Chapter III :

Radioactivity

1. Introduction :

Atomic theory in the nineteenth century presumed that nuclei had fixed compositions. But in 1896, the French scientist ***Henri Becquerel*** found that a uranium compound placed near a photographic plate made an image on the plate, even if the compound was wrapped in black cloth. He reasoned that the uranium compound was emitting some kind of radiation that passed through the cloth to expose the photographic plate. Further investigations showed that the radiation was a combination of particles and electromagnetic rays, with its ultimate source being the atomic nucleus. These emanations were ultimately called, collectively, **radioactivity**.

Following the somewhat serendipitous discovery of radioactivity by Becquerel, many prominent scientists began to investigate this new, intriguing phenomenon. Among them were Marie Curie (the first woman to win a Nobel Prize, and the only person to win two Nobel Prizes in different sciences—chemistry and physics), who was the first to coin the term "radioactivity," and Ernest Rutherford (of gold foil experiment fame), who investigated and named three of the most common types of radiation. During the beginning of the twentieth century, many radioactive substances were discovered, the properties of radiation were investigated and quantified, and a solid understanding of radiation and nuclear decay was developed.

The spontaneous change of an unstable nuclide into another is **radioactive decay**. The unstable nuclide is called the **parent nuclide**; the nuclide that results from the decay is known as the **daughter nuclide**. The daughter nuclide may be stable, or it may decay itself. The radiation produced during radioactive decay is such that the daughter nuclide lies closer to the band of stability than the parent nuclide, so the location of a nuclide relative to the band of stability can serve as a guide to the kind of decay it will undergo.

There are approximately 270 stable isotopes and 50 naturally occurring radioisotopes (radioactive isotopes). Thousands of other radioisotopes have been made in the laboratory.

2. Natural radioactivity :

It is an atomic property of some materials where the latter emit different radiation on their own, and these radiation are accompanied by the disintegration of the nucleus, called the radioactive nucleus, while the nucleus that does not disintegrate is called the stable nucleus. Radiation disintegration is usually accompanied by a change in A and Z.

3. Major Forms of Radioactivity

- ### Alpha Particle (α) :

Rutherford's experiments demonstrated that there are three main forms of radioactive emissions. The first is called an **alpha particle**, which is symbolized by the Greek letter α. An alpha particle is composed of two protons and two neutrons and is the same as a helium nucleus. (We often use ${}_{2}^{4}He$ to represent an alpha particle.) It has a 2+ charge. When a radioactive atom emits an alpha particle, the original atom's atomic number decreases by two (because of the loss of two protons), and its mass number decreases by four (because of the loss of four nuclear particles). We can represent the emission of an alpha particle with a chemical equation—for example, the alpha-particle emission of uranium-235 is as follows:

$$ {}^{235}_{92}U \longrightarrow \underbrace{{}^{4}_{2}He}_{\alpha \text{ particle}} + {}^{231}_{90}Th $$

- ### Beta Particle (β) :

The second type of radioactive emission is called a **beta particle**, which is symbolized by the Greek letter β. A beta particle is an electron ejected from the nucleus (not from the shells of electrons about the nucleus) and has a -1 charge. We can also represent a beta particle as ${}_{-1}^{0}e$. The net effect of beta particle emission on a nucleus is that a neutron is converted to a proton. The overall mass number stays the same, but because the number of protons increases by one, the atomic number goes up by one. Carbon-14 decays by emitting a beta particle:

$$ {}^{14}_{6}C \longrightarrow {}^{14}_{7}N + \underbrace{{}^{0}_{-1}e}_{\beta \text{ Particle}} $$

- ### Gamma Radiation (γ) :

The third major type of radioactive emission is not a particle but rather a very energetic form of **electromagnetic radiation** called **gamma rays**, symbolized by the Greek letter γ. In gamma decay, depicted, a nucleus changes from a higher energy state to a lower energy state through the emission of electromagnetic radiation (photons).

The number of protons (and neutrons) in the nucleus does not change in this process, so the parent and daughter atoms are the same chemical element. In the gamma decay of a nucleus, the emitted photon and recoiling nucleus each have a well-defined energy after the decay. The characteristic energy is divided between only two particles.
For example, in the decay of radioactive technetium-99, a gamma ray is emitted. Note that in radioactive decay where the emission of gamma radiation occurs, that the identity of the parent material does not change, as no particles are physically emitted.

$$^{99m}_{43}Tc \longrightarrow \ ^{99}_{43}Tc + \underbrace{^{0}_{0}\gamma}_{\gamma \text{ ray}}$$

Alpha, beta, and gamma emissions have different abilities to penetrate matter. The relatively large alpha particle is easily stopped by matter (although it may impart a significant amount of energy to the matter it contacts). Beta particles penetrate slightly into matter, perhaps a few centimeters at most. Gamma rays can penetrate deeply into matter and can impart a large amount of energy into the surrounding matter. Table 1 summarizes the properties of the three main types of radioactive emissions and the next figure summarizes the ability of each radioactive type to penetrate matter.

Table.1 The Three Main Forms of Radioactive Emissions

Characteristic	Alpha Particles	Beta Particles	Gamma Rays
Symbols	α, $^{4}_{2}He$	β, $^{0}_{-1}e$	γ
Identity	Helium nucleus	electron	Electromagnetic radiation
Charge	2+	1-	None
Mass Number	4	0	0
Penetrating Power	Minimal (will not penetrate skin)	Short (will penetrate skin and some tissues slightly)	Deep (will penetrate tissues deeply)

4. Radioactivity Laws:

4-1. Law of Radioactive Disintegration :

- Atoms of all radioactive elements undergo spontaneous disintegration and form new radioactive elements. The disintegration is accompanied by the emission of **α**, **β**, or γ-rays.
- The disintegration is at random, every atom has equal chance for disintegration at any time.
- The number of atoms that disintegrate per second is directly proportional to the number of remaining unchanged radioactive atoms present at any time. The disintegration is independent of all physical and chemical conditions like temperature, pressure chemical combination etc.

$$dN/dt \propto N \ (1)$$

N: number of atoms present at time t.

Removing proportionality sign, we get

$$dN/dt = -\lambda N \ (2)$$

λ: decay constant of the element.

Negative sign indicates that as t increases N decreases.

Rewriting Eq. (2) as $dN/dt = -\lambda dt$

Integrating both sides, we have $dN/N = -\lambda \quad dt$

$$\int_{N_0}^{N_t} \frac{dN}{N} = -\lambda \int_0^t dt$$

at t = 0, N $= N_0$, we get :

N_0 is the initial quantity of the substance that will decay (this quantity may be measured in grams, moles, number of atoms, etc.),

$$\ln N \Big]_{N_0}^{N_t} = -\lambda\, t \Rightarrow ln \frac{N_t}{N_0} = -\lambda\, t$$

$\Rightarrow \frac{N_t}{N_0} = e^{-\lambda\, t} \Rightarrow N_t = N_0$ It's the law of radioactivity.

4-2. Half-life :

half-life, in radioactivity, the interval of time required for one-half of the atomic nuclei of a radioactive sample to decay (change spontaneously into other nuclear species by emitting particles and energy), or, equivalently, the time interval required for the number of disintegrations per second of a radioactive material to decrease by one-half.

This half-life is a time that is unique time to each radioisotope of an element. Half-lives can range from less than a millionth of a second to millions of years. The half-life can be mathematically expressed as the point in time when N(t) is one half of N_0.

Replacing this expression in the law of radioactivity, where $t_{1/2}$ is the half-life, gives:

$$N_t = N_0 e^{-\lambda t_{\frac{1}{2}}} \Rightarrow \frac{N_0}{2} = N_0 e^{-\lambda t_{\frac{1}{2}}} \Rightarrow \frac{1}{2} = e^{-\lambda t_{\frac{1}{2}}}$$

Taking the logarithm of both sides of the above equation and solving for the half-life t1/2 gives:

$$\mathbf{\ln 2 = \lambda\, t_{\frac{1}{2}} \Rightarrow t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}}$$

4-3. Activity (A):

The number of radioactive nuclei cannot be measured directly. One can only determine the rate of transformation called the activity by measuring the particles emitted. It is proportional to the number of atoms :

$$A = - dN/dt = -\lambda N$$

The activity represents the number of disintegrations per second and it is measured in Becquerel Bq. [Bq] = dps. The old unit of activity was Curie Ci and represented the activity of 1g of Radium-226. 1Ci = $3.7 \cdot 10^{10}$ Bq, so 1 mCi = 37 MBq; and 1 µCi = 37 kBq.

4-4. The relationship between disintegration and activity :

$$N_t = N_0 e^{-\lambda t}$$

$$A = \lambda N \Rightarrow N = \frac{A}{\lambda} \Rightarrow$$

$$\frac{A}{\lambda} = \frac{A_0}{\lambda} e^{-\lambda t} \Rightarrow A_t = A_0 e^{-\lambda t}$$

4-5. The relationship between disintegration and mass :

$$N = \frac{m.\mathrm{N_A}}{M}, \qquad N_0 = \frac{m_0.\mathrm{N_A}}{M}$$

$$N_t = N_0 e^{-\lambda t} \Rightarrow \frac{m.\mathrm{N_A}}{M} = \frac{m_0.\mathrm{N_A}}{M} e^{-\lambda t}$$

$$\Rightarrow m_t = m_0 e^{-\lambda t}$$

5- Artificial radioactivity and nuclear reactions

These reactions occur when stable isotopes are bombarded with particles such as neutrons. This method of inducing a nuclear reaction to proceed is termed **artificial radioactivity**. This meant new nuclear reactions, which wouldn't have been viewed spontaneously, could now be observed.

5-1. Types of Nuclear Reactions :

Although the number of possible **nuclear reactions** is enormous, nuclear reactions can be sorted by type. Most nuclear reactions are accompanied by gamma emissions. Some examples are:

- **Elastic scattering**. In elastic scattering, the kinetic energy of a particle is conserved in the center-of-mass frame, but its direction of propagation is modified. There is no energy transferred into nuclear excitation in an elastic scattering reaction. It is a crucial reaction for neutron moderators in nuclear reactors. To be an effective moderator, the probability of an elastic reaction between the neutron and the nucleus must be high.

  ^{1}H (n, n) ^{1}H

- **Inelastic scattering**. In inelastic scattering, the particle is absorbed and then re-emitted. The difference of kinetic energies is saved in an excited nuclide. An inelastic scattering plays an important role in slowing down neutrons, especially at high energies and by heavy nuclei.

  ^{238}U (n, n’) ^{238}U*

- **Capture reaction**. The capture reaction is one of the two possible absorption reactions that may occur. Capture reactions result in the loss of a neutron coupled with the production of one or more gamma rays. The resulting nucleus may also undergo a subsequent decay, such as beta decay in this example, which is a very important reaction in nuclear fuel.

$$^{238}\mathbf{U}\ (\mathbf{n}, \gamma)\ ^{239}\mathbf{U}$$

- **Transfer Reaction**. Transfer reactions are nuclear reactions in which one or more nucleons are transferred to the other nucleus. Transfer reactions can occur from the projectile to the target; stripping reactions, or from the target to the projectile; pick-up reactions. These reactions are common in particle accelerators and astrophysics.

$$^{4}\mathbf{He}\ (\alpha, \mathbf{p})\ ^{7}\mathbf{Li}$$

- **Fission reactions**. Nuclear fission is a nuclear reaction in which the 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.

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

- **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 exciting because of its potential of providing energy for the future.

$$^{3}\mathbf{T}\ (\mathbf{d}, \mathbf{n})\ ^{4}\mathbf{He}$$

- **Spallation reactions**. Spallation reaction occurs when a particle hits a nucleus with sufficient energy and momentum to knock out several small fragments or smash them into many fragments. Nuclear spallation is one of the processes by which a particle accelerator may be used to produce a beam of neutrons.

$$^{209}\mathbf{Bi}\ (\alpha,\mathbf{xn})^{213\text{-}x}\mathbf{At}$$

5-2. Energy of a nuclear reaction :

During nuclear changes, either some mass is converted into energy or some energy is converted into mass. Which occurs is dependent upon the specifics of the individual reaction. From this change in mass we can calculate its energy equivalent using Einstein's equation, $\Delta E = mc^2$.

- **Determining the Energy Change of a Nuclear Reaction**

To find the energy change for a nuclear reaction you must know the masses of each species in the equation for the reaction. To calculate the energy change for a nuclear reaction:

- Calculate the sum of the masses of all of the products, and the sum of the masses of all the reactants,

- Calculate the change in mass by subtracting the combined mass of the reactants from the combined mass of the products,
- Convert the change in mass into its equivalent change in energy using Einstein's equation.
- Convert the energy change from J/atom to kJ/mol of atoms.

Example: Calculate the energy change for the following nuclear reaction. The masses of each species are given below.

$$1 \text{ neutron} + {}^{235}U \rightarrow {}^{89}Rb + {}^{144}Ce + 3 \text{ electrons} + 3 \text{ neutrons}$$

Masses:

neutron = 1.00867 amu

electron = 0.00055 amu

uranium-235 = 234.9934 amu

rubidium-89 = 88.8913 amu

cerium-144 = 143.8817 amu

- Calculate the combined masses of the products and of the reactants.

Mass of Products = 88.8913 amu + 143.8817 amu + 3 (0.00055 amu) + 3 (1.00867 amu) = 235.8007 amu

Mass of Reactants = 1.00867 amu + 234.9934 amu = 236.0021 amu

- Calculate the change in mass for the reaction (mass of products - mass of reactants).

Δmass = 235.8007 amu - 236.0021 amu = - 0.2014 amu

- Convert the change in mass into energy using Einstein's equation. Remember to change the mass into kilograms.

$\Delta E = (-\,0.2014 \text{ amu})(1.6606 \times 10^{-27} \text{ kg/amu})(2.9979 \times 10^{8} \text{ m/s})^2 = -\,3.006 \times 10^{-11} \text{ J}$

- Convert the energy change per atom of uranium-235 into kJ/mol of uranium-235.

$(-\,3.006 \times 10^{-11} \text{ J/atom})(1 \text{ kJ/1000 J})(6.023 \times 10^{23} \text{ atoms/mol}) = -\,1.811 \times 10^{10}$ kJ/mol of U-235

Note: The negative sign indicates that this nuclear reaction is **exothermic**.

6- radiation families :

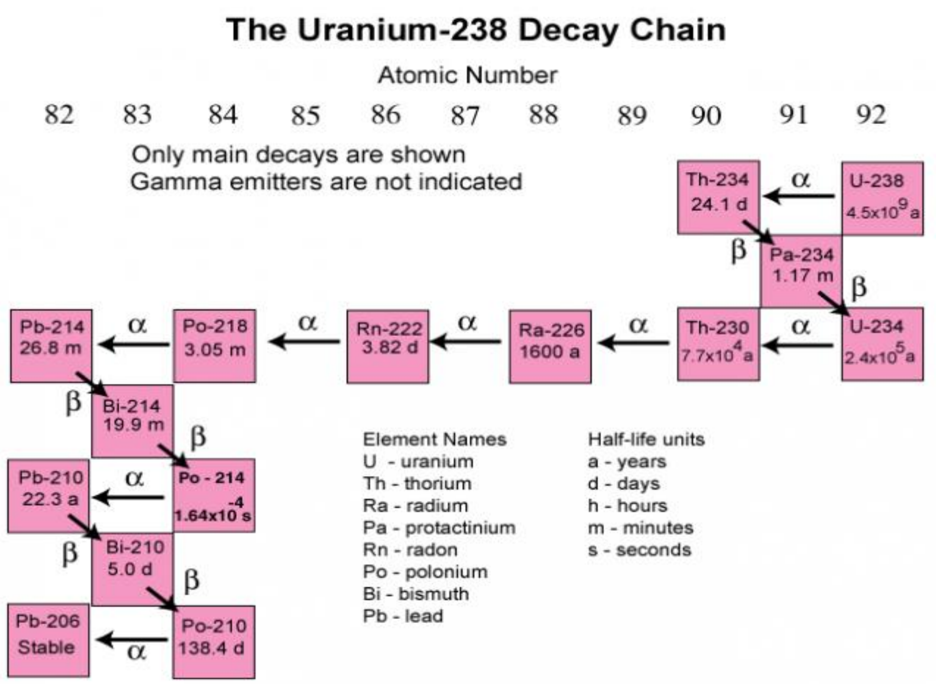
Scientists have found four principal families, or decay series, of radioactive substances—**the uranium-radium family; the actinium family; the thorium family; and the neptunium family**.

When it decays, a radionuclide transforms into a different atom - a decay product. The atoms keep transforming to new decay products until they reach a stable state and are no longer radioactive. The majority of radionuclides only decay once before becoming stable. Those that decay in more than one step are called series radionuclides. The series of decay products created to reach this balance is called the.

Each series has its own unique decay chain. The decay products within the chain are always radioactive. Only the final, stable atom in the chain is not radioactive. Some decay products are a different chemical element.

Every radionuclide has a specific decay rate, which is measured in terms of "." Radioactive half-life is the time required for half of the radioactive atoms present to decay. Some radionuclides have half-lives of mere seconds, but others have half-lives of hundreds or millions or billions of years.

- Uranium-238 decay chain is shown below:



7- radioactivity Applications :

- **Use of radioactive isotope :**

Radioactive isotopes have many useful applications. In medicine, as tracers for diagnostic purposes as well as in research on metabolic processes.

- **Uses of radioactivity :**

1. Medical use: Many diseases such as cancer are cured by radio therapy. Sterilization of medical instruments and food is another common application of radiation.
2. Scientific use: Alpha particles emitted from the radio isotopes are used for nuclear reactions.
3. Industrial use: Radio isotopes are used as fuel for atomic energy reactors.

- **Explain the applications of radio-isotopes :**

The applications of radio-isotopes are as follows:
1. Cobalt-60 is extensively employed as a radiation source to arrest the development of cancer.
2. Iodine-131 has proved effective in treating hyperthyroidism.
3. In industry, radioactive isotopes of various kinds are used for measuring the thickness of metal or plastic sheets; their precise thickness is indicated by the strength of the radiations that penetrate the material being inspected.