SOURCES OF ENERGY
Nuclear Energy

NUCLEAR FISSION:

In 1939 two German scientists Otto Hahn and Frilz Strassman very carefully analysed the products of their experiments on bombardment of uranium with neutrons. One of the product was found to be a barium isotopes emitting β-rays and having a held life of 86 minutes. This was identical to the known characteristics of ^{139}Ba. Another product of this reaction was an isotope of lanthanum ^{140}La, which as a half-life of 40 hours. The uranium atom with Z = 92 and atomic mass number of 235 disintegrates into atoms, whose atomic number is Z = 56 and atomic mass number = 139 (barium) and Z = 57 has atomic mass number = 140 (lanthanum). The mass of the products = 139 + 140 = 279 u [unified atomic mass unit]. This is more than the mass of uranium nucleus and therefore only one of the two products would be produced in a given reaction. The other product would be an atomic species with atomic number of nearly 36 and atomic mass of about 100 u. Hahn and Strassman were indeed able to find active isotopes of Strontium ^{38}Sr and Yttrium ^{39}Y. In simple language they showed that the heavy uranium atoms split into lighter atoms of smaller atomic numbers. This process in named as nuclear fission.

(a) Fission Products:

Fission of uranium produces nuclei that have a mass number range from 72[$^{72}Zn_{30}$] to mass number 158[$^{158}E_{63}$]. Nuclei of different mass numbers can be produced by fission of uranium. Fission of $^{235}U_{92}$ yield manly two group of nuclei. One of the group is a light group with atomic mass numbers in the range 85 to 140 u. The second group is a heavy group with mass numbers range from 130 to 149 u. Most commonly occurring products are molybdenum [$_{42}$Mo] and lanthanum [$_{57}$La]. There are some “PROMPT” and “DELAYED” categories, In first category prompt, the uranium nucleus splits immediately when a projectile of proper energy strikes. In delayed fission, the projectile enters the nucleus and causes instability which leads to fission of host nucleus, $^{236}U_{92}$. The fission of natural uranium and some other isotope take pale without any projectile being hit on the same.

(b) Types of Fission Reactions :

All the nuclear fission reactions can be divided into three categories:

(i) Spontaneous fission
(ii) Prompt fission
(iii) Delayed fission.

(i) When nucleus undergoes fission on its own (without being hit by a projectile like neutron), it is called spontaneous fission. A spontaneous nuclear fission does not need to be initiated. In spontaneous nuclear fission, the natural shaking motion (or oscillations) of the nucleons in a heavy nucleus causes it to break into smaller nuclei. Spontaneous fission keeps on taking place in natural uranium all the time, but at a very-very slow rate.

(ii) When a nucleus splits up into smaller nuclei instantaneously as soon as it is bombarded with a projectile (like neutrons), it is called prompt fission. About 99 percent of the uranium - 235 fission caused by slow neutrons is prompt fission. The prompt fission is produced by prompt neutrons which are emitted instantaneously by the splitting nuclei.

(iii) When a projectile like neutron enters a nucleus and causes an instability which leads to the fission of the nucleus after a short while, it is called delayed fission. About 1 percent of the uranium - 235 fission caused by neutrons is delayed fission. The delayed fission is caused by delayed neutrons, which are emitted slowly by the splitting nuclei.

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Different amount of energies are required to produce fission from on isotope to the other. There is threshold energy of projectiles below which no fission take place.

Fission of nuclei is often accompanied by emission of neutrons that cause further fission. The fission of uranium is accompanied by 2 or 3 neutrons per fission. Energies of such neutrons lie in a wide range.

Unit of energy usually used in nuclear reactions is eV or MeV.

$$1eV = 1.6 \times 10^{-19} \text{ J}$$

$$1MeV = 1.6 \times 10^{-13} \text{ J}$$

(c) Energy Released by Fission Reaction :

Energy released in a fission reaction can be calculated by comparing the masses of nucleus which has undergone fission together with that of projectile used to cause fission and the masses of fission products.

Ex 1. Consider fission of $^{235}U_{92}$, fission takes place when it bombarded with low energy neutrons (neutrons having an energy of about 0.025 eV). Velocity of such neutrons is about 2,200 ms^{-1} which is about ten times that of modern jet plane. There are many fission reactions possible. Consider most portable reaction in which $^{95}Mo_{35}$ and $^{139}La_{57}$is produced with emission of 2 neutrons.

$_{92}U^{235} + {_0n^1} \rightarrow {_{35}Mo^{95}} + {_{57}La^{139}} + 2\ {_0n^1}$ + Enery

Mass of $_{92}U^{235}$ = 235.124 amu

mass of $_0n^1$ = 1.009 amu

Initial mass = 236.133 amu (i)

Mass of $_{35}Mo^{95}$ = 94.946 amu

Mass of $_{57}La^{139}$ = 138.955 amu

Mass of $2{}_0^1n$ = 2.018 amu

Final mass = 235.919 amu (ii)

We find that the initial mass is more than final mass.

This means that mass defect [(i) - (ii)] i.e., 236.133 u – 235.919 u = 0.214 u

We know that 1 amu or 1 u gives 931 Mev energy.

$\therefore 0.214 \times 931 = 199.234 \approx 199.22$ MeV of energy is released.

(d) Process of Nuclear Fission :

The process of nuclear fission is explained by the 'Liquid drop model' of the nucleus. The liquid drop model of the nucleus to explain the process of fission was proposed by Yakov Frenkel, Neils Bohr and John Wheeler. According to the liquid drop model of the nucleus it is said that is just the same way that a drop of water might become unstable if another small drop hits it, the uranium nucleus becomes unstable and breaks up when hits by a neutron. In this model, the uranium nucleus is treated like a drop of a liquid, which is not compressible and has a uniform positive charge. It is imagined that a stretchable skin-like membrane surrounds the drop like nucleus and holds all the protons and neutrons together inside its body. In the stable stage, the uranium nucleus, like a drop of water is spherical is shape. The nuclear fission of uranium - 235 isotope by means of a slow moving neutron can be explained diagrammatically as follows :

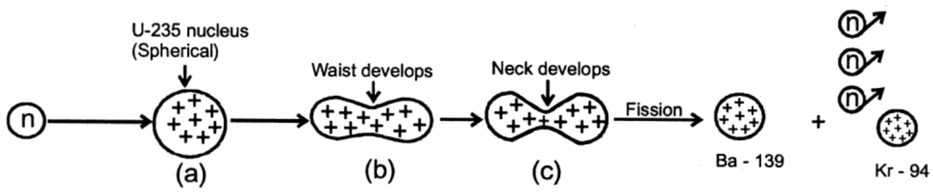
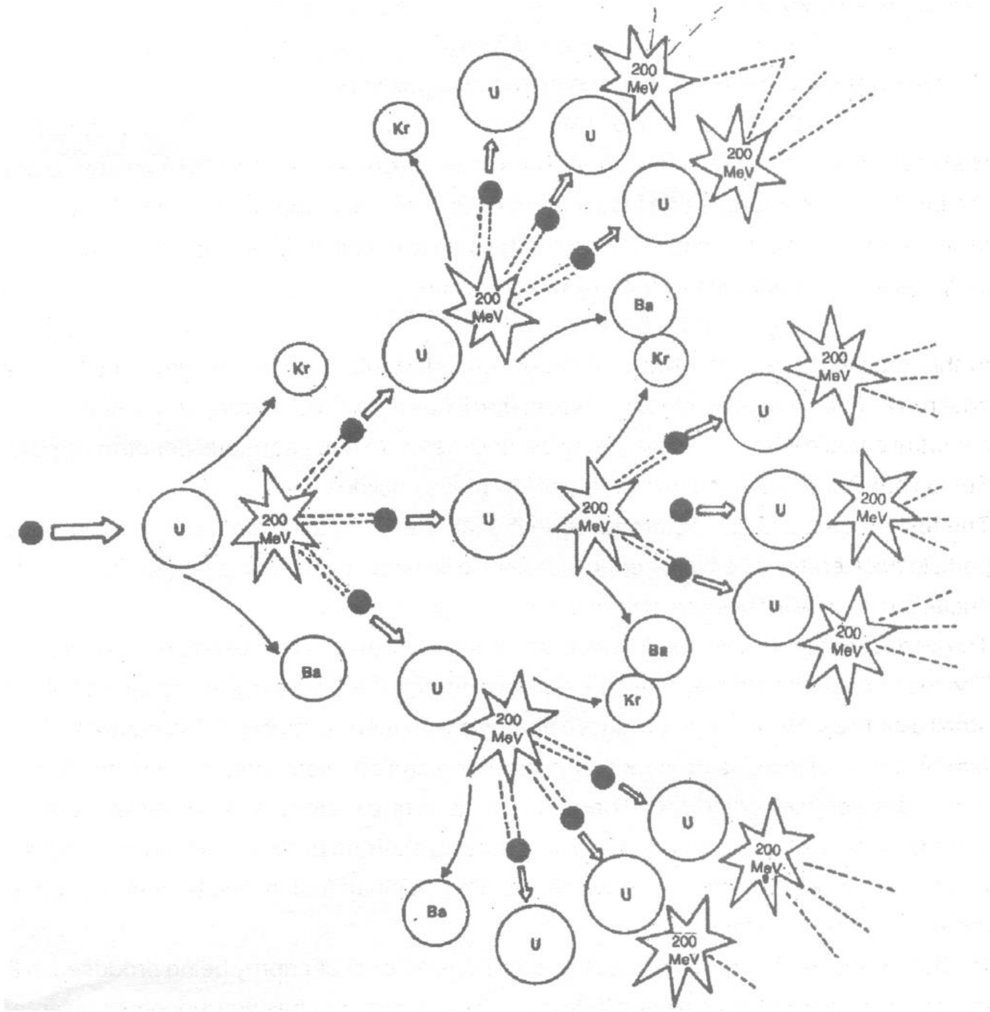


Figure (a) shows that uranium nucleus to the spherical. In this spherical nucleus the nuclear particles like protons and neutrons are very close together because of which the nuclear force of attraction and the electrostatic force of repulsion are very delicately balanced. Now, when a slow moving neutron attacks the uranium - 235 nucleus and enters into it, then the delicate balance of force inside the nucleus is disturbed. The energy of neutron is transferred to the nucleons (protons and neutrons) and by gaining this energy, the nucleons start oscillating more and more. Due to increased oscillations of the nuclear particles, the skin - like outer membrane of the nucleus gets stretched, the nucleus gets elongated and a waist develops in it. When the nucleus gets elongated then the distances between nuclear particles (protons and neutrons) increase. This increased inter-particle distance weakens the nuclear force of attraction so that the electrostatic force of repulsions becomes more dominant. Due to the increased repulsion between the protons, a neck develops in the nucleus as shown. The formation of neck decreases the nuclear force further. And the increased repulsion between protons ultimately leads to the breaking up of the uranium - 235 nucleus to from two smaller nuclei if barium - 139 and krypton-94, along with the emission of three neutrons.

(e) Chain reaction :

A reaction in which the particle which initiates (starts) the reaction is also produced during the reaction to carry on the reaction further and further is called a chain reaction. Once started a chain reaction will go on propagating by itself, until one of the reacant is all used up. The fission of uranium-235 by means of slow moving neutrons is a chain reaction, because this reaction is started by neutrons and neutrons are also produced during this reaction. The neutrons produced during the fission of a uranium atom initiate the fission of more uranium atoms, and this process goes on, like an unending chain, with the liberation of a large amount of energy at each step. The chain reaction taking place during the fission of uranium - 235 can be represented more clearly with the help of a diagram.



The fact that only 1 neutron is used up in each fission process but 3 neutrons are produced, makes the fission process in uranium - 235 a self-sustaining process or self-propagating process called chain reaction. If on the other hand on an average less than 1 neutron had been produced per fission, then the reaction would have died down like a fire in a wet fuel. It should be noted that a chain reaction involves a large number of uranium atoms. So, a chain reaction cannot occur in a very small lump of uranium - 235 isotopes, but it can take place in a sufficiently large mass of uranium - 235 isotopes. The minimum mass of uranium - 235 atoms or any other fissionable material which can support a chain reaction is called critical mass of that material.

NUCLEAR FUSIOIN :

Under special conditions, it is possible that nuclei of light elements can combine to form a nucleus of higher atomic number. For example, two deuterons can join together to form a ^3He nucleus plus a neutron. The deuteron (D) is the heavy hydrogen nucleus ($^2H_1$) consisting of one proton and one neutron. In simple language, two heavy hydrogen nuclei can combine to form a nucleus of helium (^3He). This process, in which nuclei of low atomic numbers combine to form a heavier atomic nucleus, is known as nuclear fusion. The fusion reaction is also accompanied by release of energy, like the fission phenomena. Fusion was discovered nearly 70 years ago in 1930. The typical fusion reaction mentioned above can represented by the following equation :

$$d + d \rightarrow {}^3He + n + 3.3 \text{ MeV}. \qquad ....(i)$$

Here, d represents the deuteron. Reaction is also possible:

$$d + d \rightarrow t + p + 4.0 \text{ MeV.} \qquad \text{.........(ii)}$$

Here, t is a triton (proton + two neutrons) or a heavy hydrogen nucleus ($^3H_1$) with two extra neutrons. This means that two deuterons can fuse to form either $^3He + n$, or triton + a proton. Another type of important fusion reaction involves conversion between neutron and protons. The simplest among these is the synthesis of deuteron from hydrogen by the following reaction :

$$p + p \rightarrow d + e^+ + \nu \qquad \text{........(iii)}$$

In this reaction one of the two protons is converted into a deuteron with simultaneous creation of a positron e^+ (identical to an electron except that it has a positive charge) and a neutrino ν. The neutrino is a neutral particle whose mass is negligible and therefore has enormous penetrating power.

Fusion has been observed in a variety of low mass nuclides.

The fusion reactions can be produced in the laboratory by accelerating low atomic number nuclei in a particle accelerator. The high - energy projectile is made to strike on a target made up of material whose nuclei can fuse with the projectile nucleus.

The kinetic energy of nuclei like deuteron can be sufficiently high at temperatures of 10^6 K for the nuclei to fuse. The fusing nuclei had to overcome the potential energy due to very high electrostatic repulsion at extremely small distance. However, if the kinetic energy due to thermal motion is increased sufficiently at elevated temperatures of millions of Kelwin, this repulsion can be overcome. At such high temperatures, all the atoms are completely ionised. There is a mixture of electrons and nuclei, which are moving at high speeds. This type of material consisting of moving charged particles with equal number of negative and positive charges is termed as a plasma. The nuclear fusion under such conditions is terms as thermo - nuclear reaction.

In 1939, Hans Bethe proposed that the enormous amount of energy being produced in the sun is due to thermo-nuclear reactions taking place there. This hypothesis has now become universally accepted.

(a) Secret of Sun's Energy :

The sun is a huge mass of hydrogen gas and the temperature in its extremely high.

In the sun the small deuterium atoms (isotope of H atom) collide and fuse together to form bigger atoms of helium. Each time an atom of helium is formed, tremendous energy is released in the form of heat and light. It is this energy which makes the sun shine. The main reaction taking place in sun is -

$${}_1H^2 + {}_1H^2 \xrightarrow{\text{n fusion}} {}_2He^4 + \text{Enormous amount of energy}$$

Deuteron Deuteron Helium

(heavy hydrogen) (nucleus)

Sun also contains two other isotopes of H: ordinary H, $^1H_1$ (called protium) and very heavy hydrogen $^3H_1$ (called tritium).

These two also fuse with deuterium to form helium nucleus and release energy. Thus two more reaction taking place in sun are

$${}_1H^1 + {}_1H^2 \longrightarrow {}_2He^3 + \text{large amount of energy}$$

ProtiumDeuteron Helium

$_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0n^1 +$ large amount of energy

Deuterium Tritium

(Heavy H) (Very heavy H)

Nuclear fusion reactions of various isotopes of hydrogen to form helium are going on inside the sun that produces such a great amount of energy which is radiated by the sun. Because of this energy, sun emits radiations (light) of different wavelengths of all the sun's radiation. It is the infra - red radiations which carry heat energy and hence heat up the earth.

(b) Hydrogen Bomb :

The nuclear fusion is the basis principle involved in the preparation of hydrogen bomb.
A hydrogen bomb is actually an uncontrolled nuclear fusion process.
A hydrogen bomb consists of a arrangement of nuclear fission in the centre. It is surrounded by a mixture of deuteron $^2H_1$ and lithium - 6 isotope($_3Li^6$).

The nuclear fission provides heat and neutrons. The neutrons are used in converting lithium isotope into tritium $^3H_1$ and the heat liberated is required for the fusion between $_1H^2$ and $_1 1H^3$ to start. The fusion reactions are then accompanied by the liberation of a large amount of energy.

Note : The nuclear fusion reaction occur at very high temperature, so they are also known as thermonuclear reactions.
The reactions are :

Fission (in the centre) $\xrightarrow{\text{produce}}$ heat + neutrons

$$_3Li^6 + {}_0n^1 \longrightarrow {}_1H^3 + {}_2He^4 + \text{energy}$$
$$_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0n^1 + \text{energy}$$

(Deuterium) (tritium)

$$_1H^2 + {}_1H^2 \longrightarrow {}_2He^4 + \text{energy}$$
$$_1H^3 + {}_1H^3 \longrightarrow {}_2He^4 + 2\ {}_0n^1 + \text{Energy}$$

(Note : - Tritium has to be prepared within the hydrogen bomb because it is not stable)

DIFFERENCE BETWEEN NUCLEAR FISSION AND NUCLEAR FUSION :

Nuclear fission	**Nuclear Fusion**
1. It is confined to heavy nuclei only.	**1. It is confined to lighter nuclei.**
2. A heavy nucleus splits into two lighter nuclei.	**2. To lighter nuclei fuse to form a heavy nucleus.**
3. It is a chain reaction.	**3. it is not a chain reaction.**
4. Temperature required for the reaction is not high.	**4. It is thermo nuclear reaction i.e. it required high temperature**
5. Fission reaction can be controlled.	**5. Fusion reaction is very difficult to control.**
6. Large amount of energy is released.	**6. Energy released is far more that released in a fission reaction.**
7. Large number of radioactive products are obtained i.e. large amount of nuclear waste is left.	**7. No nuclear waste is left.**