}_1^3\text{H} \longrightarrow {}_2^4\text{He} + {}_0^1\text{n} + 17.6\text{ MeV}$$

$${}_1^3\text{H} + {}_1^3\text{H} \longrightarrow {}_2^4\text{He} + 2{}_0^1\text{n} + 11\text{ MeV}$$

Though the energy libreated per fusion is smaller than the energy liberated perfission of U–235 (which is about 200 MeV), yet the hydrogen bomb is a much more powerful (1000 times) than the atom bomb. Reason behind these are.

(1) The masses per atom of deuterium and tritium are much smaller than that of uranium.

(2) There are no restrictions of critical masses for fusion process to occur.

Difference between Nuclear Fission and Nuclear Fusion

S.No	Nuclar Fission	Nuclear Fusion
1. 2.	It involves breaking up of a heavier nucleus into lighter nuclei.	It involves union of two or more lighter nuclei to form a heavier nucleus.

3.	It is a chain process.	It is not chain process.
4.	It is initated by neutrons of suitable energy and does not need high temperature.	It is initiated by very high temperature–a few million degree.
5.	It can be controlled and the energy released can be harnessed for useful purposes.	It is difficult to control this process.
6.	Large number of radioisotopes are formed and there is nuclear waste.	There is no nuclear waste in this process.
	It require minimum size of fissionable material and if the size of the material exceeds the critical size, the reaction becomes explosive.	There is no limit to the size of the fuel for the reaction to start. However, the fuel does not undergo fusion until heated to a very high temperature–a few million degrees.

Difference between Chemical and Nuclear Reaction

S.No	Chemical Reaction	Nuclear Reaction
1.	In these reactions, only the electrons of the outer most shells of the atoms are involved.	In these reaction, the nuclei of the atoms are involved.
2.	Here some bonds are broken and the some new bonds are formed	They do not involve any breaking or making of bonds.
3.	In such reactions, the energy may be evolved or absorbed.	In such reactions, energy is always evolved.
4.	The energy envolved or absorbed is not very high.	In some nuclear reactions, the energy envolved is very high (may be million times greater than those in ordinary chemical reactions)
5.	The speeds of these reactions are affected by temperature, pressure etc.	The speeds of these reactions are not affected by temperature, pressure etc.
6.	These reactions may be reversible in some cases	These reactions are irreversible

Applications of Radioactivity and Radioisotopes

(A) In medicinal Diagnosis

(1) By adding traces of a suitable radioisotope to a particlar food, it is possible to find out to which parts of the body the food is reaching.

(2) Metastable technetium ${}^{99}_{48}Tc$ is used in the diagnosis and treatment of brain tumors.

(3) ${}^{32}_{15}P$ in the form of phosphate is used in diagnosis and treatment of blood disorders, bone cancer and to distinguish between cancer cells and their healthy neighbours.

(4) ${}^{24}_{11}Na$ is used to check the circulation of blood and in diagnosis of problems occur in blood clotting

(5) Radioisotopes of iodine (${}^{123}I$, ${}^{125}I$, ${}^{131}I$) are used in the diagnosis and treatment of diseases of thyroid glands.

(6) ${}^{60}_{27}Co$ used in the diagnosis and treatment of cancer

(7) ${}^{201}Tl$ is used in diagnosis and treatment of heart diseases

(8) ${}^{59}Fe$ is used in the diagnosis of anaemia.

(9) ${}^{51}_{24}Cr$ is used in tagging leucocytes and labelling of blood platelets.

(10) ${}^{90}_{24}Sr$ is used in the treatment of eye cancer of animals.

(11) ${}^{198}_{79}Au$ is used in the treatment of prostate and cervix uterine careinoma and bladder tumors

(2) <u>Radio Carbon Dating</u>

In radio carbon dating i.e. in predicting the age of a fallen tree or dead animal. The radio active isotope ${}_6C^{14}$ is produced in the atmosphere by the action of cosmic ray neutrons (present in the upper atmosphere) on ${}_7N^{14}$.

$$ {}_7N^{14} + {}_0n^1 \longrightarrow {}_6C^{14} + {}_1H^1 $$

The ${}_6C^{14}$ is oxidized to CO_2 and this radioactive CO_2 mixes with the non-radioactive CO_2. The radioactive carbon disappears through radioactive decay but it is also being formed constantly. Thus in the atmosphere, the radio of the radioactive carbon to non–radioactive carbon remsins almost constant.

The CO_2 of the atmosphere is absorbed by the plants through the process of photosynthesis and the ratio of radioactive carbon (${}_6C^{14}$) to ordinary carbon (${}_6C^{12}$) in plants that are alive and growing is the same as that in the atmosphere. As the plants are eaten by the animals, the ratio of ${}_6C^{14}$ to ${}_6O^{12}$ is same in animals as well. When a plant or animal dies, the amount of ${}_6C^{14}$ diminishes through radioactive decay and the loss is not made up by the assimilation, of the atmospheric CO_2. The ratio of ${}_6C^{14}$ to ${}_6C^{12}$ therefore decrease.

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

Knowing that the half–life period of $_6C^{14}$ is 5770 years, the age of the animal or the plant (i.e. the time since its death) can be calculated. For exmple if in an object the ration of $_6C^{14}$ to $_6C^{12}$ diminishes to half that of the atmosphere, the object is one half life i.e, 5770 years old

The age of plant or animal (the time since its death) can be calculated from the following formula

$$t = \frac{2.303}{k} \log \frac{N_0}{N_1}$$

where $t = \frac{0.693}{k}$

where k = disintegration constant of ^{14}C

$t_{1/2}$ = Half life of ^{14}C

t = age of animal or plant

N_0 = amount or activity of ^{14}C in the living animal or plant

N_1 = amount or activity of ^{14}C in old wood or animal fossil

Example. An old piece of wood has 25.6% as much C^{14} as ordinary wood today has. Find the age of the wood. Half life period of C^{14} is 5760 years

Solution. Suppose the amount of C^{14} present in the wood originally (i.e., the same which the wood today has) = N_0

Then the amount of C^{14} present now in the old wood (N_1) = $\frac{25.6}{100}$ a = 0.256 a

The time t in which C^{14} hanged from a to 0.256a will then be given by

$$t = \frac{2.303}{k} \log \frac{N_0}{0.265\ N_0}$$

$$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{5760}$$

$$= 1.203 \times 10^{-4}\ year^{-1}$$

$$t = \frac{2.303}{1.203 \times 10^{-4}} \log \frac{1}{0.256}$$

$$= 11329 \text{ years}$$

Problem: A sample of carbon derived from one of the dead sea scrolls is found to be decaying at the rate of 11.5 disintegration per min.per gram of carbon. Estimate the age of dead sea scrolls. $t_{1/2}$ for ^{14}C = 5568 yrs. Carbon from living plants disintegrates at the rate of 15.3 disintegration per minute per gram.

Solution:

$$k = \frac{0.693}{5568} = 1.244 \times 10^{-4}\ year^{-1}$$

$$= \frac{2.303}{1.244 \times 10^{-4}} \log \frac{15.3}{11.5}$$

$$= 2.3 \times 10^{3} \text{ yrs}$$