Nuclear fission and nuclear fusion.

(1) **Nuclear fission :** The splitting of a heavier atom like that of uranium – 235 into a number of fragments of much smaller mass, by suitable bombardment with sub-atomic particles with liberation of huge amount of energy is called **Nuclear fission**. **Hahn and Startsman** discovered that when uranium-235 is bombarded with neutrons, it splits up into two relatively lighter elements.

$${}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{56}Ba^{140} + {}_{36}Kr^{93} + 2-3\ {}_{0}n^{1} + \text{Huge amount of energy}$$

Spallation reactions are similar to nuclear fission. However, they differ by the fact that they are brought by high energy bombarding particles or photons.

Elements capable of undergoing nuclear fission and their fission products. Among elements capable of undergoing nuclear fission, uranium is the most common. The natural uranium consists of three isotopes, namely $U^{234}(0.006\%)$, $U^{235}(0.7\%)$ and $U^{238}(99.3\%)$. Of the three isomers of uranium, nuclear fission of U^{235} and U^{238} are more important. Uranium-238 undergoes fission by fast moving neutrons while U^{235} undergoes fission by slow moving neutrons; of these two, U^{235} fission is of much significance. Other examples are Pu^{239} and U^{233}.

Uranium-238, the more abundant (99.3%) isotope of uranium, although itself does not undergo nuclear fission, is converted into plutonium-239.

$${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239};\ \ {}_{92}U^{239} \rightarrow {}_{93}Np^{239} + {}_{-1}e^{0};\ \ {}_{93}Np^{238} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0}$$

Which when bombarded with neutrons undergo fission to emit three neutrons per plutonium nucleus. Such material like U-238 which themselves are non-fissible but can be converted into fissible material (Pu-239) are known as **fertile materials**.

Release of tremendous amount of energy: The importance of nuclear fission lies in the release of tremendous amount of energy during this process. During the U^{235} fission nearly 0.215 mass unit per uranium nucleus is found to be converted into energy.

$$\underbrace{\underset{235.124}{U^{235}} + \underset{1.009}{{}_{0}n^{1}}}_{236.133} \rightarrow \underbrace{\underset{138.955}{Xe^{139}} + \underset{94.945}{Sr^{95}} + \underset{2\times1.009}{2\,{}_{0}n^{1}} + E}_{235.918}$$

The released energy is due to difference in the total sum of masses of the reactants and products, in according to the Einsten's mass energy relation i.e. $E = mc^2$.

Alternatively, $\Delta m = 236.133 - 235.918 = 0.215\ amu$

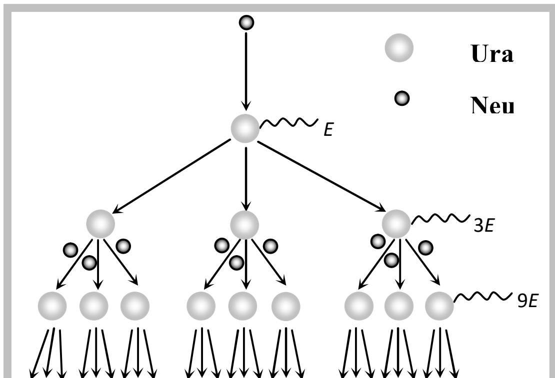
$\because 1\ amu = 931\ MeV$

$0.215\ amu = 931 \times 0.215\ MeV = 198\ MeV = 198 \times 2.3 \times 10^7\ kcal$

$\therefore$ Energy released by the fission of 1 g of $U^{235} = \dfrac{198 \times 2.3 \times 10^7}{235} = 1.9 \times 10^7\ kcal$

Recall that the combustion of 1 g of carbon releases only $94.0/12 = 7.83\ kcal$ of energy while the fission of 1 g of U^{235} releases $1.9 \times 10^7\ kcal$. Hence nuclear fission releases several million times higher energy than the ordinary chemical combustion.

Release of neutrons: During U^{235} fission it is obvious that 2-3 neutrons per uranium molecule are emitted. Some neutrons are ejected within an extremely short interval and are called prompt neutrons; fission products for an appreciable time fraction of a second to several seconds emit the rest after the fission. These are called delayed neutrons.



A fission chain reactor of Uranium.

Note: Each fission yields 3 neutrons each of which can cause further fission to give 3 neutrons goes on increasing in geometric progression 1, 3, 9, 27, 81, 243 ... and many geometric progression take place in a very small fraction of a second.

Chain reaction : With a small lump of U^{235}, most of the neutrons emitted during fission escape but if the amount of U^{235} exceeds a few kilograms (critical mass), neutrons emitted during fission are absorbed by adjacent nuclei causing further fission and so producing more neutrons. Now since each fission releases a considerable amount of energy, vast quantities of energy will be released during the chain reaction caused by U^{235} fission.

Atomic bomb: An atomic bomb is based upon the process of that nuclear fission in which no secondary neutron escapes the lump of a fissile material for which the size of the fissile material should not be less than a minimum size called the critical size. There is accordingly a sudden release of a tremendous amount of energy, which represents an explosive force much greater than that of the most powerful TNT bomb. In the World War II in 1945 two atom bombs were used against the Japanese cities of Hiroshima and Nagasaki, the former contained U-235 and the latter contained Pu-239.

Atomic pile or Nuclear reactor: It is a device to obtain the nuclear energy in a controlled way to be used for peaceful purposes. The most common reactor consists of a large assembly of graphite (an allotropic form of carbon) blocks having rods of uranium metal (fuel). Many of the neutrons formed by the fission of nuclei of ${}_{92}U^{235}$ escape into the graphite, where they are very much slow down (from a speed of about 6000 or more miles/sec to a mile/sec) and now when these low speed neutrons come back into the uranium metal they are more likely to cause additional fissions. Such a substance likes graphite, which slow down the neutrons without absorbing them is known as a **moderator**. Heavy water, D_2O is another important moderator where the nuclear reactor consists of rods of uranium metal suspended in a big tank of heavy water (swimming pool type reactor). Cadmium or boron are used as control rods for absorbing excess neutrons.

Plutonium from a nuclear reactor: For such purposes the fissile material used in nuclear reactors is the natural uranium which consists mainly (99.3%) of U-238. In a nuclear reactor some of the neutrons produced in U-235 (present in natural uranium) fission converts U-238 to a long-lived plutonium isotope, Pu-239 (another fissionable material). Plutonium is an important nuclear fuel. Such reactors in which neutrons produced from fission are partly used to carry out further fission and partly used to produce some other fissionable material are called **Breeder reactors**.

Production of radioactive isotopes by bombarding with neutrons from a nuclear reactor: These radioactive isotopes are used in medicine, industry and hospitals.

Nuclear reactors in India: India is equipped with the five nuclear reactors, namely Apsara (1952), Cirus (1960), Zerlina (1961), Purnima (1972) and R-5. Purnima uses plutonium fuel while the others utilize uranium as fuel.

Apsara the first nuclear reactor was completed on 14^{th} August 1952 at Trombay under the guidance of the late Dr. H.J. Bhabha. It is the swimming pool reactor, which consists of a lattice of enriched uranium (fuel) immersed in a large pool of water. Water acts as a moderator, coolant and shield. This reactor is simple, safe, flexible, easily accessible and cheap.

(2) **Nuclear fusion:**"Opposite to nuclear fission, nuclear fusion is defined as a process in which lighter nuclei fuse together to form a heavier nuclei. However, such processes can take place at reasonable rates only at very high temperatures of the order of several million degrees, which exist only in the interior of stars. Such processes are, therefore, called **thermonuclear reactions** (temperature dependent reactions). Once a fusion reaction initiates, the energy released in the process is sufficient to maintain the temperature and to keep the process going on.

$$\boxed{\underset{\text{Hydrogen}}{4\,{}_1H^1} \rightarrow \underset{\text{Helium}}{{}_2He^4} + \underset{\text{Positron}}{2\,{}_{+1}e^0} + \text{Energy}}$$

This is not a simple reaction but involves a set of the thermonuclear reactions, which take place in stars including sun. In other words, energy of sun is derived due to nuclear fission.

Calculation of energy released in nuclear fusion: Let us write the reaction involving the fusion of four hydrogen nuclei to form helium nucleus.

$$\underset{\substack{\text{Hydrogen}\\ \text{Mass: } 4\times 1.008144 \\ \text{or } =4.032576}}{4\,{}_1H^1} \rightarrow \underset{\substack{\text{Helium}\\ 4.003873}}{{}_2He^4} + \underset{\substack{\text{Positron}\\ 2\times 0.000558 = 0.001116}}{2\,{}_{+1}e^0} \quad (\text{Helium} + \text{Positron} = 4.004989)$$

∴ Loss is mass, $\Delta m = 4.032576 - 4.004989 = 0.027587\ amu$

∴ Energy released $= 0.027587 \times 931\ MeV = 26.7\ MeV$

∴ Energy released/gm of hydrogen consumed $= \frac{26.7}{4} = 6.7\ MeV = 6.7 \times 2.3 \times 10^7\ kcal = 1.54 \times 10^8\ kcal$

Controlled nuclear fusion: Unlike the fission process, the fusion process could not be controlled. Since there are estimated to be some 10^{17} pounds of deuterium $({}_1H^2)$ in the water of the earth, and since each pound is equivalent in energy to 2500 tonnes of coal, a controlled fusion reactor would provide a virtually inexhaustible supply of energy.

Comparison of nuclear fission and nuclear fusion: Now let us compare the efficiency of the energy conversion of the two processes, i.e. nuclear fission and nuclear fusion

Nuclear fission reaction, ${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 2-3\ {}_0n^1 + 200\ MeV$

If one atom of uranium is fissioned by one neutron, the percent efficiency in terms of mass converted into energy (where 1 mass unit = 931 MeV) will be: $\frac{200\ MeV}{(235+1)\text{ mass units} \times 931} \times 100 = 0.09\%$

Nuclear fusion reaction, ${}_1H^2 + {}_1H^3 \rightarrow {}_2He^4 + {}_0n^1 + 17.8\ MeV$

The percent efficiency of the reaction = $\frac{17.8\ MeV}{(2+3\text{ mass units}) \times 931} \times 100 = 0.35\%$

Thus it indicates that for these two fission and fusion reactions the percent efficiency is approximately four times greater for the fusion reaction.

Hydrogen bomb: Hydrogen bomb is based on the fusion of hydrogen nuclei into heavier ones by the thermonuclear reactions with release of enormous energy.

As mentioned earlier the above nuclear reactions can take place only at very high temperatures. Therefore, it is necessary to have an external source of energy to provide the required high temperature. For this purpose, the atom bomb, (i.e., fission bomb) is used as a primer, which by exploding provides the high temperature necessary for successful working of hydrogen bomb (i.e., fusion bomb). In the preparation of a hydrogen bomb, a suitable quantity of deuterium or tritium or a mixture of both is enclosed in a space surrounding an ordinary atomic bomb. The first hydrogen bomb was exploded in November 1952 in Marshall Islands; in 1953 Russia exploded a powerful hydrogen bomb having power of 1 million tonnes of TNT

A hydrogen bomb is far more powerful than an atom bomb. Thus if it were possible to have sufficiently high temperatures required for nuclear fusion, the deuterium present in sea (as D_2O) sufficient to provide all energy requirements of the world for millions of years.

Note: The first nuclear reactor was assembled by Fermi in 1942.

Difference between Nuclear fission and fusion

Nuclear fission	Nuclear fusion
The process occurs only in the nuclei of heavy elements.	The process occurs only in the nuclei of light elements.
The process involves the fission of the heavy nucleus to the lighter nuclei of comparable masses.	The process involves the fission of the lighter nuclei to heavy nucleus.
The process can take place at ordinary temperature.	The process takes place at higher temperature $10^8\ ^oC)$.
The energy liberated during this process is high (200 MeV per fission)	The energy liberated during the process is comparatively low (3 to 24 MeV per fusion)
Percentage efficiency of the energy conversion is comparatively less.	Percentage efficiency of the energy conversion is high (four times to that of the fission process).
The process can be controlled for useful purposes.	The process cannot be controlled.