NUCLEAR FISSION

Nuclear fission, is a form of elemental transmutation process, in which the nucleus of an heavy atom, splits into two or more smaller fragments of more or less comparable atomic and mass numbers as **fission** products, accompanied by some by product particles. It is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). In order for fission to produce energy, the total binding energy of the resulting elements must be more negative (greater binding energy) than that of the starting element. Nuclear fission of heavy elements was discovered on December 17, 1938 by German Otto Hahn and his assistant Fritz Strassmann, and explained theoretically in January 1939 by Lise Meitner and her nephew Otto Robert Frisch.

In nuclear fission the nucleus of an atom breaks up into two lighter nuclei. **The process may take place spontaneously in some cases or may be induced by the excitation of the nucleus with a variety of particles (e.g., neutrons, protons, deuterons, or alpha particles) or with electromagnetic radiation in the form of gamma rays.**

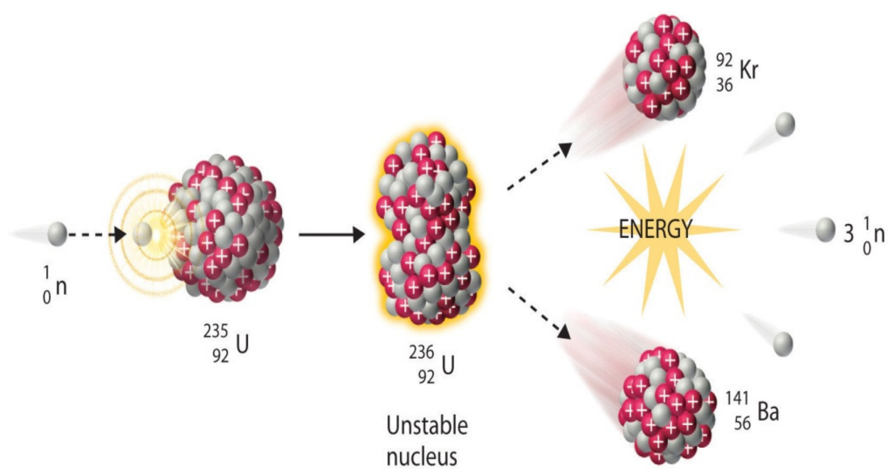

Fig. 4.1. Schematic diagram of a nuclear fission triggered by a neutron.

Equation of a nuclear fission

$_{Z}P^{A} + {}_{0}n^{1} \rightarrow {}_{Z1}X^{A1} + {}_{Z2}Y^{A2} + a_{0}n^{1} + Q$……………………………………(4.1)

Where $_{Z}P^{A}$ $\rightarrow$ parent atom with atomic number Z and mass number A

$_{0}n^{1}$ $\rightarrow$ neutron

$_{Z1}X^{A1}$ $\rightarrow$ A daughter fragment with atomic number Z_1 and mass number A_1

$_{Z2}Y^{A2}$ $\rightarrow$ A daughter fragment with atomic number Z_2 and mass number A_2

a$\rightarrow$ number of neutrons emited.

Q $\rightarrow$ energy released.

Here $Z_1 + Z_2 = Z$, and $A_1 + A_2 \approx A$

Examples of nuclear fission

1. $_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236}$ (unstable nucleus) $\rightarrow {}_{36}Kr^{92} + {}_{56}Ba^{141} + 3\ {}_0n^1$ + Energy

2. $_{94}Pu^{239} + {}_0n^1 \rightarrow {}_{94}Pu^{240}$ (unstable nucleus) $\rightarrow {}_{54}Xe^{134} + {}_{40}Zr^{103} + 3\ {}_0n^1$ + Energy

Relativity and energy released in nuclear fission

In relativity theory, Einstein introduced mass as a new type of energy Beforehand, the mass of something in kilograms was just a measure of how much stuff was present and how resistant it was to being moved around. In Einstein's new world, mass became a way to measure the total energy present in an object, even when it was not being heated, moved or irradiated or whatever else. Mass is just a super-concentrated form of energy and, moreover, these things can turn from one form to the other and back again. According to Einstein the energy equivalent to a mass 'm' is $E = mc^2$, where 'c' is the velocity of light.

When a nuclear fission occurs, it has been found that the mass of the product side is less than the mass of the reactant side. This difference between the masses of reactant and products is called **mass deficit** (Δm). This loss of mass results in corresponding release of energy according to the relation $E = \Delta m.c^2$. Let us take as an example the fission of uranium-235, on being bombarded with a neutron. The reaction is given by: $_{92}U^{235} + {}_0n^1 \rightarrow {}_{36}Kr^{92} + {}_{56}Ba^{141} + 3\ {}_0n^1$

Mass of uranium-235 ($_{92}U^{235}$) = 235.1175 a.m.u.

Mass of neutron ($_0n^1$) = 1.00898 a.m.u.

Total mass of reactants = 236.12648 a.m.u

Mass of Barium ($_{56}Ba^{141}$) = 140.9577 a.m.u

Mass of Krypton ($_{36}Kr^{92}$) = 91.9264 a.m.u.

Mass of 3 neutrons (3 $_0n^1$) = 3.02694 a.m.u.

Mass of products of fission = 235.91104 a.m.u.

Mass deficit =Δm = 236.12648 a.m.u - 235.91104 a.m.u. = 0.21544 a.m.u

The corresponding energy equivalent of this mass = 0.21544 a.m.u $\times$ 931.2MeV = 200.5MeV

(931.2MeV being the energy equivalent of 1 a.m.u. of mass as obtained from Einsteins' relation)

Hence 200.5 MeV of energy is released is the process of fission of U-235.

Chain reaction:

In the fission process, a large quantity of energy is released, radioactive products are formed, and several neutrons are emitted. These neutrons can induce fission in a nearby nucleus of fissionable material and release more neutrons that can repeat the sequence, causing a **chain reaction** in which a large number of nuclei undergo fission and an enormous amount of energy is released. **In other words, chain reaction is a self propagating reaction, in which the neutrons as well as the energy generated in fission reaction goes on multiplying in geometrical progression at each step till the whole of the fissionable material is exhausted.**

For example three neutrons are released in the fission of U-235. These three neutron in turn can trigger fission in neighbouring three more U-235 nuclei producing nine neutrons releasing three times more energy than the first fission. The process continues resulting in a cascade of fission releasing three times more energy in each step than the preceding one resulting in generation of a huge amount of energy. If controlled in a nuclear reactor, such a chain reaction can provide power for society's benefit. If uncontrolled, as in the case of the so-called atomic bomb, it can lead to an explosion of awesome destructive force.

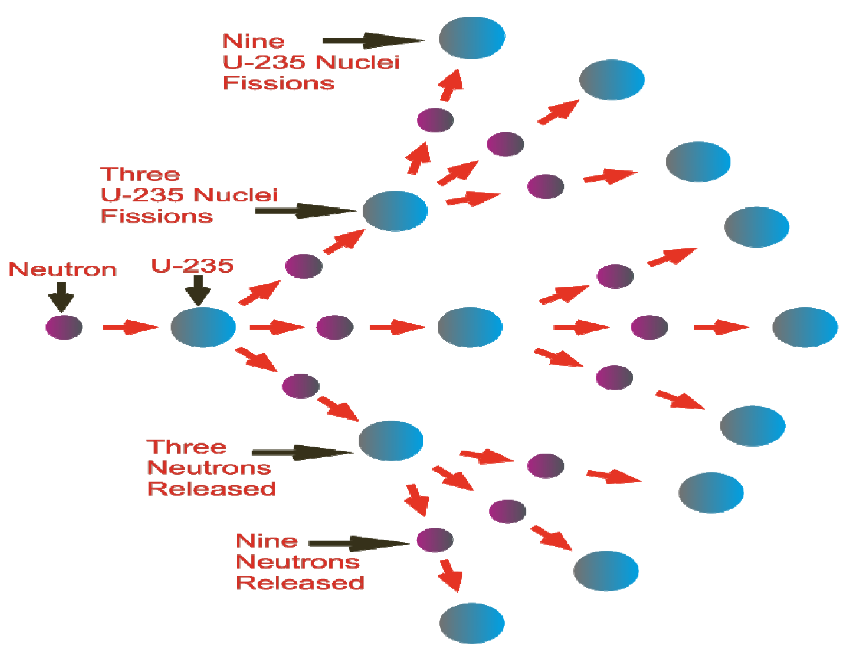

Fig. 4.2. Chain reaction in Uranium -235.

Nature of fission products .

A fissionable nucleus gives onle two fission fragments. Although the sum of mass numbers of the two large fission products is almost equal to the parent nucleus but there is a wide distribution of possible products. For eg. Fission of U-235 can produce three sets of fragments

1. ${}_{92}U^{235}$ + ${}_{0}n^{1}$ ⟶ ${}_{92}U^{236}$ (unstable nucleus) ⟶ ${}_{36}Kr^{92}$ + ${}_{56}Ba^{141}$ + 3 ${}_{0}n^{1}$ + Q_1

2. ${}_{92}U^{235}$ + ${}_{0}n^{1}$ ⟶ ${}_{92}U^{236}$ (unstable nucleus) ⟶ ${}_{54}Xe^{140}$ + ${}_{38}Sr^{94}$ + 2 ${}_{0}n^{1}$ + Q_2

3. ${}_{92}U^{235}$ + ${}_{0}n^{1}$ ⟶ ${}_{92}U^{236}$ (unstable nucleus) ⟶ ${}_{50}Sn^{132}$ + ${}_{42}Mo^{101}$ + 3 ${}_{0}n^{1}$ + Q_3

Q_1, Q_2 and Q_3 are the energies released in the three cases. The number of neutrons emitted may also differ. The mass distribution of the fission products of U-235 is shown in the form of a **fission yield curve**, in which the percentage yield (in log scale) of the different products is plotted against mass number.

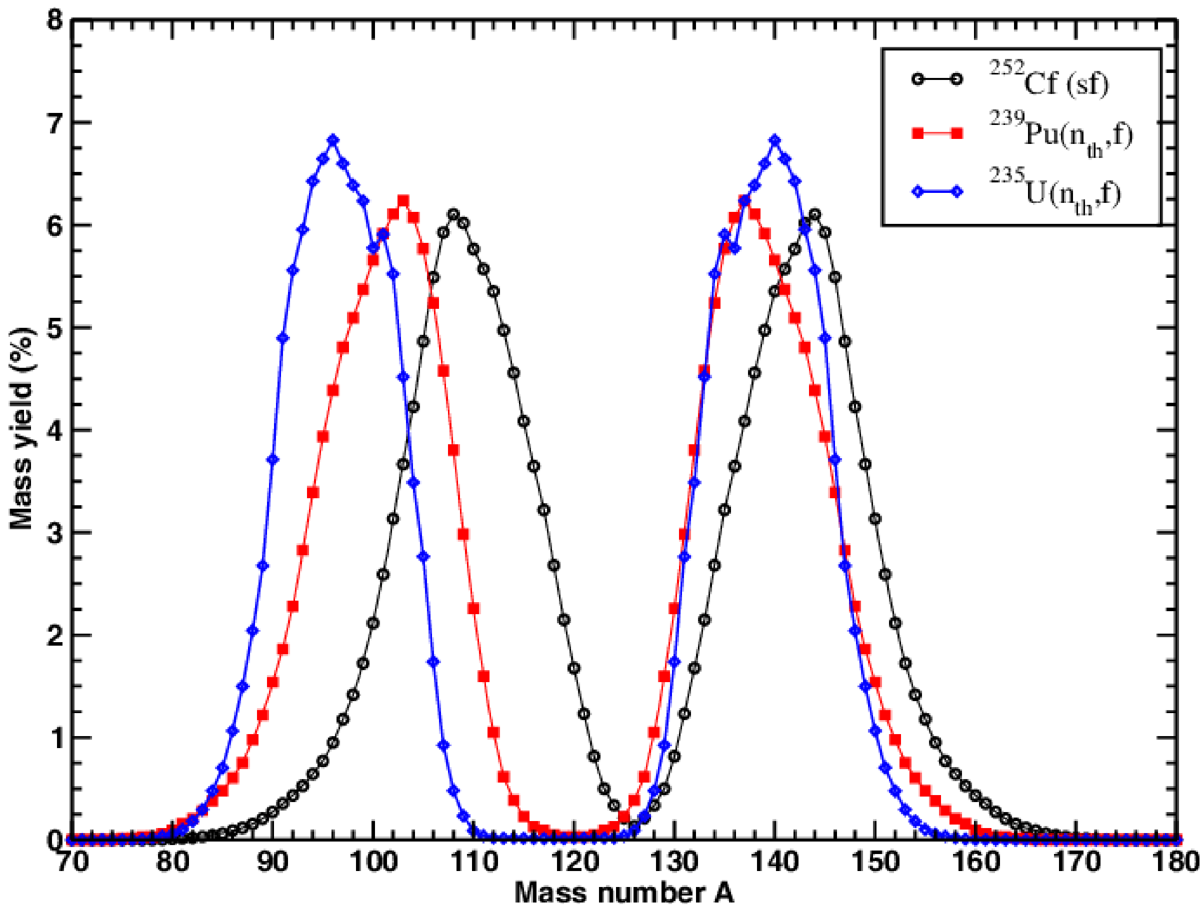

Fig 4.3. Fission yield curve of U-235, Pu-239 and Cf-252

There is a tendency of masses to concentrate respectively around 95 and around 140 as seen from the two peaks of the figure (4.2). In fact about 97% of the fission products fall within the narrow range of 85-108 for lighter fragment and from 130-149 for heavier fragment. There is a minima $\rightarrow$zero near mass number $\approx$ half the mass number of parent nucleus, which shows that division in two equal fragments is very low. A comparison of the fission yield curves for different heavy nuclei shows that the distribution of heavier products are practically the same for all of them, whereas the lighter fragment yields are displaced by approximately six a.m.u. with respect to each other.

The **energy distribution** of the fission products can be obtained from the distribution of their kinetic energies. Considering the nucleus undergoing fission to be at rest initially and ignoring the energy of emitted nutrons in comparisn to the energy of the heavier fragments, the law of momentum conservation demands that :

$$M_1V_1 = M_2V_2 \quad \text{.......................................(4.2)}$$

M_1 and M_2 are the masses of the two fragments and v_1 and v_2 are their velocities respectively. If E_1 and E_2 be respectively the kinetic energies of fragments (1) and (2) then:

$$\frac{E_1}{E_2} = \frac{\frac{1}{2}M_1V_1^2}{\frac{1}{2}M_2V_2^2} \quad \text{..(4.3)}$$

Using equation (4.2) in (4.3):

$$\frac{E_1}{E_2} = \frac{M_2}{M_1} \quad \text{..(4.4)}$$

For the two peaks at mass numbers approximately at 95 and 140 respectively, the corresponding energy ratio is

$$\frac{E_1}{E_2} = \frac{M_2}{M_1} = \frac{140}{95} \approx \frac{3}{2} \quad \text{....................................(4.5)}$$

So the energy will be distributed between the fragments that the energy of the lighter fragment is approximately two third of the energy of the heavier fragment.

Neutron emission in Nuclear fission

The harnessing of nuclear energy obtained from fission either in a nuclear reactor or in a bomb depends on the production rate of neutrons emitted in a fission chain reaction. Fig. (4.4) shows the distribution of fission neutron energy, in which the average energy is $\approx$ 2.0MeV and the most probable energy is about 0.7MeV.

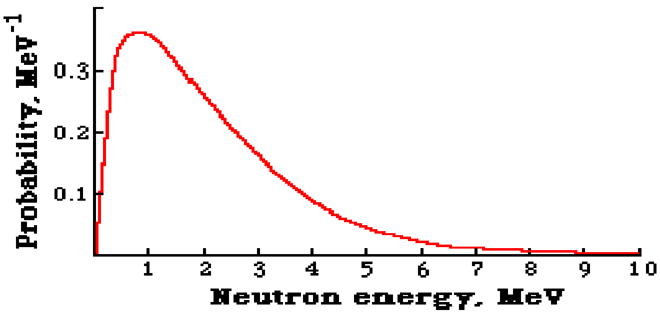

Fig. 4.4. Fission neutron spectrum.

The number of neutrons born per individual fission is always an integer, but the gross average **(ν_{av})** is about 2.5 neutrons per fission which is a not an integer. This is because a fissionable nucleus can divide itself in a number of different ways.

Most of the neutrons are emitted within possibly 10^{-13} seconds and are called **prompt neutrons.** A smaller number of neutrons are also emitted with a survival time of several seconds to more than one minute after the fission. These neutrona are called **delayed neutrons**.

For sufficiently large piece of fissionable substance the neutrons released in first fission process will be absorbed by the other nuclei to produce more fissions, which in turn produces more neutrons. Also a small part of the compound nucleus decay to stable state by gamma emission like the example given below:

$$ {}_{0}^{1}n + {}_{94}^{239}Pu \rightarrow [{}_{94}^{240}Pu] \xrightarrow{73\%} fission\ (e.g.\ {}_{54}^{134}Xe + {}_{40}^{103}Zr + 3\ {}_{0}^{1}n) $$

$$ {}_{0}^{1}n + {}_{94}^{239}Pu \rightarrow [{}_{94}^{240}Pu] \xrightarrow{27\%} {}_{94}^{240}Pu + \gamma $$

NUCLEAR REACTOR

A **nuclear reactor**, is a device used to initiate and control a self-sustained **nuclear** chain reaction. **Nuclear reactors** are used at **nuclear** power plants for electricity generation or some other purposes.

Nuclear reactors operate on the principle of nuclear fission. For a finite mass of fissionable material continuous self-sustaining series of fissions constitutes a fission chain reaction. A large amount of energy is released in this process, and this energy is the basis of nuclear power systems. In a **nuclear reactor** the chain reaction is maintained at a controlled, nearly constant rate.

Basic Principle of nuclear reactor.

1. Neutron induced fission releases energy plus extra "fast" neutrons.

2. "Fast" neutrons are slowed down to thermal neutrons by a "moderator" such as water or graphite, allowing chain reaction to take place. Water also serves the purpose of coolant.

3. Chain reaction is controlled by controlling the condition of the moderator, or by use of neutron absorbing materials (e.g. cadmium control rods)

4. Heat is removed by some form of heat exchanger where it is used to run a heat engine.

Construction and Features of a nuclear reactor

Shape of the reactor: Each fission of U^{235} nucleus releases 2 or 3 neutrons and an energy of about 200MeV most of which are either lost through the reactor surface or absorbed without producing further fission. For the reaction to be self sustained at least one neutron should always be available to continue the chain reaction. For this purpose the size of the reactor should be such that it has a small surface area compared to its volume (Fig. 4.5 shows the cylindrical shape of the reactor). Secondly the fuel should be surrounded by such a material that scatters neutrons without absorbing them, so that most of the escaping neutrons are reflected back.

Use of a moderator: Natural Uranium contains two isotopes – $_{92}U^{235}$ and $_{92}U^{238}$ the former being just 7% of the total. The U^{238} isotope readily captures fast neutrons and changes to a $_{92}U^{239}$ without undergoing fission. **Also the capture cross section of U^{238} is very small for slow neutrons whereas for U^{235}, it is extremely large**. Hence, to prevent unproductive absorption, the fast neutrons liberated in the fission process, have to be slowed down. **A moderator is a substance whose nuclei absorb energy from the incident fast neutron and renders them slow with energies less than 1eV at the temperature of operation of the reactor**.To accomplish the slowing down of fission neutrons, the uranium reactor consists of a large number of uranium blocks dispersed in the form of a lattice (Fig 4.5 shows uranium blocks used as fuel) in a large pool of 'light' water (H_2O), heavy water (D_2O) or graphite used as moderator.

Use of absorbers: In order to control the chain reaction, the reactor makes use of rods made of Cadmium or Boron which readily absorb slow neutrons. As these rods are inserted deeper into the reactor, more and more slow neutrons are absorbed by them and the progress of the reaction is further damped due to larger absorption of neutrons. The number of control rods inserted, and the distance to which they are inserted, strongly influence the reactivity of the reactor. When reactivity (effective neutron multiplication factor) is above 1, the rate of the nuclear chain reaction increases exponentially with time. When reactivity is below 1, the rate of the reaction decreases exponentially with time. When all control rods are fully inserted, they keep reactivity barely above 0, which quickly slows a running reactor to a stop and keeps it in shutdown mode. If all control rods are fully removed, reactivity is significantly above 1, and the reactor quickly runs hotter and hotter, until some other factor slows the reaction rate. Maintaining a constant power output requires keeping the long-term average neutron multiplication factor close to 1. Thus by adjusting the length of the absorber rods, the rate of fission can be controlled(fig. 4.5 shows the **control rods**)

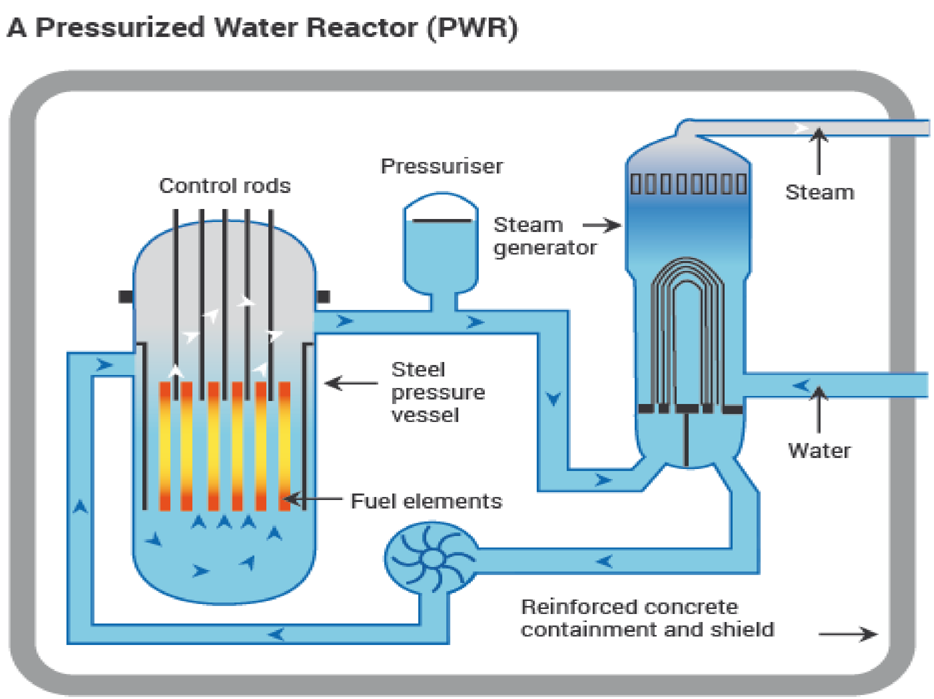

Fig. 4.5. Schematic diagram of a nuclear reactor

Working of a nuclear reactor

For the nuclear reactor to function, the control rods are slowly pulled out of the reactor, thereby decreasing the neutron capture area. If now a single neutron from a sponteneous fission, strikes a U^{235} nucleus, it splits into the daughter fragments, and neutrons are released. These neutrons are slowed down to thermal level, by collision with the moderator nuclei and then proceed to produce further fission. The intensity of the neutrons produced by fission is allowed to reach the desired value by keeping requisite depths of control rods within the reactor and power is produced at the required rate. The energy may be used for electricity generation or for any other purposes.

NUCLEAR FUSION

Nuclear fusion is a reaction in which two or more atomic nuclei are combined to form one or more different atomic nuclei and subatomic particles (neutrons or protons). The difference in mass between the reactants and products is manifested the release of energy. This difference in mass arises due to the difference in atomic "binding energy" between the atomic nuclei before and after the reaction. Fusion is the process that powers active or "main sequence" stars, or other high magnitude stars.

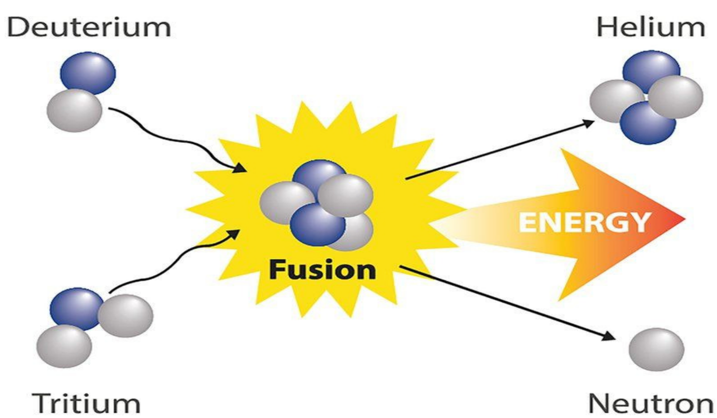

Fig. 4.6. Nuclear fission of Deuterium and Tritium.

Equation of nuclear fusion

$$_{Z1}X^{A1} + _{Z2}Y^{A2} \rightarrow _{Z3}A^{A3} + _{Z4}N^{A4} + \text{energy}$$

Where X and Y are two light nuclei with atomic numbers Z_1 and Z_2 and mass numbers A_1 and A_2 respectively. A is the heavy nucleus formed with atomic number Z_3 and mass number A_3 . $_{Z4}N^{A4}$ is an elementary particle like alpha, beta or neutron which may or may not bre produced.

From charge conservation: $Z_1 + Z_2 = Z_3 + Z_4$

From mass number conservation: $A_1 + A_2 = A_3 + A_4$

Examples of nuclear fission

1. $_1H^2 + _1H^2 \rightarrow _2He^3 + _0n^1 + \text{energy}$
2. $_1H^2 + _1H^3 \rightarrow _2He^4 + _0n^1 + \text{energy}$
3. $_1H^1 + _6C^{12} \rightarrow _7N^{13} + \text{energy}$

Types of fission

Fusion reactions are of two basic types:

1. Those that preserve the number of protons and neutrons Reactions of this type are most important for practical fusion energy production.

2 Those that involve a conversion between protons and neutrons. This type of reaction are crucial to the initiation of star burning.

Mechanism of nuclear fusion

The nuclei are positively charged. So for two nuclei to approach each other and fuse, they must have enough kinetic energy to allow them to surmount the electrostatic repulsion between them. The average kinetic energy required to trigger fusion at a detectable rate is of the order of 0.1MeV for nuclei of lowest atomic number (e g. isotopes of hydrogen). Higher atomic number nuclei require still more energy. The ambient temperatures required for supplying this energy (10^9 K) is too high to generate on Earth. So the only way of generating power through nuclear radiation is nuclear fission. Hence, a fission reaction is required in order to carry out a fusion reaction. So it is said that **fission precedes fusion.**

Energy released in fusion reactions

Energy is released in a nuclear reaction if the total mass of the resultant particles is less than the mass of the initial reactants, which is usually the case in fusion reaction. The D-T (Deuterium-tritium) fusion reaction has a positive *Q*-value of 2.8×10^{-12} joule. The H-H fusion reaction is also exoergic, with a *Q*-value of 6.7×10^{-14} joule. To develop a sense for these figures, one might consider that one kilogram of deuterium would contain roughly 3×10^{29} atoms. If one kilogram of deuterium were to be consumed through the fusion reaction with tritium, the energy released would be 8.4×10^{17} joules. This can be compared with the energy content of one kilogram of coal—namely, 2.9×10^7joules. In other words, one kilogram of deuterium has the energy equivalent of approximately 29 billion kg of coal.

Thermonuclear reaction driving stellar energy

Electromagnetic energy is being continuously being produced in stars including the sun, thereby producing light and heat. The sun emits energy at a rate of about 10^{26} Joules/sec. Evidences show that the sun has been radiating energy at this rate for several billion years. Such a huge source of energy cannot occur from Chemical reactions. So the question arises about the source of stellar energy. Initially it was suggested that the sun was contracting, thereby converting the gravitational energy to heat and light. But mathematically it was shown that this process could not supply more than 1% of the energy needed if the sun has to sustain itself for billions of years.

With the discovery of radioactivity, it appeared that atomic energy might possibly be the source of stellar energy. In 1920, Eddington proposed that, since presence of hydrogen and helium is abundant in the sun, stellar energy is most probably liberated during formation of helium from hydrogen. However, he could not suggest any mechanism for this process. Finally in 1929, Atkinson and Houtermans used the measured masses of light elements to show that large amounts of energy could be released by fusing small nuclei in very high stellar temperatures via thermonuclear reaction. **Thermonuclear fusion is a way to achieve nuclear fusion by using extremely high temperatures.**

It has been mentioned that the average energy required to trigger fusion at a detectable rate is ≥ 0.1MeV, which requires an ambient temperature of $\approx 10^9$ Kelvin. Such temperature is much higher than those existing in most of the stars (Core temperature of the sun is $\approx 50 \times 10^6$ K). But fission does not occur in the stars to generate such temperature. So there must be some other factors which make fusion to occur at lower temperature. These factors are:

1. Temperature is the measure of average kinetic energy. This implies that though the average kinetic energy is ≈ 0.1 MeV but some nuclei at the ambient temperature would actually have much higher energy than 0.1 MeV, while others would be much lower. **It is the nuclei in the high-energy tail of the velocity distribution that account for most of the fusion reactions.**

2. The other factor is **quantum tunneling**. The nuclei do not actually require enough energy to overcome the Coulomb barrier completely. **If they have nearly enough energy, they can tunnel through the remaining barrier.** The temperature in stars' cores is generally insufficient to allow atomic nuclei to overcome the Coulomb barrier and achieve thermonuclear fusion. **Quantum tunneling increases the probability of penetrating this barrier even with a lower energy**. Though this probability is still low, the extremely large number of nuclei in the core of a star is sufficient to sustain a steady fusion reaction for billions of years. Our sun can be treated as a best example for this kind of tunneling effect.