Nuclear Fission and Fusion

A. Nuclear Fission

1. The process of splitting up of the nucleus of a heavy atom into two nuclei more or less of equal fragments when bombarded with neutron simultaneously releasing a large amount of energy is called nuclear fission.

   $^{235}_{92}U + ^{1}_{0}n \rightarrow (^{236}_{92}U) \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + Q$.

2. Where Q is energy released which is about 200 MeV.
3. This phenomenon was first observed by Strassmann and Hann. It was explained by Neils Bohr and J.A. Wheeler on the basis of liquid drop model of the nucleus. According to liquid drop model, the nucleus behaves like a liquid drop and owing to surface tension it tries to be perfectly spherical in shape. When a neutron is absorbed by the nucleus, a compound nucleus is formed and some excitation energy is imparted to the nucleus. This excitation energy tries to deform the nucleus where as the surface tension of the nucleus tries to keep the nucleus in spherical shape. Due to the struggle between the surface tension and the excitation energy, strong oscillations are set up inside the compound nucleus. These oscillations will distort the shape of the compound nucleus from spherical to ellipsoid.
4. If the excitation energy is sufficiently large, the ellipsoidal nucleus may attain the dumbbell shape. In this case the effect of nuclear attractive force is decreased because of the much increased surface area of the nucleus. Further the Coulombic repulsive force drives the two portions of the dumb bell still farther and the nucleus undergoes fission, liberating two nuclei Ba and Kr and neutrons. These newly liberated neutrons are called prompt neutrons. In this process the products are not always the same; their atomic number varies from 34 to 58. Hence the number of prompt neutrons will also change with the mass number of the products. The products, emitted neutrons finally become stable. These occur within few seconds after the fission reaction. These are called delayed neutrons. They play an important role in controlling the nuclear chain reaction in a nuclear reactor.

5. **Chain Reaction:** A chain reaction is a self propagating process in which a number of neutrons multiply rapidly during fission till the whole fissionable material is disintegrated.

6. Neutron multiplication factor K and conditions required for sustained chain reaction:

In the fission of uranium nuclei, on an average 2.5 neutrons are emitted per fission. The neutrons produced in a fission event are fast neutrons and are referred to as "neutrons of first generation". There is certain probability for some neutrons to escape without participating in further fission process. Therefore all emitted neutrons are not available for further fissions. The basic conditions for self sustained chain reaction is that at least one neutron should be available. The requirements are given below.

a) Fast neutrons should be changed into slow neutrons by passing through moderators.

b) At least one thermal neutron should be available to initiate the fission reaction.

c) The state of the chain reaction depends on the neutron multiplication factor 'K' which is defined as

$$K = \frac{\text{number of neutrons in present generation}}{\text{number of neutrons in the previous generation}}$$

When K<1, the number of neutrons in successive generations decreases and the chain reaction cannot continue. This state is called 'sub-critical state'.

If K=1, the chain reaction will proceed at a steady rate and this state is called 'critical state'.

If K>1, the number of neutrons increases and the reaction is said to be 'supercritical'.

7. **Critical mass:** If the mass of uranium is too small, the neutron may escape without participating further fission. To start the fission reaction mass of material should be more than the critical mass or critical size.

8. **Principal and working of a nuclear reactor**

The device giving large amount of nuclear energy through fission process at a controlled rate is called a nuclear reactor or atomic pile. The first nuclear reactor was put into operation in Chicago (USA) in 1942 by Fermi. In the nuclear reactor the first fission reaction results in the production of fast neutrons. If fast moving neutrons are allowed to pass through moderator they become thermal neutrons. Subsequently these thermal neutrons are utilized for further fission reactions to produce a large amount of energy.

9. Essential features of a nuclear reactor

i) **Nuclear Fuel:** The fissionable material used in the reactor is called nuclear fuel.

ii) The uranium isotopes $_{92}U^{235}$ and $_{92}U^{238}$, plutonium $_{94}Pu^{236}$ and thorium $_{90}Th^{232}$ are commonly used as fuels in the reactors. The rods of these fuels are tightly sealed in aluminium cylinders.

iii) **Moderators:** The purpose of the moderator is to slow down the fast moving neutrons produced as a result of nuclear fission. Some of the suitable materials used as moderators are heavy water, beryllium, carbon in the form of pure graphite, hydrocarbon plastics etc.

iv) **Control rods:** These are the materials used in the nuclear reactors that can absorb the neutrons and control the nuclear chain reaction. Cadmium or boron rods are generally used for this purpose. When the control rods are completely inserted into the carbon blocks, they absorb neutrons to such an extent that the chain reaction completely comes to halt.

v) **Safety rods:** These are used to reduce the neutrons rate to less than one abruptly to stop the chain reaction whenever required.

vi) **Protective Shielding:** To prevent the spreading of the radioactive effect to the space around the nuclear reactor, lead blocks, concrete walls of thickness 10 m are used.

vii) **Coolant:** The material used to absorb the heat generated in the reactor is called coolant. Commonly used coolants are light water, heavy water and sodium gas.

The coolant releases the heat energy to water and is thus converted into steam, which is used to run the turbines. These turbines in turn generate the power.

10. Radio-isotopes (Uses)

i) Radio-isotopes are produced in nuclear reactor.

ii) Isotopes are used to test wear and tear of engine parts like piston rings, gears, ball bearings and helps in deciding the efficiency of lubricants.

iii) Radio-iodine ($_{53}I^{131}$) has half life of 8 days is used in determining functioning of thyroid gland, information about the size and location of brain tumour.

iv) Restriction in blood circulation can be detected using radio sodium.

v) Leukemia disease is treated by radiation from radio-isotopes of phosphorus.

vi) To find the age of ancient objects found in excavations, manuscripts etc., the technique of radio-carbon dating is used.

vii) Radio-isotopes are used to test the metal castings and weldings.

11. Radiation hazards

i) Damage to the intestinal mucosa, impairment of the production of the blood corpuscles, damage to the system of producing antibodies which are important in the defence against infections, damage to the lens of the eye, production of cancers including leukemia etc.

ii) The radiation damage to human beings is due to intake of radioactive materials and exposure to radiation.

iii) Radio-iodine is extremely dangerous as it is concentrated in the thyroid gland, a very sensitive organ.

iv) Irradiation of the body with small dose of γ-rays or X-rays increases the body temperature.

v) Radiation causes genetic mutation.

vi) Radon inhaled is injurious to lungs.

vii) Because of small penetrating power of α-radiation into our bodies, its damage is the least. The main external hazard is posed by γ-rays and neutrons.

viii) To prevent radiation hazards, rules have been worked out by International Commission of Radiation Protection (ICRP).

ix) Tolerance doses which are permissible for individuals when exposed professionally.

B. Nuclear Fusion

1. The process of the formation of a single stable nucleus by fusing two or more lighter nuclei is called nuclear fusion.

   $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + 24\,MeV$.

2. If the energy released per nucleon in fusion is considered, then it is much higher in a fusion reaction than in the fission reaction, which is almost 7 times.
3. To carry out the fusion of two nuclei temperature nearly equal to 10^7 K is required. Once the fusion takes place the energy released can maintain the minimum required temperature for further and the fusion continues. Nuclear fusion reaction is also termed as thermo nuclear reaction. The secret behind the production of energy of the sun and the stars is nothing but the thermo nuclear reactions (Nuclear fusion).
4. Hydrogen bomb is based on the principle of nuclear fusion.
5. **Energy of the Sun and the Stars**

   Scientists proposed two types of cyclic processes for sources of energy in the sun and stars. The first one is known as carbon-nitrogen cycle and the second one is proton-proton cycle.

   1. Carbon-Nitrogen Cycle: Bethe (1938) proposed a set of reactions taking place in the central part of the sun and stars in which carbon and nitrogen act as catalysts.

   $^{1}_{1}H + ^{12}_{6}C \rightarrow ^{13}_{7}N + Q_1$

   $^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{1}e$

   $^{1}_{1}H + ^{13}_{6}C \rightarrow ^{14}_{7}N + Q_2$

   $^{1}_{1}H + ^{14}_{7}N \rightarrow ^{15}_{8}O + Q_3$

   $^{15}_{8}O \rightarrow ^{15}_{7}N + ^{0}_{1}e + Q_4$

   $^{1}_{1}H + ^{15}_{7}N \rightarrow ^{12}_{6}C + ^{4}_{2}He$

   All the above reactions are added to give the following net nuclear reaction.

   $4^{1}_{1}H \rightarrow ^{4}_{2}He + 2^{0}_{1}e + Q$

The above set of six reactions is called carbon-nitrogen cycle. In this process the four protons are fused to form 2 positrons and helium nuclei releasing 26.72 MeV of energy.

2. Proton-Proton Cycle: Recent experiments show that the carbon-nitrogen cycle comes at a rather late stage in the life of the stars. Scientists proposed another nuclear fusion cycle process which takes place comparatively at low temperatures than carbon-nitrogen cycle and gives the same amount of energy as shown below.

$${}_1^1H + {}_1^1H \rightarrow {}_1^2H + {}_1^0e + Q_1$$

$${}_1^1H + {}_1^2H \rightarrow {}_2^3He + Q_2$$

$${}_1^1H + {}_2^3He \rightarrow {}_2^4He + {}_1^0e + Q_3$$

On adding $4{}_1^1H \rightarrow {}_2^4He + 2{}_1^0e + Q$

Energy released in this cycle is 24.6 MeV.

6. At the interior of sun, the temperature is of the order of 2×10^6 K at which both of the above mentioned processes are equally probable. Stars having temperature more than that of sun obtain their energy from carbon-nitrogen cycle and the stars at low temperature follow proton-proton cycle in energy emission.
7. Positron is the anti-particle of electron and was first discovered by Anderson, although theoretically its existence was predicted by Dirac.
8. **Pair production**

   A γ-ray can disintegrate in to positron and an electron.

   $$\gamma \rightarrow e^+ + e^-$$

   The minimum energy of γ-ray to produce pair is 1.02 MeV.
9. **Pair Annihilation:** An electron and positron have the same mass and spin. However, they have the opposite charge. They annihilate each other, with the emission of 2 photons, when they come into contact. This is represented by the equation.

   $$e^- + e^+ = 2\gamma$$

   The two photons move in opposite direction.