Nuclear Reactions

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Nuclear Reactions

- A nuclear reaction is considered to be the process in which two nuclear particles (two nuclei or a nucleus and a nucleon) interact to produce two or more nuclear particles or γ-rays. Thus, **nuclear reaction** must cause a transformation of at least one nuclide to another.
  Natural nuclear reactions occur also in the interaction between cosmic rays and matter.
- The most notable **man-controlled nuclear reaction** is the fission reaction which occurs in **nuclear reactors**.

Nuclear Reactors are devices to initiate and control a nuclear chain reaction.

Nuclear Scattering

If a nucleus interacts with another nucleus or particle without changing the nature of any nuclide, the process is referred to a **nuclear scattering**, rather than a nuclear reaction.

- **Elastic Scattering:** Occurs, when no energy is transferred between the target nucleus and the incident particle.

$$^{208}Pb\ (n, n)\ ^{208}Pb$$

- **Inelastic Scattering:** Occurs, when energy is transferred. The difference of kinetic energies is saved in excited nuclide.

$$^{40}Ca\ (\alpha, \alpha')\ ^{40*}Ca$$

Notation of Nuclear Reactions

- Standard nuclear notation shows the chemical symbol, the mass number and the atomic number of the isotope.

- If the initial nuclei are denoted by ***a*** and ***b***, and the product nuclei are denoted by ***c*** and ***d***, the reaction can be represented by the equation:

$$a + b \rightarrow c + d$$

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He + 2.8\,Mev$$

- Instead of using the full equations in the style above, in many situations a compact notation is used to describe nuclear reactions.
- This style of the form **a(b,c)d** is equivalent to **a** + **b** producing **c** + **d**.
- Light particles are often abbreviated in this shorthand, typically p means proton, n(neutron), d(deuteron), α(alpha particle or helium-4), β(beta particle or electron), γ (gamma photon) etc.
- The previous reaction would be written as **10B(n,α)7Li.**

Basic Classification of Nuclear Reactions

- Interaction time is critical for defining the reaction mechanism.
- The classification; according to **the time scale** of reactions, there are **two extreme scenarios** for nuclear reactions; Direct Reactions and Compound Nuclear Reactions

➢ **A)-Direct Reactions**

A projectile and a target nucleus are within the range of nuclear forces for **the very short time** allowing for an **interaction of a single nucleon only.**

- In fact, there is always some **non-direct** (multiple internuclear interaction) component in all reactions, but the direct reactions have this component limited.

B)-Compound Nuclear Reactions

A projectile and a target nucleus are within the range of nuclear forces for the time allowing for a **large number of interactions between nucleons.**

Types of Nuclear Reactions

Although the number of possible **nuclear reactions** is enormous, these can be sorted by types. Most of nuclear reactions are accompanied by gamma emission. Some types are:

- **Capture Reactions:** Both charged and neutral particles can be captured by nuclei. This is accompanied by the emission of γ–rays. Neutron capture reaction produces radioactive nuclides (induced radioactivity).

238U (n, γ) 239U

- **Transfer Reactions:** The absorption of a particle accompanied by the emission of one or more particles is called the transfer reaction.

$$4He\ (\alpha, p)\ 7Li$$

- **Fission Reactions :** Nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and photons (in the form of gamma rays), and releases a large amount of energy.

$$235U(n,3\ n)\textit{fission products}$$

- **Fusion reactions:** Occur when, two or more atomic nuclei collide at a very high speed and join to form a new type of atomic nucleus. The fusion reaction of deuterium and tritium is particularly interesting because of its potential of providing energy for the future.

3T (d, n) 4He

- **Spallation reactions:** Occur, when a nucleus is hit by a particle with sufficient energy and momentum to knock out several small fragments or, smash it into many fragments.

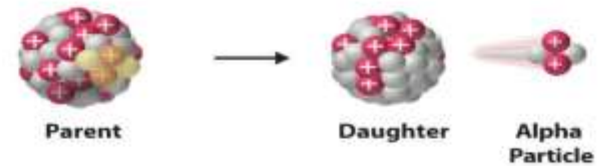
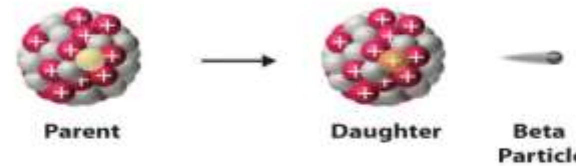
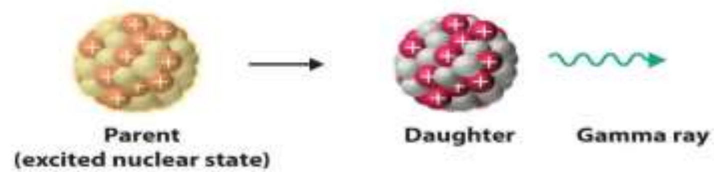
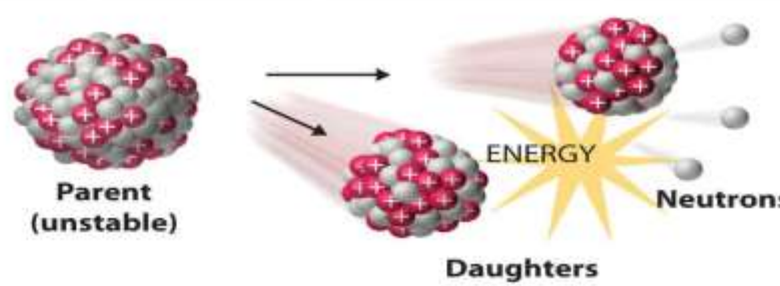
- **Nuclear decay (Radioactive decay):** Occurs when an unstable atom loses energy by emitting ionizing radiations. There are many types of radioactive decay:
  Alpha radioactivity: Alpha particles consist of two protons and two neutrons bound together into a particle identical to a helium nucleus.

  Beta radioactivity: Beta particles are high-energy, high-speed electrons or positrons emitted by certain types of radioactive nuclei such as potassium-40.

Gamma radioactivity: They are produced by the decay of nuclei as they transition from a high energy state to a lower state known as gamma decay. Most of nuclear reactions are accompanied by gamma emission.

Neutron emission : Neutron emission is a type of radioactive decay of nuclei containing excess neutrons (especially fission products), in which a neutron is simply ejected from the nucleus.

This type of radiation plays key role in nuclear reactor control.

Decay Type	Radiation Emitted	Generic Equation	Model
Alpha decay	${}^{4}_{2}\alpha$	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$	
Beta decay	${}^{0}_{-1}\beta$	${}^{A}_{Z}X \longrightarrow {}_{Z+1}{}^{A}X' + {}^{0}_{-1}\beta$	
Positron emission	${}^{0}_{+1}\beta$	${}^{A}_{Z}X \longrightarrow {}_{Z-1}{}^{A}X' + {}^{0}_{+1}\beta$	
Electron capture	X rays	${}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}_{Z-1}{}^{A}X' + \text{X ray}$	
Gamma emission	${}^{0}_{0}\gamma$	${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$	
Spontaneous fission	Neutrons	${}^{A+B+C}_{Z+Y}X \longrightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n$	

Conservation Laws in Nuclear Reactions

For purposes of analyzing non-relativistic reactions, it is sufficient to note four of the fundamental laws governing these reactions.

1-Conservation of nucleons. The total number of nucleons before and after a reaction are the same.

2-Conservation of charge. The sum of the charges on all the particles before and after a reaction are the same

3-Conservation of momentum. The total momentum of the interacting particles before and after a reaction are the same.

4-Conservation of energy. Energy, including rest mass energy, is conserved in nuclear reactions

Energetics of Nuclear Reactions (Q value)

- In nuclear and particle physics the energetics of nuclear reactions is determined by the Q-value of that reaction.

- The Q-value of the reaction is defined as the difference between the sum of the mass energies of the initial reactants to the sum of the mass energies of the final products, in energy units (usually in MeV).

- Consider a typical reaction, in which the projectile a and the target A gives place to two products, B and b.

This can also be expressed in the notation that we used so far,

$$\mathbf{a + A \rightarrow B + b} \qquad \text{or}$$

$$\mathbf{A(a,b)B}$$

The Q-value of this reaction is given by:

$$Q = [m_a + m_A - (m_b + m_B)]c^2 \qquad (\text{As } E=mc^2)$$

which is the same as the excess kinetic energy of the final products:

$$Q = T_{final} - T_{initial}$$

$$= (T_b + T_B) - (T_a + T_A)$$

On the base of Q value, the reactions are divided into two types.

1-Exothermic (or **exoergic**).

The reactions in which there is an increase in the kinetic energy of the productsi.e.**Q is positive**.

For exothermic reactions $Q > 0$ & $M_R > M_P$ some of the mass energy is converted to kinetic energy. There is a net release of energy.

2- **Endothermic** (or **endoergic**)

The reactions in which there is a decrease in the kinetic energy of the products i.e.**Q is negative**.

For endothermic reactions $Q < 0$ & $M_R < M_P$ some of the incoming particle's kinetic energy is converted to mass. They require a net energy input.

- The **energy released in a nuclear reaction** can appear mainly in one of three ways:

(a) Kinetic energy

Kinetic energy of the products

(b) Emission of gamma rays

Gamma rays are emitted by unstable nuclei in their transition from a high energy state to a lower state known as gamma decay.

(c) Metastable state

Some energy may remain in the nucleus, as a metastable energy level.

- A small amount of energy may also emerge in the form of X-rays.

- Generally, products of nuclear reactions may have different atomic numbers, and thus the configuration of their electron shells is different in comparison with reactants.

- As the **electrons rearrange** themselves and drop to lower energy levels, i.e. in internal conversion X-rays may be emitted (atom electron interaction).