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Nuclear Reactions : Q Equation

6.1 Nuclear reactions

Our knowledge of nuclear structure is mostly the outcome of experiments of bombarding a nucleus with various projectiles such as protons, neutrons, deuterons, α-particles etc. On bombardment, the mass number or atomic number or both of the target nucleus may change, that is, nuclear transmutation may occur. A *nuclear reaction* is then said to take place. A *nuclear reaction* is thus a process that occurs when a nuclear particle, such as proton, neutron, deuteron, α-particle, a nucleus etc., comes in close contact (within 10^{-15} m) with another, and energy and momentum exchanges take place. The final products are also some nuclear particle(s) that leave the point of contact in different directions. The process results in the *transmutation* of the target nucleus.

Changes in a nuclear reaction usually involve *strong nuclear force*. Processes that involve weak interactions (e.g. β-decay) or are purely electromagnetic (e.g. Coulomb scattering) are *not usually included* under nuclear reactions. Changes of nuclear states due to e.m interactions however are included.

Like a chemical reaction, a nuclear reaction has also a reaction equation. A *general equation* representing a ***nuclear reaction*** is of the form :

$$X + x \rightarrow Y + y \quad \text{or,} \quad X(x, y)Y$$

where **X, Y are target and product nuclei, x and y are bombarding and ejected particles.**

In a nuclear reaction, charge number, mass number, total energy etc. are conserved.

${}_2He + {}_2He$ or, ${}_3Li\,(p, \alpha)\,{}_2He$

6.3 Types of nuclear reactions

On the basis of the projectile used, the particle ejected and the residual nucleus formed, there are different types of nuclear reactions classified as follows.

1. Elastic scattering — In *elastic scattering* reaction, *the projectile and the outgoing particle are the same*, i.e., the projectile is scattered in different directions and there is no loss of energy. The *residual nucleus is the same as the target nucleus* and is left in the ground state as the latter. So, it can be represented as $X(x, x)X$. An example of elastic scattering is the scattering of neutrons by graphite : $^{12}C\ (n, n)\ ^{12}C$.

2. Inelastic scattering — In *inelastic scattering*, the *projectile and the outgoing particle are also the same.* They are scattered in different directions with different energy, as there is loss of energy due to collision. The residual nucleus, which is the same as target nucleus, is left in an *excited state* so that the process can be represented as $X(x, x)X^*$. An example is the collision of fast neutrons and U-238.

3. Pickup reactions — When the projectile gains nucleons from the target, the nuclear reaction is called ***pickup reaction.*** For example,

$$^{16}_{8}O\ \left(^{2}_{1}H, ^{3}_{1}H\right)\ ^{15}_{8}O$$

4. Stripping reactions — In ***stripping reactions***, one or more nucleons from the projectile are captured by the target nucleus i.e., the projectile loses nucleons to the target; the remaining stripped nucleus is emitted in a different direction.

- In pickup or stripping reactions, the involved nucleon is assumed to enter or leave (the shell of) the target nucleus without disturbing the other nucleons. So, these reactions are also called ***direct reactions.***

5. Compound nuclear reactions — Here the incident projectile A is captured by the target nucleus B to form a compound nucleus C^* in an *excited* state. The de-excitation of the compound nucleus C^* occurs into a product nucleus D and an emission of a particle E or a γ-photon.

So, this type of nuclear reaction may be represented by $A + B \to C^* \to D + E$.

The ***same compound nucleus may be formed in a number of different ways and may also decay in a number of ways independent of the mode of its formation.*** For instance, the compound nucleus $^{64}_{30}Zn$ may be formed in an excited state $(^{64}_{30}Zn)^*$ by two different ways and then decays variously as shown :

1. $^{63}_{29}\text{Cu} + ^{1}_{1}\text{H} \rightarrow \left(^{64}_{30}\text{Zn}\right)^{*} \rightarrow ^{63}_{30}\text{Zn} + ^{1}_{0}\text{n}$

$\rightarrow ^{62}_{30}\text{Zn} + ^{1}_{0}\text{n} + ^{1}_{0}\text{n}$

$\rightarrow ^{62}_{29}\text{Cu} + ^{1}_{0}\text{n} + ^{1}_{1}\text{H}$

2. $^{60}_{28}\text{Ni} + ^{4}_{2}\text{He} \rightarrow \left(^{64}_{30}\text{Zn}\right)^{*} \rightarrow ^{63}_{30}\text{Zn} + ^{1}_{0}\text{n}$

$\rightarrow ^{62}_{30}\text{Zn} + ^{1}_{0}\text{n} + ^{1}_{0}\text{n}$

$\rightarrow ^{62}_{29}\text{Cu} + ^{1}_{0}\text{n} + ^{1}_{1}\text{H}$

● We shall study Bohr's idea of compound nucleus and the experimental investigations of the above reactions by Ghoshal later in appropriate time and place.

6. Radiative capture — Here, the incident particle is absorbed by the target nucleus to form the excited compound nucleus which disintegrates to produce one or more *γ-photons* and goes down to the ground state. So the process is $X(x, \gamma)Y$.

7. Photodisintegration — Here, a very *energetic photon is absorbed* by the target nucleus so that it is raised to an excited state and subsequently disintegrates. It can be represented as $X(\gamma, y)Y$.

There are many other types of nuclear reactions such as *elementary particle reaction* involving production of elementary particles, *many body reaction* in which two or more particles are emitted by the compound nucleus, ***nuclear fission*** in which heavy nuclei disintegrate into two nuclei of comparable size, ***nuclear fusion*** in which light nuclei combine to form a heavier nucleus etc.

● So, nuclear reactions can be broadly divided into two distinct classes known as ***compound nuclear reactions*** and *direct reactions*.

In the former, the incident particle is captured to form a nucleus in highly excited state, called ***compound nucleus*** which then decays.

In *direct reactions*, the incident nucleon interacts with the nucleus as it passes, without forming an intermediate state. A quantitative difference between the two types of reactions is the time of interaction. In direct reaction, it is of the order of time of transit of the incident particle over a nuclear diameter, which is $\sim 3 \times 10^{-22}$ s (nuclear time). The fastest decay time known is longer than this by several orders of magnitude.

● **Neutron activation**—Neutrons are electrically neutral and so interact more easily with nuclei. When a nucleus is bombarded by neutrons, a compound nucleus is formed. For instance, when $^{113}_{48}\text{Cd}$ is bombarded by neutrons, the compound nucleus $^{144}_{48}\text{Cd}^{*}$ results which decays as

$$^{113}_{48}\text{Cd} + ^{1}_{0}\text{n} \rightarrow ^{114}_{48}\text{Cd}^{*} = ^{114}_{48}\text{Cd} + \gamma.$$

The γ-ray energies and intensities are characteristic of ^{114}Cd nucleus. Since they are unique, the compound nucleus $^{114}\text{Cd}^{*}$ and the target nucleus ^{113}Cd may be identified. The general technique, known as ***neutron activation analysis***, is a powerful method of identifying elements.