1. Nuclear Reaction

The process of bombarding a target nucleus by a fast moving projectile and the subsequent interaction between the two is known as the nuclear reaction. This is also known as an alteration of one element into another.

- Let a target nucleus X is bombarded by particle a. During this process a new nucleus Y is formed and a particle (or $\gamma-$ray) b is emitted. This nuclear reaction is expressed as:

  $a+X \rightarrow Y+b \quad or \quad X(a,b)Y$ ....(1)

  Example 1: $\alpha({}_2^4He)+{}_4^9Be \rightarrow {}_6^{12}C+n \quad or \quad {}_4^9Be(\alpha,n)\,{}_6^{12}C$

- If more than one particle (say b_1, b_2 and b_3) are emitted, then the reaction is expressed as

  $a+X \rightarrow Y+b_1+b_2+b_3 \quad or \quad X(a,b_1\,b_2\,b_3)Y$ .... (2)

  Example 2: ${}_7^{14}N+{}_{92}^{238}U \rightarrow {}_{97}^{243}Bk+\alpha({}_2^4He)+5n \quad or \quad {}_{92}^{238}U({}_7^{14}N,\,\alpha\,5n){}_{97}^{243}Bk$

1.1. Types of Nuclear Reactions:

There are two types of nuclear reactions. The first is based on the reaction mechanism while the second is based on the mass of the projectile.

a) Reactions based on the reaction mechanism:

- **Elastic Scattering**: in elastic scattering incident particle strikes the target nucleus and leaves the nucleus without any energy loss. The direction of the incident particle generally changes.
  $\alpha({}_2^4He)+{}_{82}^{208}Pb \rightarrow {}_{82}^{208}Pb+\alpha({}_2^4He)$
- **Inelastic Scattering:** in inelastic scattering the incident particle loses some of its kinetic energy to the target nucleus. The target nucleus is excited to the higher quantum state. This excited nucleus decays by $\gamma-$emission.

  $\alpha({}_2^4He)+{}_{26}^{56}Fe \rightarrow {}_{26}^{56}Fe^*+\alpha({}_2^4He)$

  where (*) on the product nucleus indicates that the nucleus is in the excited state.
- **Radiative Capture:** in such reactions incident particle is captured by the nucleus with the emission of γ-rays.
  $\alpha({}_2^4He)+{}_6^{12}C \rightarrow {}_8^{16}O^* \rightarrow {}_8^{16}O+\gamma$
- **Compound Nucleus Reactions:** the incident particle is absorbed by the target nucleus and a compound system is formed, then a particle or group of particles is ejected.
  $\alpha({}_2^4He)+{}_{13}^{27}Al \rightarrow {}_{15}^{31}P^* \rightarrow {}_{15}^{30}P+n$
- **Photodisintegration:** high energy $\gamma-$ray photons are absorbed by the nucleus and the nucleus ejects a particle or a group of particles.
  $\gamma+{}_8^{16}O \rightarrow {}_6^{12}C+2H+2n$

- **Direct Reaction:** there are two types of direct reactions:
    - Pickup Reactions: If the fast moving incident particle passes through the nucleus or becomes very close to the nucleus, it picks up one or a few nucleons from the nucleus and keeps on moving in the forward direction.
    $${}^{59}_{27}Co + {}^{2}_{1}H \rightarrow {}^{57}_{26}Fe + \alpha({}^{4}_{2}He) \quad (pickup\ \ reaction)$$
    - Stripping Reactions: If the fast moving incident particle passes through the nucleus or becomes very close to the nucleus, it loses one or a few nucleons to the nucleus and keeps on moving in the forward direction.
    $${}^{63}_{29}Cu + {}^{2}_{1}H \rightarrow {}^{64}_{29}Cu + {}^{1}_{1}H \quad (stripping\ \ reaction)$$

- **Heavy Ion Reactions:** the reaction in which the moving incident particle is a heavy ion. ${}^{207}_{82}Pb + {}^{107}_{47}Ag \rightarrow {}^{106}_{47}Ag + {}^{208}_{82}Pb$
- **Fission Reactions:** when heavy nuclei capture incident particle, they break into generally two fragments with the emission of few particles.
  ${}^{235}_{92}U + n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n$
- **Fusion Reactions:** when two light nuclei combine to form a heavier nucleus, the reaction is known as fusion reaction.
  ${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + n$
- **Elementary particle Production reactions:** when very high energy ($E > 300\,\text{MeV}$) incident particles like protons, etc. interact with protons or neutrons, variety of elementary particles like mesons, pions, etc. are produced.

b) Reactions based on the mass of projectile:

- **Reaction Induced by particles of mass 1 (proton or neutron):**
    - **proton-induced reactions:**

      (p,γ): ${}^{A}_{z}X + {}^{1}H \rightarrow {}^{A+1}_{z+1}Y + \gamma$

      (p,α): ${}^{A}_{z}X + {}^{1}H \rightarrow {}^{A-3}_{z-1}Y + \alpha$

      (p,n): ${}^{A}_{z}X + {}^{1}H \rightarrow {}_{z+1}{}^{A}Y + n$
    - **neutron-induced reactions:**

      (n,γ): ${}^{A}_{z}X + n \rightarrow {}^{A+1}_{z}Y + \gamma$

      (n,α): ${}^{A}_{z}X + n \rightarrow {}^{A-3}_{z-2}Y + \alpha$

      (n,p): ${}^{A}_{z}X + n \rightarrow {}_{z-1}{}^{A}Y + {}^{1}H$

      $(n,2n)$: ${}^{A}_{z}X + n \rightarrow {}^{A-1}_{z}Y + 2n$

- **Reaction Induced by particles of mass 2 (deuteron)**

  (d,p): ${}^{A}_{z}X + {}^{2}_{1}H \rightarrow {}^{A+1}_{z}Y + {}^{1}H$

  (d,n): ${}^{A}_{z}X + {}^{2}_{1}H \rightarrow {}^{A+1}_{z+1}Y + n$

  (d,t): ${}^{A}_{z}X + {}^{2}_{1}H \rightarrow {}^{A-1}_{z}Y + {}^{3}_{1}H$

- **Reaction Induced by particles of mass 3 ($_1^3H$ *and* $_2^3He$)**

  Such as: (t,d), (t,n), $(_2^3He, p)$, $(_2^3He, n)$

- **Reaction Induced by particles of mass 4 (α-particle)**

  (α, p): $_z^AX + _2^4He \rightarrow _{z+1}^{A+3}Y + {}^1H$

  (α, n): $_z^AX + _2^4He \rightarrow _{z+2}^{A+3}Y + n$

  $(\alpha, 2n)$: $_z^AX + _2^4He \rightarrow _{z+2}^{A+2}Y + 2n$

- **Reaction Induced by heavy ions**

  $_{13}^{27}Al(_7^{14}N, _7^{16}N)\ _{13}^{25}Al$

- **Reaction Induced by γ-rays**

  $_4^9Be + \gamma \rightarrow _4^8Be + n$

1.2. Conservation laws in nuclear Reactions:

- Conservation of mass – energy
- Conservation of linear momentum.
- Conservation of charge/ atomic number.
- Conservation of nucleons/ mass number.
- Conservation of angular momentum.
- Conservation of spin.
- Conservation of statistics.
- Conservation of parity.
- Conservation of Lepton number.

  Note: Leptons are spin ½ fermions which interact through the electromagnetic and weak interactions, but not through the strong interactions. Electron, Muon, and Tau particles are examples for leptons.

2. Compound Nucleus

Compound nucleus hypothesis was proposed in 1936 by Bohr. With this hypothesis, the nuclear reaction takes place in two stages: (a) Formation of compound nucleus (b) Decay of compound nucleus.

a) Formation of compound nucleus: the incident particle strongly interacts with the nucleons of the target nucleus, giving away its energy to all the nucleons. , Here, the incident particle losing its identity and becomes a part of the nucleus. This new formed nucleus is in a highly excited state and is called compound nucleus. The formation of compound nucleus is expressed as: $M_1 + M_2 \rightarrow M_C^*$

Examples: $_1^1H + _{29}^{63}Cu \rightarrow _{30}^{64}Zn^*$, $_2^4He + _{28}^{60}Ni \rightarrow _{30}^{64}Zn^*$

b) **Decay of compound nucleus:** the decay of compound nucleus is expressed as: $M_C^* \rightarrow M_3 + M_4$

The compound nucleus decays by one of the following modes:

$_{30}^{64}Zn^* \rightarrow _{30}^{63}Zn + n$, $_{30}^{64}Zn^* \rightarrow _{30}^{62}Zn + 2n$, $_{30}^{64}Zn^* \rightarrow _{29}^{62}Cu + n + _1^1H$

Notes:

1. The decay of compound nucleus is independent of the way that it was formed.
2. The decay of the compound nucleus depends upon the energy, angular momentum and parity brought in by the incident particle.

3. Nuclear Fission

A reaction $X(a,b)Y$ is called fission, if b and Y have comparable masses. The fission in some nuclei takes place spontaneously. Usually fission is produced only if sufficient energy is given to a nucleus by capture of a slow neutron or by bombardment with $n, p, d, \ldots$ or gamma rays. As far as we know, the fission process always proceeds through a compound nucleus stage. The compound nucleus breaks up into two parts with some prompt neutron emission.

4. Nuclear Fusion

Fusion of two lighter nuclei into one heavier nucleus is not so easy. Before combining the two light nuclei, their mutual Coulomb repulsion must be overcome. In contrast fission induced by thermal neutrons has no such Coulomb barrier and thus very low energy neutrons can induce fission in heavy nuclei. Suppose we wish to fuse two ^{20}Ne nuclei to form ^{40}Ca nucleus. The Coulomb barrier for two ^{20}Ne nuclei is about 21 MeV.

Unlike fission, fusion is not a natural process on earth. Like we have spontaneous fission, spontaneous fusion does not exist. This is because of the limitation imposed due to the Coulomb barrier. However, once we overcome Coulomb barrier, fusion becomes a dominant mode as two fusion nuclei quickly reach a state of minimum energy.

5. Stellar Burning

a) Proton-proton Cycle

$$p + p \rightarrow d + e^{+} + \upsilon + 0.42\,MeV$$
$$p + d \rightarrow {}^{3}_{2}He + \gamma + 5.49\,MeV$$
$${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + p + p + 12.86\,MeV$$

b) Carbon- Nitrogen Cycle

$$p + {}^{12}_{6}C \rightarrow {}^{13}_{7}N + \gamma + 1.95\,MeV$$
$${}^{13}_{7}N \rightarrow {}^{13}_{6}C + e^{+} + \upsilon + 1.20\,MeV$$
$$p + {}^{13}_{6}C \rightarrow {}^{14}_{7}N + \gamma + 7.55\,MeV$$
$$p + {}^{14}_{7}N \rightarrow {}^{15}_{8}O + \gamma + 7.34\,MeV$$
$${}^{15}_{8}O \rightarrow {}^{15}_{7}N + e^{+} + \upsilon + 1.68\,MeV$$
$$p + {}^{15}_{7}N \rightarrow {}^{12}_{6}C + {}^{4}_{2}He + 4.96\,MeV$$

c) Deuteron- Deuteron Cycle

$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H + 4.0\,MeV$$
$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + n + 3.2\,MeV$$
$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + n + 17.6\,MeV$$