Nuclear fission

Breaking up of a heavy nucleus into two or more relatively light fragments with release of large amount of energy.

Examples

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3\,^{1}_{0}n + Q$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{133}_{51}Sb + ^{99}_{41}Nb + 4\,^{1}_{0}n + Q$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2\,^{1}_{0}n + Q$$

In all examples notice that A and Z are always balanced

- Neutrons obtained directly during fission are called *prompt neutrons* and those obtained from further decay of daughter nuclei are called *delayed neutrons*.
- Neutrons are best suited projectiles to initiate nuclear reactions as they are not repelled by electrostatic forces when approaching a nucleus.

Average energy of the neutrons obtained in fission of U235 is 2 MeV.

Q value of a nuclear reaction is energy liberated in the reaction.

Note : Only one of the above reactions may be remembered as an example.

Nuclear chain reaction

It is a phenomenon in which the neutrons obtained in reaction initiate fission in other nuclei resulting in emission of more neutrons and this process continues.

A chain reaction may be controlled by suitable mechanism.

Neutron multiplication factor

Neutron multiplication factor (k) is a measure of number of neutrons and determines the nature of reaction.

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

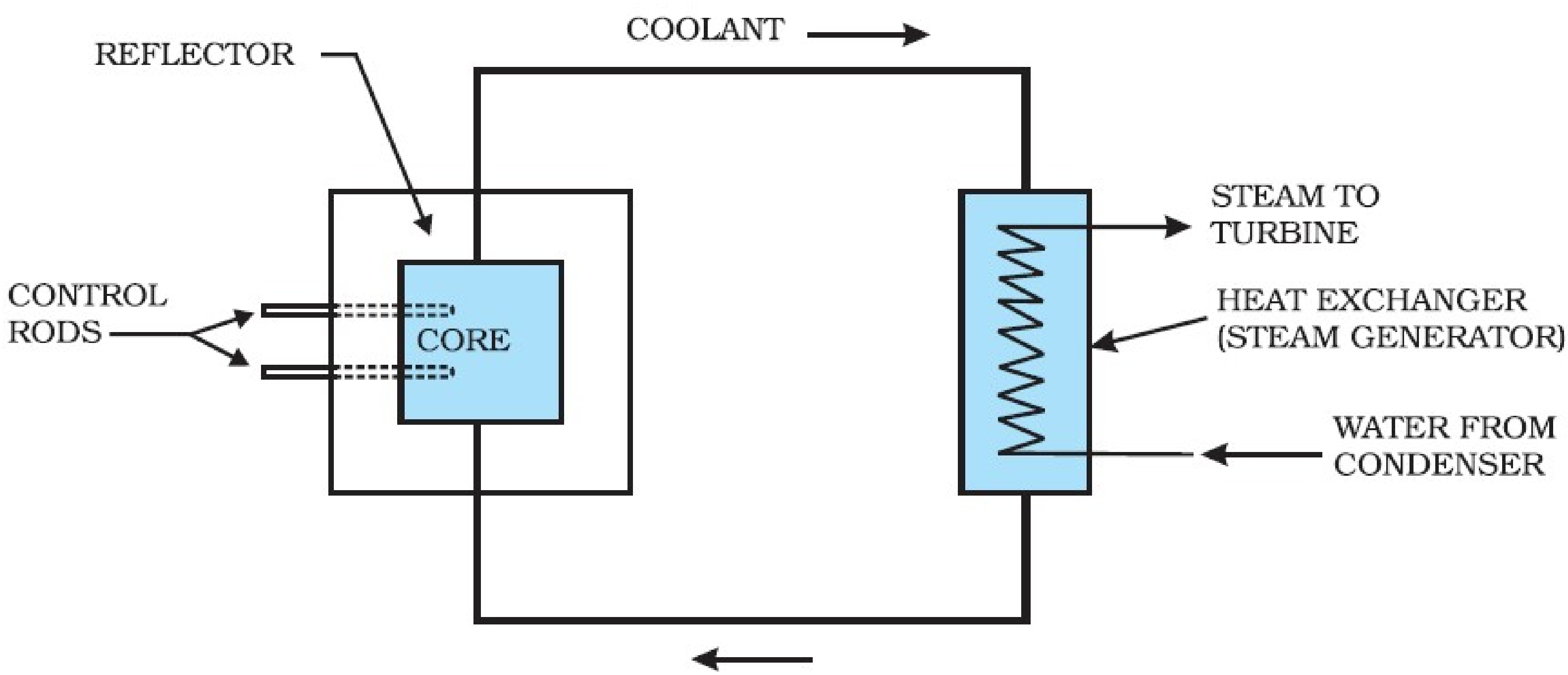
$k > 1$: supercritical state (increasing reaction rate)

$k = 1$: critical state (sustained reaction rate)

$k < 1$: subcritical state (decreasing reaction rate)

Nuclear reactor

Nuclear reactor is device used to initiate and sustain nuclear fission reaction.
Nuclear reactor works on the principle of energy obtained from a sustained and controlled chain reaction.



Schematic diagram of nuclear reactor

Nuclear reactor

Nuclear fuel : It is a highly radioactive material that undergoes fission reaction

All naturally occurring heavy metals are not radioactive. Naturally occurring metals are converted to highly radioactive nuclei by suitable mechanism.

Naturally occurring U238 is not fissionable. It is converted to highly radioactive plutonium through the following reactions

$$ {}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e + \bar{\nu} $$

$$ {}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e + \bar{\nu} $$

Plutonium thus obtained undergoes fission with slow neutrons.

U : uranium

Np : neptunium

Pu : plutonium

${}^{0}_{-1}e$: β particle

${}^{1}_{0}n$: neutron

ν : neutrino

$\bar{\nu}$: anti-neutrino

Nuclear reactor

Parts of a nuclear reactor

Core: It contains suitably fabricated fissionable material such as enriched uranium, moderators and control rods.

Moderators: These are used to reduce the energy of prompt neutrons to the level of *thermal neutrons* (having kinetic energy close to the average energy of the surrounding particles). This increases the probability of their initiating further fission reactions. Eg : Water, heavy water, graphite etc.

Control rods: Control rods are made up of high neutron absorbing materials. They are used to control the rate of reaction. Eg : cadmium

Coolant: Heat energy liberated due to fission reaction is drained out using a coolant. This heat is used to generate steam which is used to run turbines.

Shielding : Suitable shielding is used (concrete, lead etc) to protect the surrounding from nuclear radiation.

Nuclear fusion

It is combination of two light nuclei to form relatively heavy nucleus

Examples

$$ {}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{1}e + \nu $$

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n $$

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H $$

In all examples notice that A and Z are always balanced

Nuclear fusion is the basic reaction taking place in the sun, leading to emission of large amounts of heat and light.

Two of the most important reactions taking place in stars are

1. Carbon - Nitrogen cycle (at relatively high temperatures)
2. Proton - Proton cycle (at relatively low temperatures)

Interesting facts !

- The sun radiates about 10^{26} J of energy per second.
- Elements such as hydrogen and helium are in the state of plasma in the stars.
- Temperature inside the sun i.e. about 15 to 30 million degrees kelvin is favorable for such reactions
- In about 1 million years the sun loses about 10^{-7} of its mass due to the C-N cycle
- Considering the present age of the sun to be about 10^{10} years, this cycle will go on for another 30 billion years

Energy emitted from starts is due to continuous nuclear fusion reactions taking place in the stars. There are two predominant cycles of fusion reactions identified in stars.

Proton-proton cycle in stars

$$\left.\begin{array}{l} {}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{1}e + \nu + \text{energy} \\ {}^{0}_{1}e + {}^{0}_{-1}e \rightarrow \gamma + \gamma + \text{energy} \\ {}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma + \text{energy} \end{array}\right\}$$

The above set of reactions occur twice to give 1 helium isotope each. Two such unstable ^{3}He isotopes undergo fusion to resulting formation of a stable ^{4}He and two protons which again take part in subsequent fusion.

$${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}H + {}^{1}_{1}H + \text{energy}$$

Equivalent reaction

$$4\,{}^{1}_{1}H + 2\,{}^{0}_{-1}e \rightarrow {}^{4}_{2}He + 2\nu + 6\gamma \qquad 26.7\text{MeV}$$

Carbon-Nitrogen cycle in stars

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

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

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

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

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

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

Equivalent reaction

$$4\,^{1}_{1}H \rightarrow 2\,^{4}_{2}He + 2\,^{0}_{1}e + 2\nu + 25.6\text{MeV}$$

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