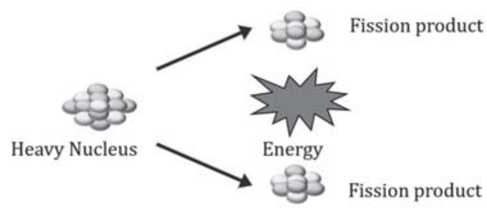
## NUCLEAR FISSION AND FUSION

### Nuclear fission

When the nucleus of an atom splits into lighter nuclei through a nuclear reaction, the process is termed as nuclear fission.




It is energetically favorable for the heavy nucleus to break into two middle-weight nuclei.

The binding energy per nucleon of middle weight nuclei is greater than the binding energy per nucleon of heavy nuclei as middle weight nuclei are more stable.

Let a heavy nuclei X having mass no. 240 breaks into two middle weight nuclei Y and Z both having mass no. 120.

$$^{240}X \rightarrow {}^{120}Y \quad + \quad t^{120}Z$$

Binding energy per nucleon $\Rightarrow$ 7.6MeV 8.5MeV 8.5MeV

Binding energy of X

$$BE_{\lambda} = 240 \times 7.6 = 1824\text{MeV}$$

Binding energy of Y and Z

$$BE_Y + BE_z = 240 \times 8.5 = 2040\text{MeV}$$

Energy difference,

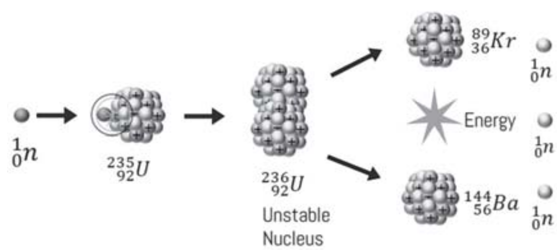
$$\Delta E = 216\text{MeV}$$

Fission of 1 kg of uranium generates $10^{14}$ J of energy; compared to the burning of 1 kg of coal that gives $10^{7}$ J.

### Uranium fission

A Uranium ore contains, 99%U − 238 and only 0.7% U − 235.

The most easily fissionable Uranium isotope is $U - 236$ . As it is highly unstable, it is not found in the nature, but can made artificially by colliding a thermal neutron with $U - 235$.

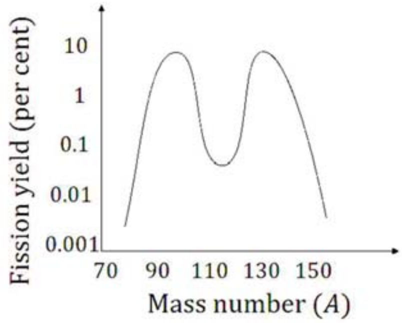



$$^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3\,^{1}_{0}n$$

$$^{236}_{92}U \rightarrow {}^{133}_{51}Sb + {}^{99}_{41}Nb + 4\,^{1}_{0}n$$

$$^{236}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,^{1}_{0}n$$

On an average 2.5 neutrons are released in Uranium fission.

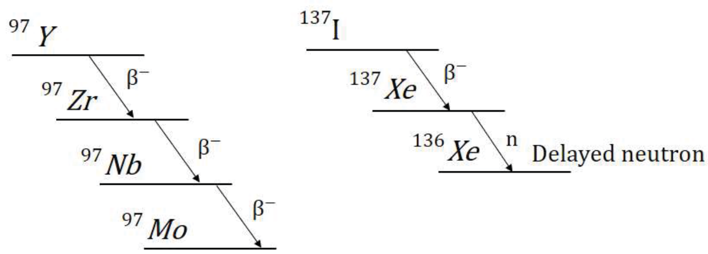



A range of nuclei are formed in the fission of Uranium, but, the nuclei having mass no. 95 and 140 has the maximum yield

The fission products formed are not always stable. The unstable fission products further decays into a stable nuclei.

Example: ${}^{236}_{92}U$ breaks into ${}^{97}_{39}Y$ and ${}^{137}_{53}I$.

$${}^{236}_{92}U \longrightarrow {}^{137}_{53}I + {}^{97}_{39}Y + 2n$$

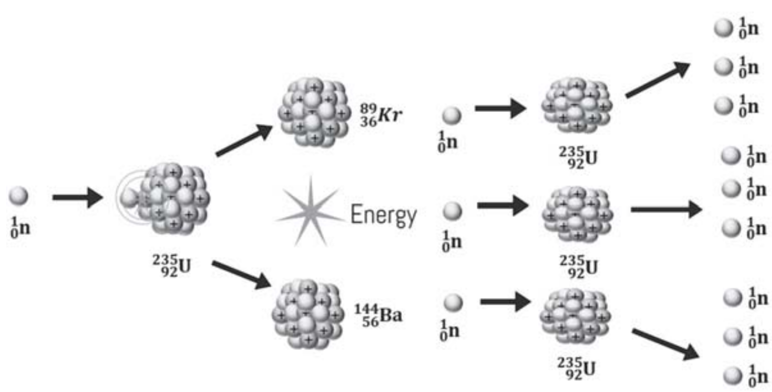



In each fission event, about 200 MeV of energy is released.

Energy released appears in the form of kinetic energies of the two fragments

## Chain reaction

A thermal neutron (0.04 $eV$) on bombardment with ${}^{235}_{92}U$ produces 3 neutrons. Now, the three secondary neutrons produced in the reaction may bring about the fission of three more ${}^{235}_{92}U$ nuclei and produce 9 neutrons, which in turn, can bring about the fission of nine ${}^{235}_{92}U$ nuclei and so on. Thus a continuous reaction called nuclear chain reaction would start and a huge amount of energy will be released in a short time.




### Disadvantages of chain reaction

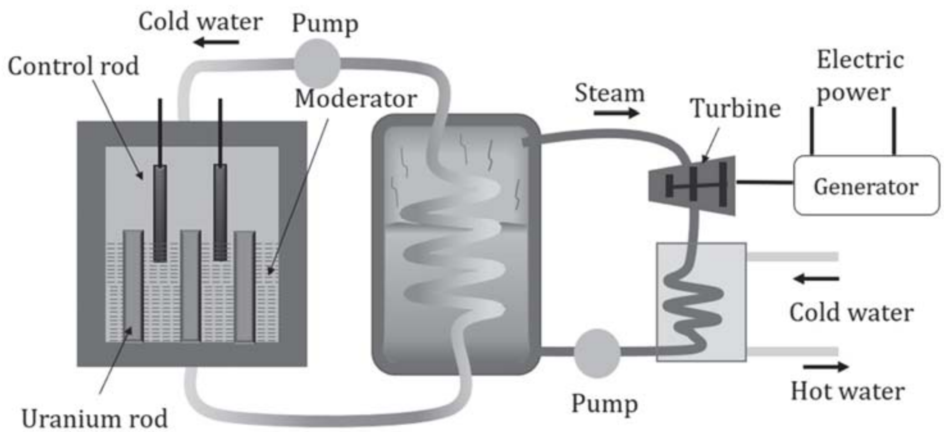
1. Nuclear fuel will get used up very quickly.
2. If the reaction is happening at very high rate, the energy released will almost be uncontrollable and this may lead to disaster

The neutrons which are released in nuclear fission have energy of the order of 2 $MeV$ ( fast moving neutrons). So, some of these fast moving neutrons even on collision with ${}^{235}_{92}U$ will not cause fission.

$U - 238$ is a very good absorber of fast moving neutron $(1 - 100NeV)$
By using smaller chunks of Uranium, the probability of thermal neutrons hitting the Uranium nuclei will decrease. Thus the chain reaction can be controlled.

Multiplication factor $K$ :
This ratio, representing the number of fissions produced by a particular generation of neutrons compared to the number of fissions from the previous generation, is known as the "fission yield." It is a measure of growth rate of neutrons in a reactor.
$K = 1$: Operation of reactor is critical
$K > 1$: Reaction rate increases exponentially

Nuclear reactor




Within the reactor, the core serves as the location for nuclear fission, housing Uranium rods along with a moderator to decelerate neutrons. Encircling the core is a reflector, minimizing neutron leakage. Control rods, typically composed of cadmium, enable the reactor's shutdown by absorbing neutrons effectively. Heat generated during fission is extracted by circulating cold water, which in turn heats water within a tank, producing steam. This steam propels turbines, generating electricity.

Core
- Site of nuclear fission
- Contains fuel element

Moderator
- To slow down the neutrons
- Light nuclei used like $H_2O$,$D_2O$, graphite

Control rods
- To control reaction rate
- Made of neutron absorbing material like cadmium

Safety rods
- Make $K < 1$ rapidly
- Can be used when required

Coolant
- To remove energy (heat) released in fission
- Water, helium etc

**Breeder Reactor**

$Pu^{240}$ used as nuclear fuel.

When fast neutrons strike Uranium fuel in a reactor, $U_{92}^{238}$ (which is present along with $U_{92}^{235}$ in natural Uranium) absorbs a neutron and becomes $U_{92}^{239}$ . This is radioactive and undergoes $\beta$-decay twice to produce $Pu_{94}^{239}$

$$U_{92}^{238} + n \rightarrow U_{92}^{239} \xrightarrow{\beta^-} Np_{93}^{239} \xrightarrow{\beta^-} Pu_{94}^{239}$$

If more than one neutron can be absorbed by $U^{238}$ rods per fission, then we produce more fuel than we consume.

**Types of nuclear Reactor**

**Research reactors –**

- Primary objective is to provide facility of research
- Source for production of variety of radioactive isotopes

**Fast Breeder reactors –**

- Use fast neutrons for sustaining the chain reaction
- Generate more fuel than they consume

**Pressurized Heavy water reactors ( PHWRs) –**

- Heavy water used as coolant
- Use natural uranium as fuel

**Nuclear fusion**

Nuclear fusion refers to the process where two or more atomic nuclei combine to create a single, heavier nucleus.

Examples:

$$H_1^1 + H_1^1 \rightarrow H_1^2 + v + 0.42\text{MeV}$$
$$H_1^2 + H_1^2 \rightarrow He_2^3 + n + 3.27\text{MeV}$$

In order for fusion to occur, two nuclei must approach each other closely enough for the attractive short-range nuclear force to influence them.

Height of coulomb barrier depends on charge and radii of two interacting nuclei.

Example: barrier height for two protons is, $\approx 400\ keV$

The temperature at which two nuclei will have enough energy to overcome coulomb barrier

$$\frac{3}{2}kT = K$$

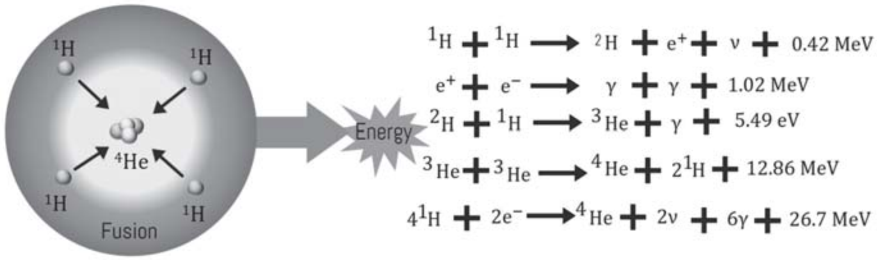
$K =$ Average Kinetic energy
$T =$ Temperature in absolute scale
$k =$ Boltzmann constant $= 1.38 \times 10^{-23}$ J/K

- To achieve K.E of 400 $keV$, a temperature of $3 \times 10^9\ K$ is required

When fusion is achieved by raising the temperature of the system so that particles have enough kinetic energy to overcome the Coulomb repulsion, it is called thermonuclear fusion .

- From Maxwell's speed distribution, it can be seen that, there are few nuclei which have very high speeds, so, their K.E would also be much greater than the average K.E.
- Thus, they would be able to fuse. Once the fusion process starts, the energy released would be sufficient to keep the fusion process going on.

Fusion in sun




Energy released in fusion exceeds the energy liberated in the fission of heavy nuclei.
Example: In nuclear fusion four $^1H$ nuclei i.e. 4 $amu$ produces 26.7 $MeV$ of energy whereas in nuclear fission of $U^{236}$ i.e. 236 $amu$ produces 216 $MeV$ of energy. Therefore, energy liberated per nucleon in nuclear fusion is much greater than that in nuclear fission.

Stellar life cycle

Molecular clouds

- These are huge clouds, composed of dust, H, He.
- Can be millions of times the mass of the sun.

- When a molecular cloud collects sufficient material, the gravitational force pulls this material inward, causing it to accelerate. As a result, collisions start to happen.
- Due to these collisions, heat is generated, initiating the nuclear fusion process where hydrogen atoms combine to form helium. This marks the birth of a star.
- The energy released during the fusion process exerts outward pressure, known as thermal pressure. However, the inward force of gravity counteracts this expansion, preventing the star from growing larger. Thus, throughout most of its lifespan, the star remains in a state of equilibrium, where the thermal pressure and gravity offset each other.
- As the star consumes a significant portion of its hydrogen fuel, the gravitational force becomes more dominant than the thermal pressure, causing the core of the star to contract or shrink.
- As the core shrinks, the temperature rises, leading to an increase in the rate of nuclear fusion.
- With the heightened rate of nuclear fusion, the outward pressure surpasses the force of gravity, causing the star to expand. This marks the transition into a phase known as the red giant.
- Once all the hydrogen is consumed, gravity regains dominance, causing the core to contract further. This increased compression raises the temperature to such levels that helium fusion commences. Helium fuses into carbon, which subsequently fuses into oxygen. Thus, carbon and oxygen are synthesized in the star's core.
- Eventually, as all the helium is exhausted, the thermal pressure diminishes, and gravity asserts its dominance to such an extent that the star undergoes a collapse.
- If the mass of the core of the star is less than 1.4 $M_0$ ($Chandrashekhar\ limit$).
- Where, $M_0$ is the solar mass, the star will become a white dwarf.
- If the mass of the core is in between 1.4 $M_0$ and 3 $M_0$, the gravity will be so high that the star collapses on itself and there will be a huge explosion which is called the supernova. Supernova is the brightest event in the whole universe. In this case a neutron star is formed.
- Within a white dwarf, the electrons encircling the nucleus repel each other, creating a force that counteracts gravity's attempt to compress the star. This phenomenon is known as electron degeneracy pressure.
- In a neutron star, the gravitational force is immensely strong, causing electrons to merge with protons, forming neutrons. Consequently, the core consists solely of neutrons, and the pressure resulting from neutron degeneracy prevents further collapse.
- If the mass of the core is greater than 3 $M_0$, the gravity is so intense that even the neutrons will get crushed and a black hole is formed