MBC - MRIDUL BHAIYA CLASSES

NUCLIE

BY MRIDUL BHAIYA

PHYSIC NOTES

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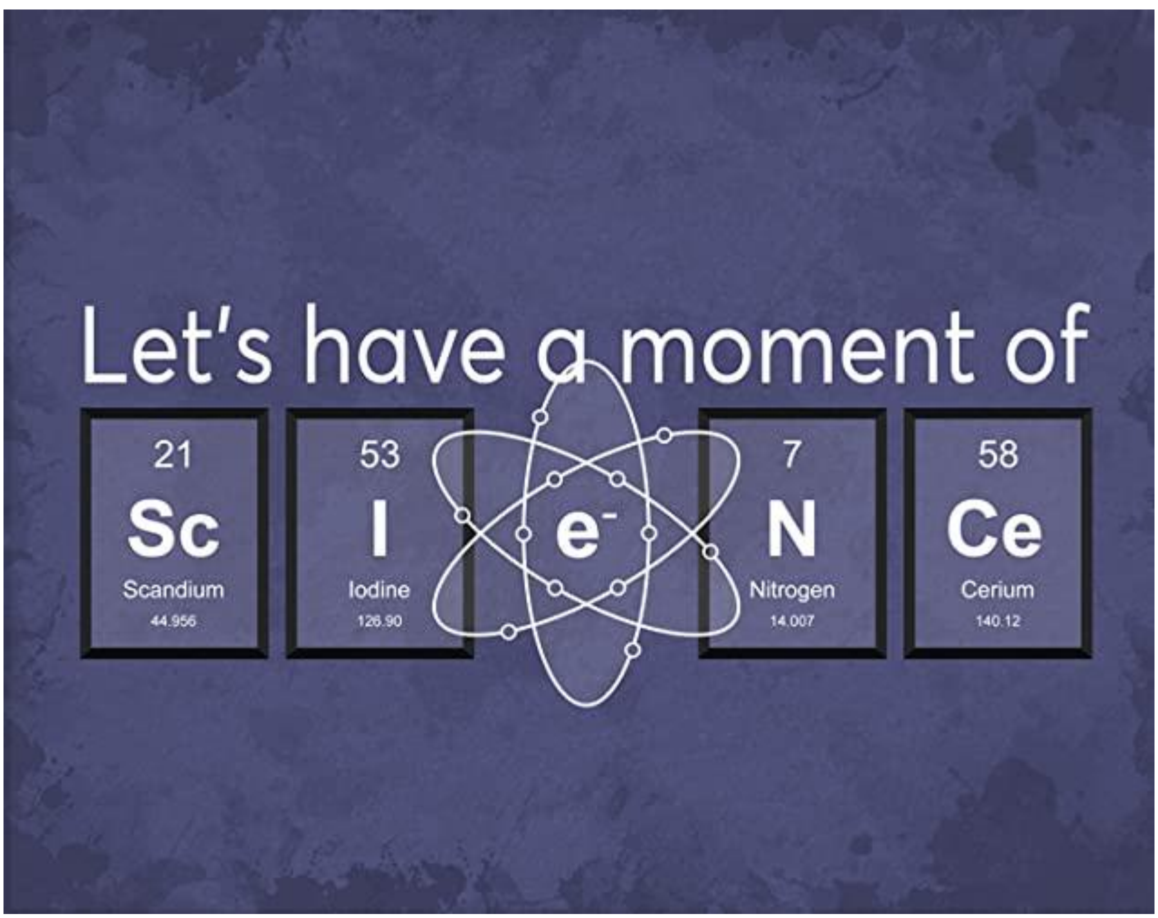
CLASS XII

PHYSICS NOTES

NUCLIE

✓ Detailed notes
✓ PYQs with answers
✓ Graphics included



NUCLIE

INTRODUCTION

In previous chapter we have learnt that :

- → Radius of a nucleus was smaller than the radius of an atom by a factor of about 10^4
- → Most of the space in atom is empty
- → Most of the mass (More than 99.9%) of atom is present at the centre.
- → Positive charge is present at the centre called **NUCLEUS.**

What are we going to learn :

❑ Does the nucleus have structure just as the atom does?

❑ What are the constituents of the nucleus ?

❑ How are these held together ?

❑ What is the mass of Nucleus ?

❑ What is the size of Nucleus ?

ATOMIC MASSES AND COMPOSITION OF NUCLEUS

Atomic masses are very small so it is not convenient to measure them in kg.

To measure atomic masses a new quantity is used called AMU (Atomic mass unit)

1 AMU (u)

This unit is the atomic mass unit (u), defined as $1/12^{th}$ of the same of the carbon (^{12}C)

$$1u = \frac{mass\ of\ one\ ^{12}_{6}C\ atom}{12}$$

$$= \frac{1.992647 \times 10^{-27}}{12}$$

$$= 1.660536 \times 10^{-27}$$

The atomic masses of most of the element is very close to integral multiple of mass of hydrogen atom.

❑ Why mass of chlorine atom is 35.46 u ?

The answer to this question is **ISOTOPES.**

Chlorine has two isotopes ^{35}Cl and ^{37}Cl whose mass is 34.98 u and 36.98 u repectively.

Chlorine has two isotopes ^{35}Cl and ^{37}Cl whose abundance are 75.4 % and 24.6 % repectively.

So mass of chlorine obtained is

$$= \frac{75.4 \times 34.98 \times 24.6 \times 36.98}{100}$$

= 35.47 u

ISOTOPES

Atomic species having same atomic number but different mass number are called isotopes.

For Example : Hydrogen has 3 Isotopes (Hydrogen, deuterium and tritium).

❑ Practically every element consists of mixture of several isotopes.

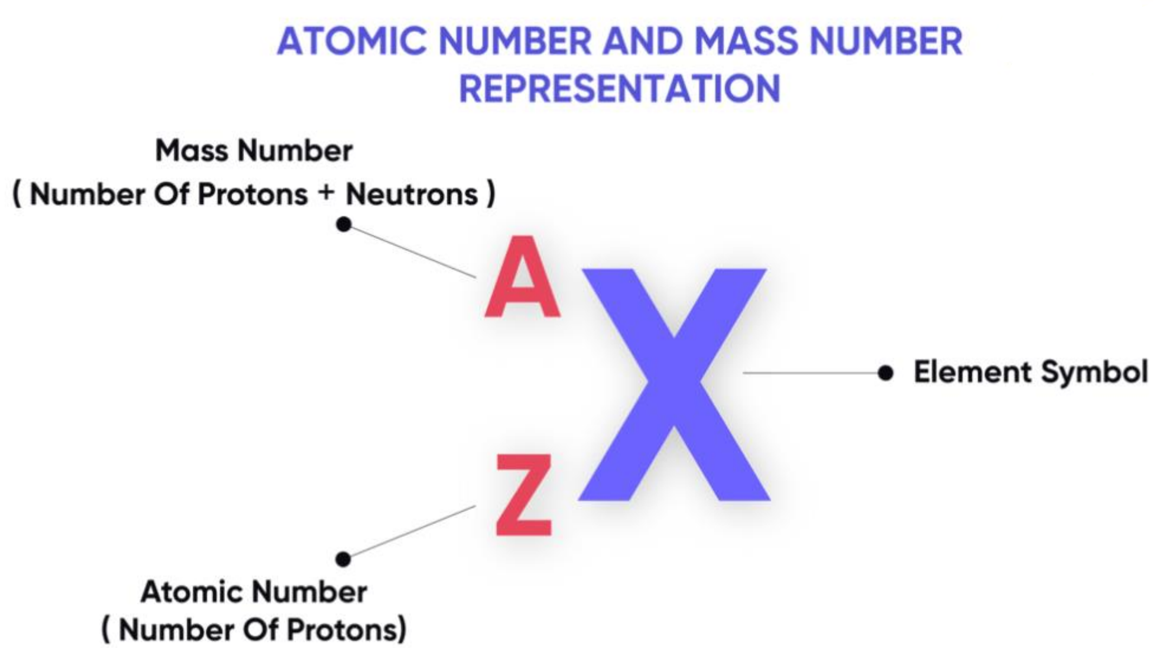
❑ The abundance of different isotopes differ from element to element.

❑ For example : Relative abundance of hydrogen is 99.985%

REPRESENTATION OF NUCLIE

ATOMIC NUMBER (Z)

Number of proton in the nuclues of atom represents atomic number.



For example : Atomic number of Hydrogen is 1 and Helium is 2.

MASS NUMBER (A)

Mass of protons + Number of Neutrons in the nuclues of the atom represents mass number.

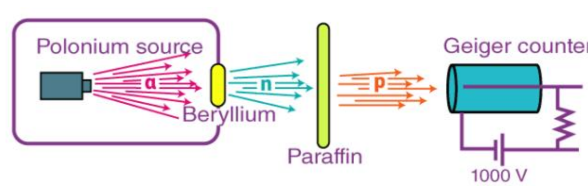
A (mass number) is always integer.

Atomic mass can be non- integer

For example : Mass number of Helium is 4

DISCOVERY OF NEUTRON

All the isotopes of hydrogen are having only one proton but mass of their nuclei are in the ration 1 : 2 : 3.



Discovery of neutron

From the above point it is obvious that there is something else present in the nucleus which is Neutral.

Mass of this neutral matter is approximately equal to mass of proton.

Mass of neutron = 1.00866u = 1.6749×10^{-27} kg.

Verification by JAMES CHADWICK

In 1932 he came up with a experiment in which he bombarded alpha-particles with beryllium nuclei and observe some neutral radiation emitted.

This neutral raditation is able to knock out from light nuclei.

Only neutral radiation known at that time was photons.

If the neutral radiation consists of photons the energy of photon would have to be much higher then the available from the bombardment of beryllium nuclei with alpha-particle.

Now it is assumed that the neutral raditation consists of new type of neutral particle called **NEUTRONS.**

COMPOSITION OF NUCLEUS

The compostion of a nucleus can now be described using the following terms and symbols.

Z $\rightarrow$ atomic number = number of protons

N $\rightarrow$ neutron number = number of neutrons

A $\rightarrow$ Mass number = Z + N = total number of protons and neutrons

Nucleons :

Since protons and neutrons are the constituents particle of nucleus so a new term for protons and neutrons is used called **NUCLEONS**

Number of nucleons in an atom is equal to mass number A

ISOBARS

All the elements having same mass number are called isobars.

For example : ${}^{14}_{6}C$ and ${}^{14}_{7}N$ are isobars

ISOTONES

Nuclides with same neutron number N but different atomic number Z

N = A – Z

For Example : ${}^{198}_{80}Hg$ and ${}^{197}_{79}Hg$ are called isotones.

SIZE OF NUCLEUS

Radius of Nuclei

It has been found that a nucleus of mass number A has a radius

R = $R_0 A^{1/3}$

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

Volume of Nuclei

V = $\frac{4\pi}{3} R^3$ $\qquad$ V ∝ A

V = $\frac{4\pi}{3} (R_0 A^{1/3})^3$

V = $\frac{4\pi}{3} R_0^3 A$

Density of Nuclei

Density = $\frac{Mass}{Volume}$

Density = $\frac{Au}{\frac{4\pi}{3} R_0^3 A}$

Hence Density of nucleus is independent of mass number

The density of nucleus is approximately 2.3×10^{17} Kg m^{-3}

Example : Given the mass of iron nucleus as 55.85u and A = 56, find the nuclear density?

Answer – 2.3×10^{17} Kg m^{-3}

MASS ENERGY

Eistein showed that mass is another form of energy.

One can convert mass-energy into other form of energy like kinetic energy etc.

Einstein gave famous mass-energy equivalent relation.

$E = mc^2$

Energy in nuclear reaction is conserved provided mass – energy is also included.

Example : Calculate the energy equivalent of 1g of substance.

$E = mc^2$

$$= \left[\frac{1}{1000}\right]\left[3\times10^{8}\right]^{2}$$

$$= \frac{9\times10^{16}}{10^{3}} = 9\times10^{13}\ J$$

Energy Equivalence of 1u :

Einstein showed that mass is another form of energy.

$1u = 1.6605 \times 10^{-27}$ kg

$E = 1.6605 \times 10^{-27}$ kg $\times c^2$

Einstein's mass – energy equivalence

$E=mc^2$

Big Idea

mass and energy are interconvertible

Einstein's equation relates rest mass to an equivalent energy

1 kg = c^2 J of energy (a lot!)

1 amu = 931.46 MeV = 0.93146 GeV of energy

E = 1.6605 × 10^{-27} kg × (3 × 10^8)^2

E = 1.4924 × 10^{-10} J

E = $\frac{1.4924 \times 10^{-10} \text{ eV}}{1.602 \times 10^{-19}}$

E = 931.5 MeV

1u = $\frac{931.5 \text{ MeV}}{c^2}$

NUCLEAR BINDING ENERGY

It is expected that mass of nucleus is equal to the total mass of its constituents particles i.e. protons and neutrons but in reality mass of the nucleus is less than that of mass of constituent particles.

Let's take example of $^{16}_{8}O$

Mass of 8 neutrons = 8 × 1.00866 u

Mass of 8 protons = 8 × 1.00727 u

Therefore the expected mass of $^{16}_{8}O$ nuclues = 8 × 2.01593 u = 16.12744 u

But actually mass of $^{16}_{8}O$ nuclues is found to be 15..99053 u which is 0.13691 u less than mass of constituent particles.

Why this mass difference ?

When the constituent particles combined to form stable nucleus, energy is released and this energy come from the mass defect

$$\boxed{\Delta M = [Zm_p + (A - Z)m_n] - M}$$

If one wants to break the oxygen nucleus into 8 proton and 8 neutrons this extra energy ΔMc^2 has to be supplied.

If certain number of neutrons and protons are brought together to form a nucleus of certain charge and mass, an energy E_b will be released in this process

The energy E_b is called the binding energy of nucleus.

Stability of nucleus

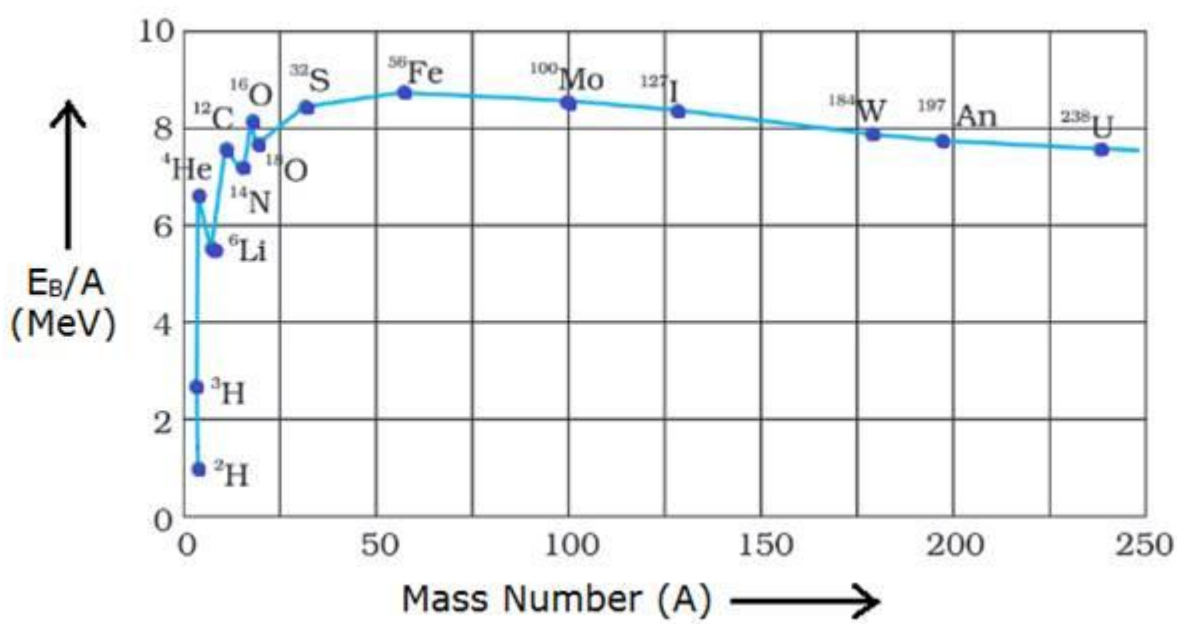
Nucleus having greater binding energy per nucleon is more stable.

$$\boxed{E_{bn} = E_0 / A}$$

Binding Energy per nucleus vs mass number graph

Observation

- Binding energy per nucleon is almost constant for middle mass number (30 < A < 170)



- Maximum B.E per nucleon is for A = 56
- E_{bn} is lower for both light nuclie (A < 30) and heavy nuclie (A > 170).

Conclusions

→ The force is attractive and sufficiently strong to produce a binding energy of a few MeV per nucleon.

→ Nuclear force is a short range force

→ When a heavy nuclie breaks into smaller stable nuclei (Nuclear fission) energy is released.

→ When two very light nuclei join together to form a heavy stable nuclei (Nuclear fusion) energy released.

NUCLEAR FORCE

Neutrons and protons are binded together by a very strong force which is attractive in nature.

This attractive force is strong enough to overcome the repulsion between protons

Nuclear force are much stronger than the Coulomb force acting between the charges.

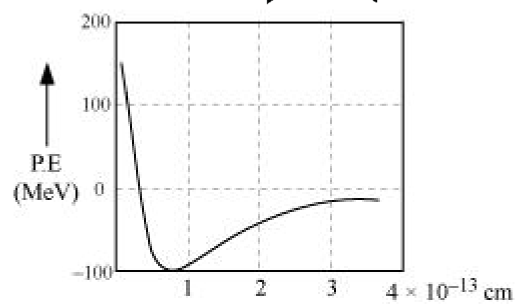
Nuclear force are short range forces

Nuclear forces between neutron-neutron, proton-proton, neutron-proton is approximately same.

Potential energy of a pair of nucleons as a function of their separation.

When distance between two nucleus is less than 0.8 fm than the nuclear force between then become repulsive

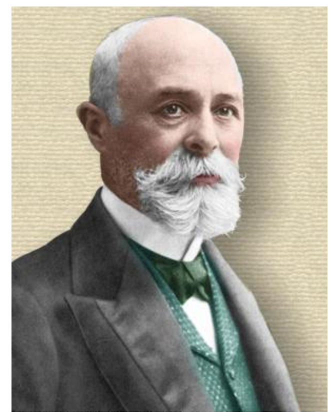
The potential energy is minimum is distance between the two nucleons is 0.8 fm.



Potential energy of a pair of nucleons as a function of their separation.

RADIOACTIVITY

In 1896 Radioactivity is discovered by Henri Becquerel accidently.

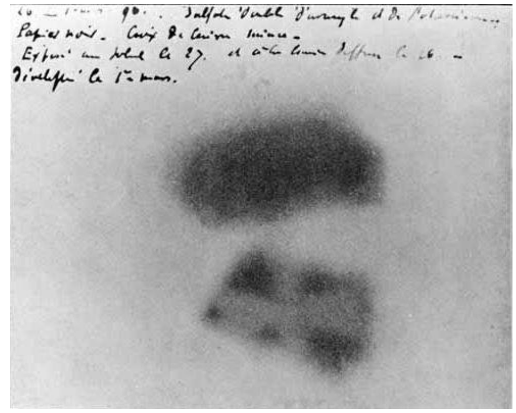


He accidentally placed a piece of uranium ore on the top of an unexposed photographic plate. Later, when the plate was developed, the image of the rock was found on the plate.

Radation coming from fluorescence and phosphorescence of compounds does not effect photographic plate.

Radiation coming from uranium potassium sulphate affects photographic plate.

Radioactive decay



Radioactivity is a nuclear phenomenon in which an unstable nucleus undergoes a decay.

This is referred to as radioactive decay. Three types of radioactive decay occur in nature :

→ α-decay in which a helium nucleus is emitted

→ β-decay in which a electrons or positrons is emitted.

→ γ- decay in which high energy (hundreds of keV or more) photons are emitted.

Law of radioactive decay

It is found that the number of nuclei undergoing the decay per unit time is proportional to the total number of nuclei in the sample

$$\boxed{\frac{\Delta N}{\Delta t} \propto N}$$

Where λ is called the radioactive decay constant or disintegration constant

$$\boxed{\frac{dN}{dt} = -\lambda N}$$

Derivation

$$\frac{dN}{dt} = -\lambda N$$

$$\frac{\mathrm{d}N}{N} = -\lambda \mathrm{d}t$$

Integrating both sides we get-

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{t_0}^{t} dt$$

$$\ln N - \ln N_0 = -\lambda (t - t_0)$$

Where N_0 is the number of radioactive nuclie in the sample arbitary time t_0 and N is the number of nuclie at any subsequent time t. For $t_0 = 0$

$$\ln \frac{N}{N_0} = -\lambda t$$

which gives

$$\boxed{N(t) = N_0 \, e^{-\lambda t}}$$

Activity

The total decay rate R of a sample is the number of nuclei disintegrating per unit time. Suppose in time interval dt, the decay count is ΔN. Then $dN = -\Delta N$. the positive R is defined as-

$$R = -\frac{dN}{dt}$$

Differentiating the expression for N(t), we get-

$$R = \lambda N_0 \, e^{-\lambda t}$$

$$\boxed{R = R_0 \, e^{-\lambda t}}$$

Also,

$$\boxed{R = \lambda N}$$

The SI unit for activity is Becquerel

1 becquerel is simple equal to 1 disintegration or decay per second.

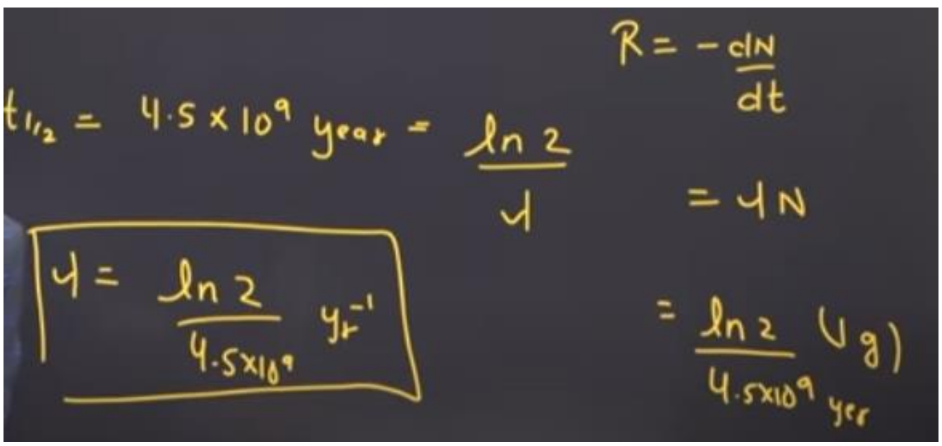
$$\boxed{\begin{aligned} 1 \text{ curie} = 1 \text{ Ci} &= 3.7 \times 10^{10} \text{ decays per second} \\ &= 3.7 \times 10^{10} \text{ Bq} \end{aligned}}$$

HALF LIFE

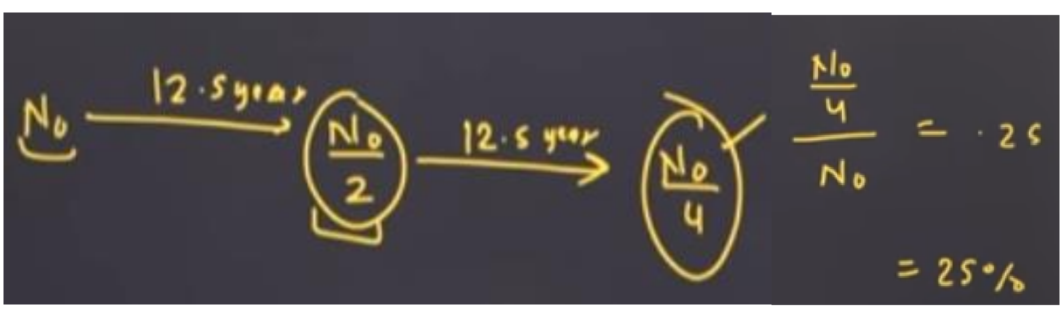
Half life of a radionuclide (denoted by $T_{1/2}$) is the time it takes for a sample that has initially, say N_0 radio nuclie to reduce to $N_0/2$ and t = $T_{1/2}$ in the equation, we get

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Example : The half life of $^{238}_{92}U$ undergoing α-decay is 4.5×10^9 years. What is the activity of 1g sample of $^{238}_{92}U$?



Example : Titium has a half-life of 12.5y undergoing beta decay. What fraction of a sample of pure tritium will remain undecayed after 25y.



MEAN LIFE / AVERAGE LIFE (τ)

Consider any arbitary time t. the number of nuclie which disintegrate in time interval from t to t + Δt will be -

$$R(t)\Delta t = \lambda N_0 e^{-\lambda t}\Delta t$$

And each of them has lived for time t so the total life would be

$= t\lambda N_0 e^{-\lambda t}$

Upon integrating, we get –

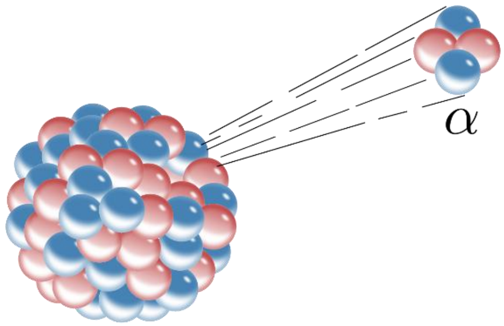
$\tau = 1/\lambda$

Therefore,

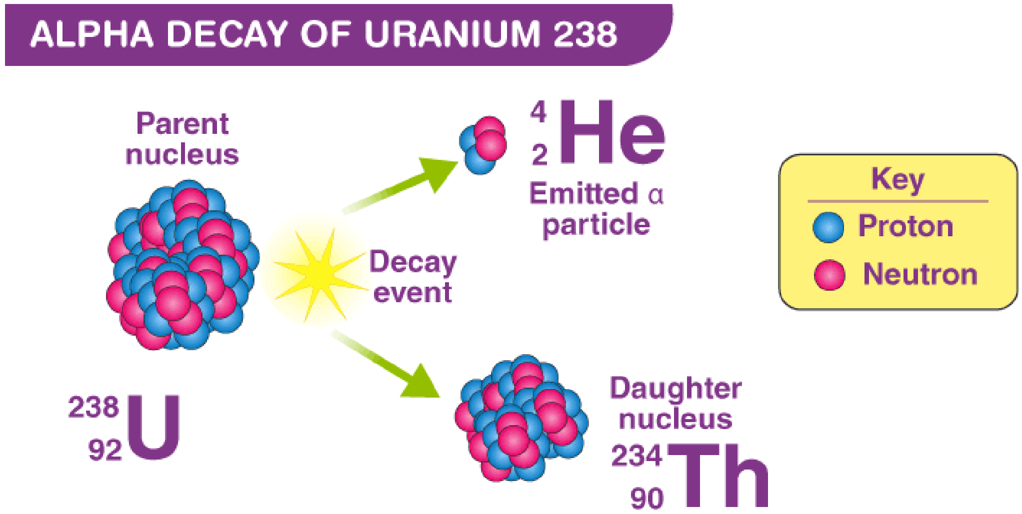
$$\boxed{T_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2}$$

ALPHA DECAY

In α-decay, the mass number of the product nucleus (daughter nucleus) is four less than that of the decaying nucleus (parent nucleus), while the atomic number decreases by two. In general, α-decay of parent nucleus $^{A}_{Z}X$ results in a daughter nucleus $^{A-4}_{Z-2}Y$



$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He}$$



Q – value of a nuclear reaction is the difference between the initial mass energy and the total mass energy of the decay products.

Q – value For Alpha Decay

$$Q = (m_X - m_Y - m_{He})\, c^2$$

→ For a spontaneous nuclear reaction mass of reactant is greater than the mass of decay products

→ If Q > 0 , then the process is exothermic

Example : We are given the following atomic masses

$^{238}_{92}U = 238.05079$ u $^{4}_{2}\mathrm{He} = 4.00260$ u

$^{234}_{90}\mathrm{Th} = 234.04363$ u $^{1}_{1}\mathrm{H} = 1.00783$ u

$^{237}_{91}\mathrm{Pa} = 237.05121$ u

Here the symbol Pa is for the element protactinium (z = 91).

a.) Calculate the energy released during the alpha decay of $^{238}_{92}U$

b.) Show that $^{238}_{92}U$ can not spontaneously emit a proton.

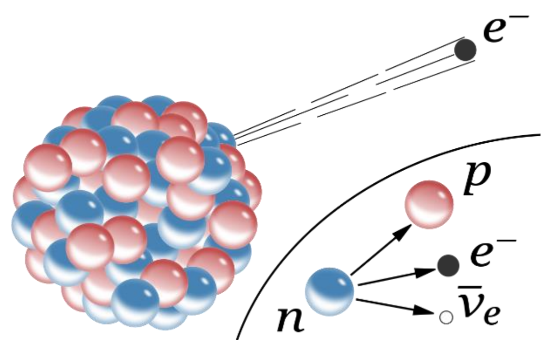
BETA DECAY

In beta decay, a nucleus spontaneously emits an electron (β^-decay) or a positron (β^+ decay).

β^-decay

when a neutron is converted into proton and electron with emission of antineutrino ($\bar{\nu}$)

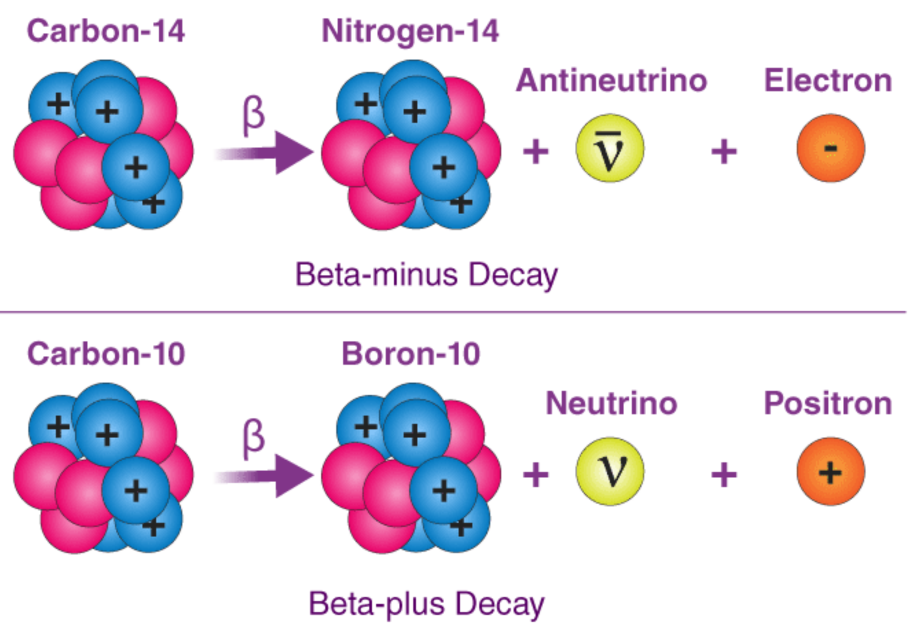
$$n \rightarrow p + e^- + \bar{\nu}$$



B^+decay

When a proton is converted into neutron and positron with emission of neutrino (ν)

$$p \rightarrow n + e^+ + \nu$$



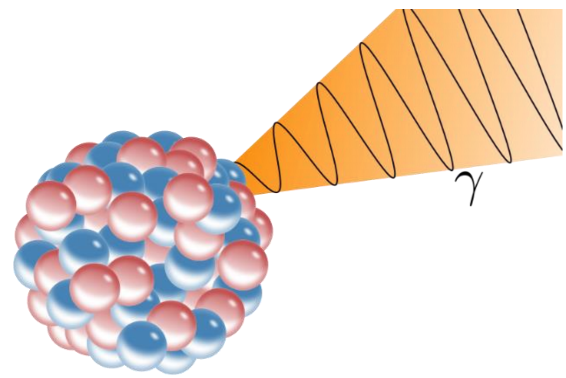
NEUTRINOS

→ Neutrinos are neutral particles with very small (possibly, even zero) mass compared to electrons

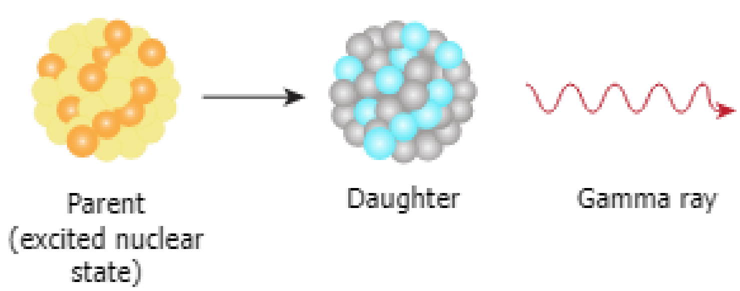
→ They have only weak interaction with other particles.

→ They are, therefore, very difficult to detect, since they can penetrate large quantity of matter (even earth) without any interaction.

GAMMA DECAY



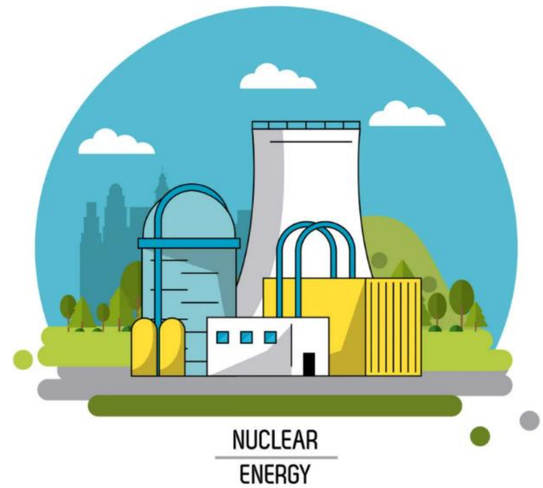
- ❖ A nucleus has discrete levels like an atom
- ❖ Energy of these level is although very high (is of order MeV)
- ❖ When a nucleus is in excited state spontaneously decays into its ground state, and a photon is released of energy equal to the energy gaps of two energy state
- ❖ This emission of photon is called **gamma decay**
- ❖ Typically a gamma rays is emitted when a α or β decay results in a daughter nucleus in an excited state.
- ❖ A familiar example is the successive emission of gamma rays of energies 1.17 MeV and 1.33 MeV from the de-exitation of ${}^{60}_{28}\mathrm{Ni}$ Nuclie formed from β^{-}decay of ${}^{60}_{27}\mathrm{Co}$.



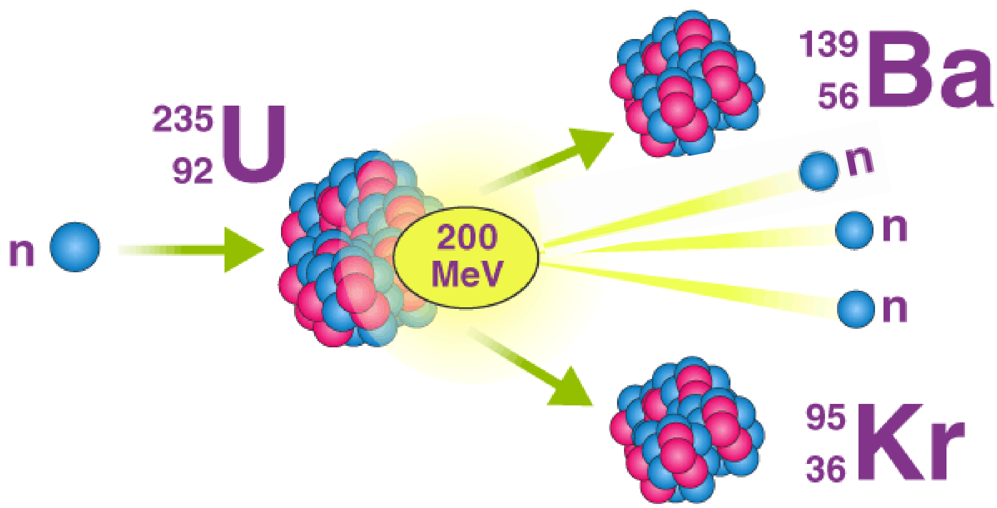
$${}^{Am}_{Z}X \longrightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma$$

NUCLEAR ENERGY

- When a heavy nuclei (A > 170) decay into small stable nuclei than binding energy is released
- When two small nuclie fuse together to form a heavy stable nuclie energy is released
- Energy released in nuclear reaction is very high (is of orfer MeV).



NUCLEAR FISSION



NUCLEAR FISSION

- An example of fission is when a uranium isotope ${}^{238}_{92}U$ bombarded with a neutron breaks into two intermediate mass nuclear fragments

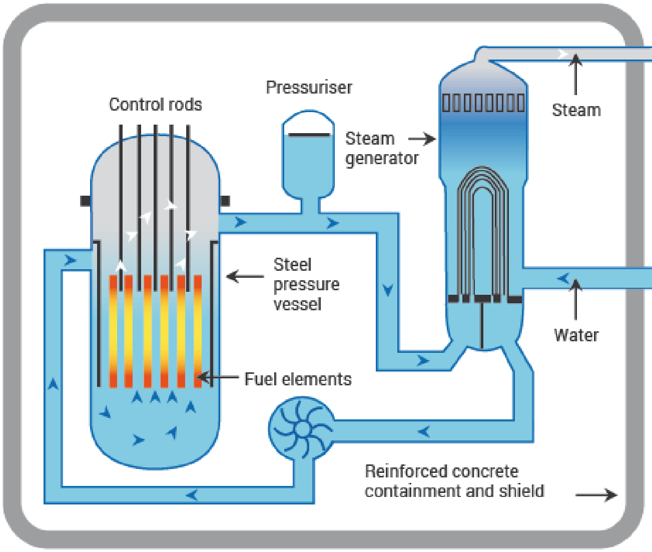
$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{235}_{92}U \rightarrow {}^{144}_{56}Ba \rightarrow {}^{89}_{36}Kr + 3\,{}^{1}_{0}n $$

- ❖ The energy released (the Q value) in the fission reaction of nuclei like uranium is of the order of 200 MeV per fissioning nucleus.
- ❖ The same reaction can produce other pairs of intermediate mass fragments

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{133}_{51}Sb \rightarrow {}^{99}_{38}Nb + 4{}^{1}_{0}n$$

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{140}_{54}Xe \rightarrow {}^{94}_{38}Sr + 2{}^{1}_{0}n$$

NUCLEAR REACTOR



- ❖ In fission reaction on an average 2.5 neutrons are released per reaction with huge amount of energy.
- ❖ These released neutrons further react with nuclear substance and further release new neutrons and a chain reaction is initiated
- ❖ This is what happened in **Nuclear Reactor**
- ❖ If the chain reaction is uncontrolled then it leads to explosive energy, this is what happened in **Nuclear Bomb.**
- ❖ In nuclear reactor controlled chain reaction take place.

Component of Nuclear Reactor

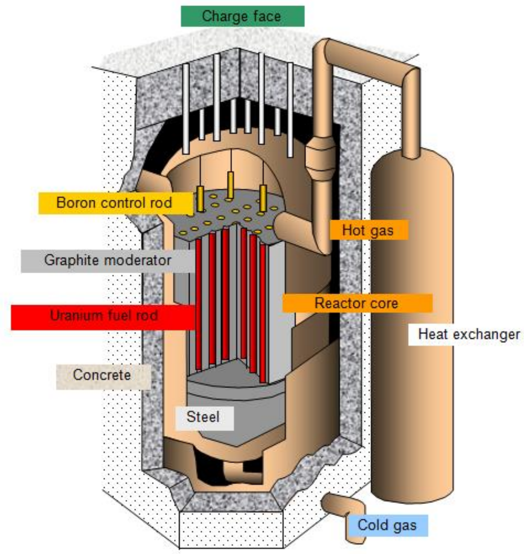
- Core
- Fuel Rods
- Control Rods
- Moderator

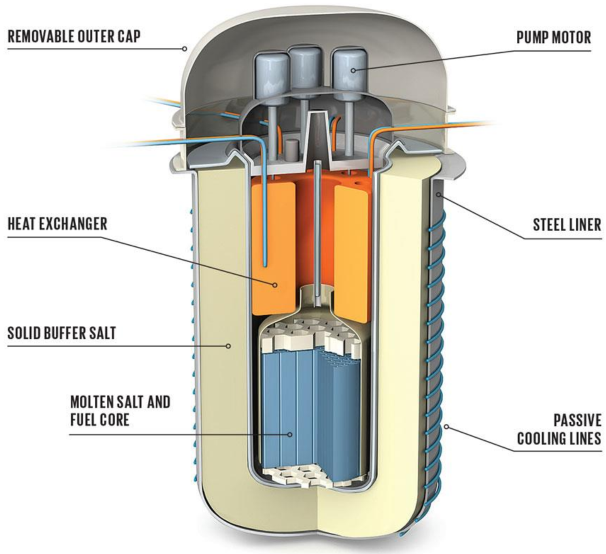
CORE

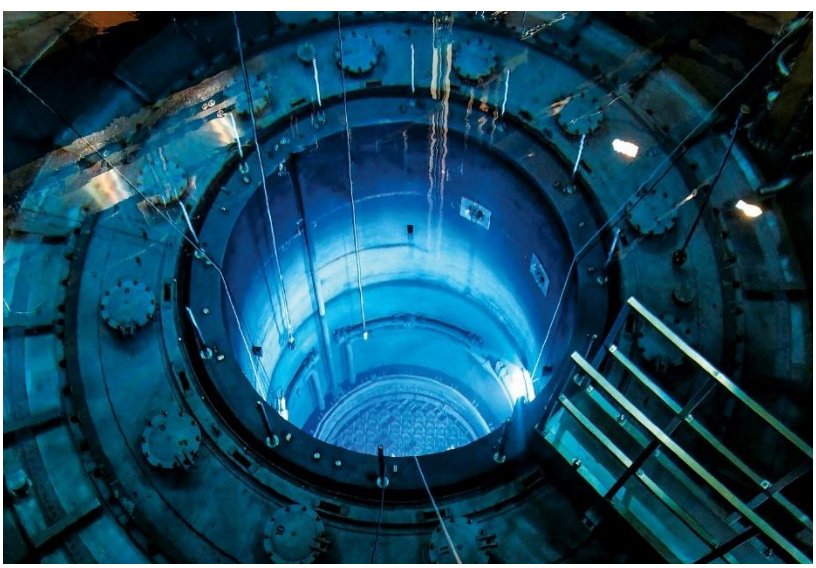
→ It contains the fuel elements

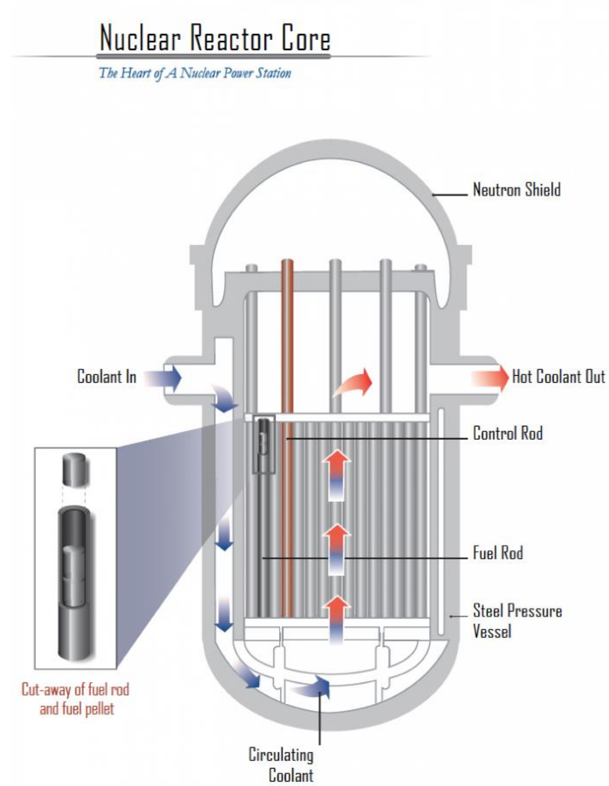
→ The core contains a moderator to slow down the neutrons.

→ The core is surrounded by a reflector to reduce leakage.

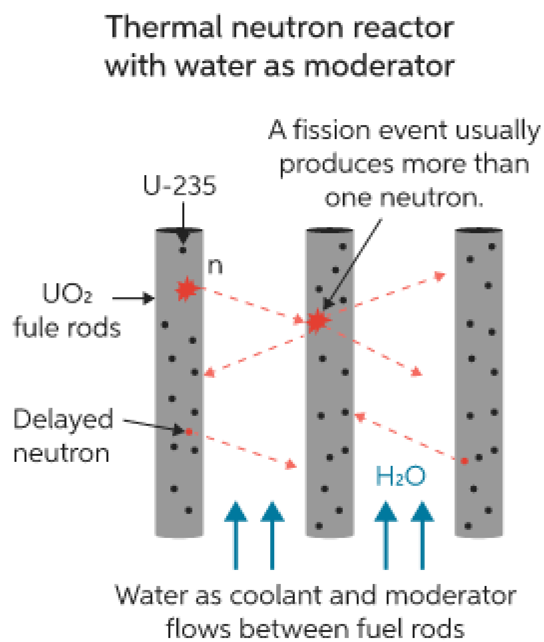








MODERATOR



→ Experimentally it is observed that slow neutrons are able to cause fission in $^{238}_{92}U$ than fast neutron

→ To sloe down the neutrons **Moderators** are used.

→ The moderators commonly used are water, heavy water and graphite.

MULTIPLICATION FACTOR

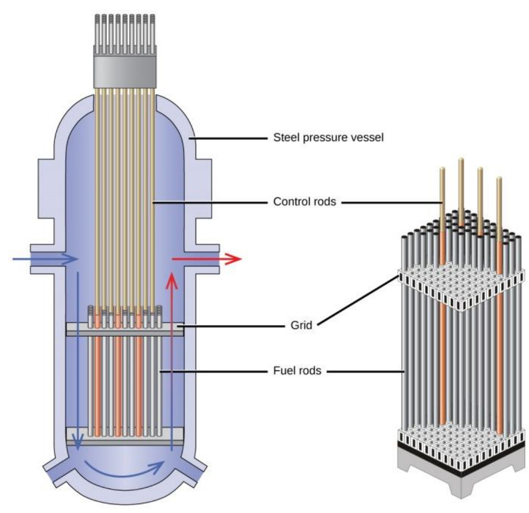
❖ $K = \frac{\text{number of neutron generated in } n^{th} \text{ reaction}}{\text{number of neutron generated in } (n\text{-}1)^{th} \text{ reaction}}$

❖ For K = 1, the operation of the reaction is said to be critical which is what we wish it to be for steady power operation.

❖ For K > 1, the reaction rate and reactor power exponentially high and it becomes super critical and can even explode.

CONTROL RODS

→ The reactor can be shut down by means of rods (made of cadmium) that have high absorpotion of neutrons



NUCLEAR FUSION

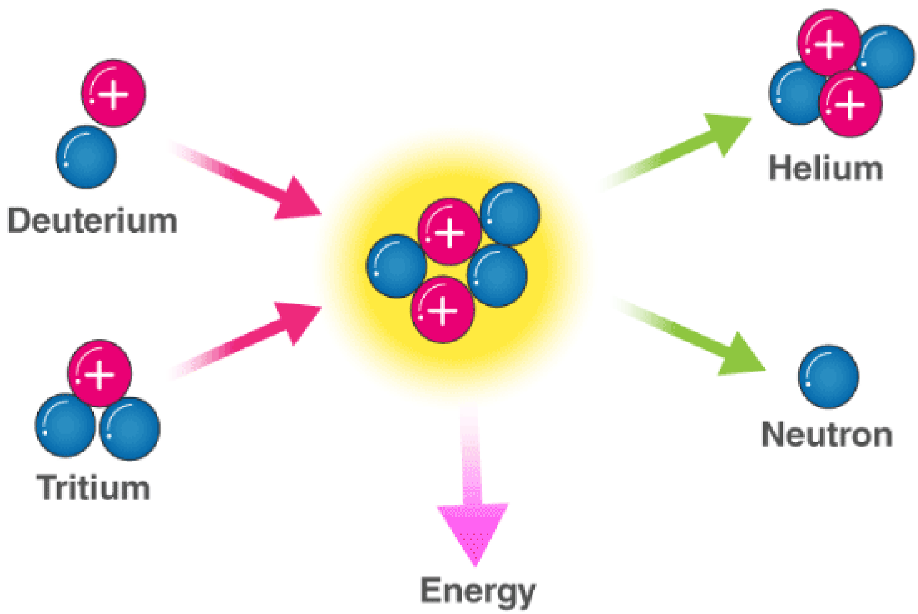
When two light nuclie fuse to form a larger stable nuclei then energy is released and this process is known as **Nuclear Fusion**

For example :

$$ {}_1^1H + {}_1^1H \rightarrow {}_1^2H + {}_1^2H + e^+ + \nu + 0.42\ MeV $$

$$ {}_1^2H + {}_1^2H \rightarrow {}_2^4He + n + 3.27\ MeV $$

$$ {}_1^2H + {}_1^2H \rightarrow {}_1^3H + {}_1^1H + 4.03\ MeV $$



Nuclear fusion

→ For fusion to take place the two nuclei must come close enough to overcome the repulsion between nucleons

→ The heught of the barrier depends on the charges and radii of the two interacting nuclei.

→ For example, that the barrier height for two protons is ~400 keV and is higher for nuclei with higher charges

→ Estimated temperature required for two protons to combined is nearly 3×10^9 K

Thermonuclear Fusion

When fusion is achieved by raising the temperature of the system so that particles have enough kinetic energy to overcome the coulomb repulsive behaviour, it is called Thermonuclear Fusion.

Energy in Sun

The fusion reaction in the sun is a multi-step process

$$ {}_1^1H + {}_1^1H \rightarrow {}_1^2H + {}_1^2H + e^+ + \nu + 0.42\ MeV \qquad ..(i)$$

$$ e^+ + e^- \rightarrow \gamma + \gamma + 1.02\ MeV \qquad ..(ii)$$

$$ {}_1^2H + {}_1^1H \rightarrow {}_2^3He + \gamma + 5.49\ MeV \qquad ..(iii)$$

$$ {}_2^3He + {}_2^3He \rightarrow {}_2^4He + {}_1^1H + {}_1^1H + {}_1^1H + 12.86\ MeV \qquad ..(iv)$$

For the fourth reaction to occur, the first three reactions must occur twice, in which case two light helium nuclei unite to form ordinary helium nucleus. If we consider the combination 2(i) + 2(ii) + 2(iii) + (iv), the net effect is

$$ 4{}_1^2H + 2e^- \rightarrow {}_2^4He + 2\nu + 6\gamma + 26.7\ MeV $$

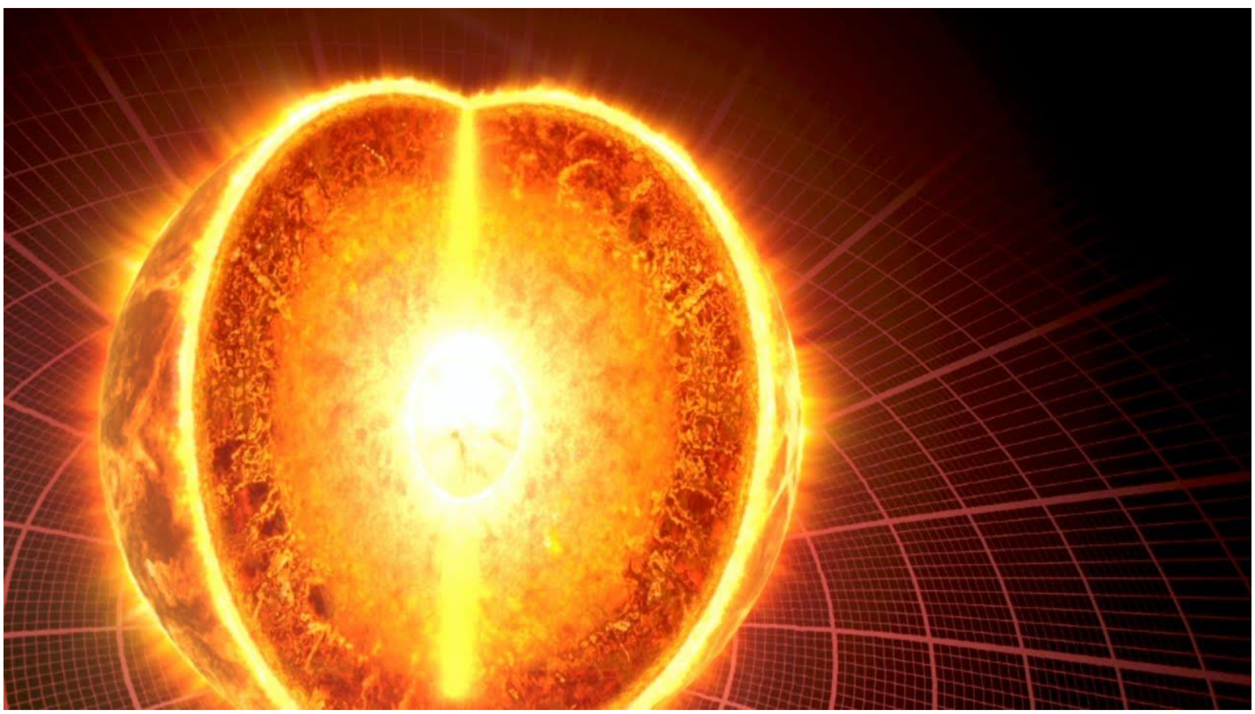
Thus, four hydrogen atoms combine to form ${}_2^4He$ atom with a release of 26.7 MeV of energy.

INTERESTING FACTS

- ❖ As the hydrogen in the core gets depleted and becomes helium, the core starts to cool.
- ❖ There is enough hydrogen in the sun to keep it going for another 5 billion years

CONTROLLED THERMONUCLEAR FUSION

- ❖ In controlled fusion reactors, the aim is to generate steady power by heating the nuclear fuel to a temperature in the range of 10^8K
- ❖ At these temperature, the fuel is a mixture of positive ions and electrons (plasma)
- ❖ The challenges is to confine this plasma, since no container can stand a high temperature.
- ❖ If these challenges overcome then we will hopefully have almost unlimited power supply to humanity.



This Chapter Ends here !! But not your work

Go to Practice Questions, Solve Dpps attend MCQs and revise the notes after some 2^{nd} 4^{th} and 7^{th} day

To get 95+ you have to keep on revising what you studied.

[Remember Consistency and HardWork Gives Great Result]

NOTES MADE BY

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