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3.1. Radioactivity

The atomic structure of most elements contains a nucleus that is stable. Under normal conditions, these elements are not radioactive.

Radioactive elements contain a nucleus that is unstable in an excited state that can not be sustained indefinitely; it must relax, or **decay**, to a more stable configuration.

Decay occurs spontaneously and transforms the nucleus from a high energy configuration to one that is lower in energy. This can only happen if the nucleus releases energy. The energy is emitted by the relaxing nucleus as radiation.

The unstable nuclide is called **the parent nuclide**; the nuclide that results from the decay is known as the **daughter nuclide**.

Radioactivity was discovered by Henri Becquerel in 1896. The term radioactivity was actually coined by Marie Curie, who together with her husband Pierre, began investigating the phenomenon recently discovered by Becquerel. The Curies extracted uranium from ore and to their surprise, found that the leftover ore showed more activity than the pure uranium. This led to the discoveries of the elements polonium and radium.

Of the nuclei found on Earth, there are approximately 270 stable isotopes and 50 naturally occurring radioisotopes (radioactive isotopes). Thousands of other radioisotopes have been made in the laboratory.

3.2 Natural radioactivity: main types of radiation

The radiations in general consisted of three types called: alpha (α), beta (β) and gamma (γ) radiations after the first three letters in the Greek alphabet (see figure below).

The radiation emitted transforms the element into a new element. The process is called **a decay** or **a disintegration**.

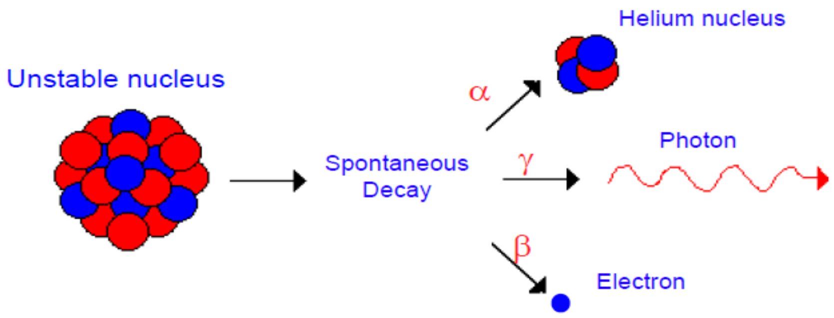


Fig3.1 Types of radiation.

❖ **Alpha (α) emission**: is the emission of an α particle (^4_2He) from the nucleus.

For example, polonium-210 undergoes α decay:

$$^{210}_{84}\text{Po} \longrightarrow {}^4_2\text{He} + {}^{206}_{82}\text{Pb} \quad \text{or} \quad {}^{210}_{84}\text{Po} \longrightarrow {}^4_2\alpha + {}^{206}_{82}\text{Pb}$$

Alpha decay occurs primarily in heavy nuclei (A > 200, Z > 83).

❖ **Beta (β) emission**:

- **β^- emission**

Nuclei that contain too many neutrons often undergo beta (β) decay, in which a neutron is converted to a proton and a high-energy electron that is ejected from the nucleus as a β particle:

$$\underset{\substack{\text{unstable}\\\text{neutron in}\\\text{nucleus}}}{{}^1_0\text{n}} \rightarrow \underset{\substack{\text{proton}\\\text{retained}\\\text{by nucleus}}}{{}^1_1\text{p}} + \underset{\substack{\text{beta particle}\\\text{emitted by}\\\text{nucleus}}}{{}^{\ 0}_{-1}\beta}$$

The general reaction for beta decay is therefore.

$$\underset{\text{parent}}{{}^A_Z\text{X}} \rightarrow \underset{\text{daughter}}{{}^{\ \ A}_{Z+1}\text{X}'} + \underset{\text{beta particle}}{{}^{\ 0}_{-1}\beta}$$

Iodine-131 is an example of a nuclide that undergoes **β** $^-$ ($^{\ 0}_{-1}\beta$ or $^{\ 0}_{-1}e$) decay.

$$^{131}_{53}\text{I} \longrightarrow {}^{\ 0}_{-1}\text{e} + {}^{131}_{54}\text{X} \quad \text{or} \quad {}^{131}_{53}\text{I} \longrightarrow {}^{\ 0}_{-1}\beta + {}^{131}_{54}\text{Xe}$$

- **β^+ emission**

Because a positron has the same mass as an electron but opposite charge, positron emission is the opposite of beta decay. Thus positron emission is characteristic of neutron-poor nuclei, which decay by transforming a proton to a neutron and emitting a high-energy positron:

$$^1_1\text{p} \rightarrow {}^1_0\,\text{n} + {}^{\ 0}_{+1}\beta$$

The general reaction for positron emission is therefore.

$$\underset{\text{parent}}{{}^{A}_{Z}\mathrm{X}} \rightarrow \underset{\text{daughter}}{{}^{A}_{Z-1}\mathrm{X}'} + \underset{\text{positron}}{{}^{0}_{+1}\beta}$$

For example, carbon-11 undergoes positron emission to form boron-11:

$${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\beta$$

❖ **Gamma γ emission**

The third major type of radioactive emission is not a particle but rather a very energetic form of electromagnetic radiation called gamma rays, in gamma decay, a nucleus in an excited state releases energy in the form of a photon when it returns to the ground state. These high-energy photons are γ rays.

$${}^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{0}\gamma$$

Gamma emission can occur virtually instantaneously, as it does in the alpha decay of uranium-238 to thorium-234, where the asterisk denotes an excited state:

$${}^{238}_{92}\mathrm{U} \rightarrow \underset{\substack{\text{excited}\\ \text{nuclear}\\ \text{state}}}{{}^{234}_{90}\mathrm{Th}^{*}} + {}^{4}_{2}\alpha \xrightarrow{\text{relaxation}} {}^{234}_{90}\mathrm{Th} + {}^{0}_{0}\gamma$$

Table 3.1 summarizes the properties of the three main types of radioactive emissions and Figure 3.2 summarizes the ability of each radioactive type to penetrate matter.

Table 3.1 The Three Main Forms of Radioactive Emissions.

Symbols	α, ${}^{4}_{2}\mathrm{He}$	β, ${}^{0}_{-1}\mathrm{e}$	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)

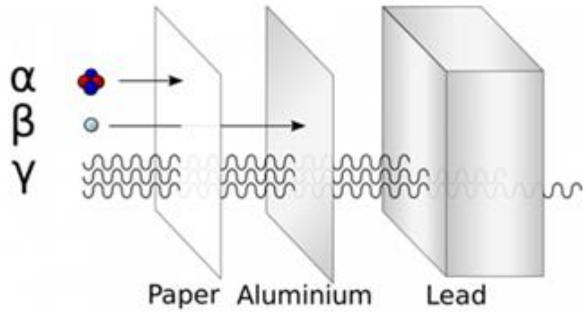


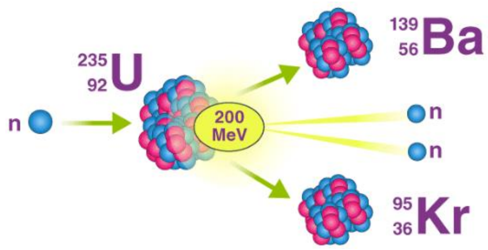
Figure 3.2 Illustration of the relative abilities of three different types of ionizing radiation to penetrate solid matter. Typical alpha particles (α) are stopped by a sheet of paper, while beta particles (β) are stopped by an aluminum plate. Gamma radiation (γ) is damped when it penetrates lead.

3.3 Artificial radioactivity

It is a process obtained by bombardment of nuclides by alpha particles ($\boldsymbol{\alpha}$), proton, deuterium, electrons, neutron, etc. There are three types of nuclear reactions:

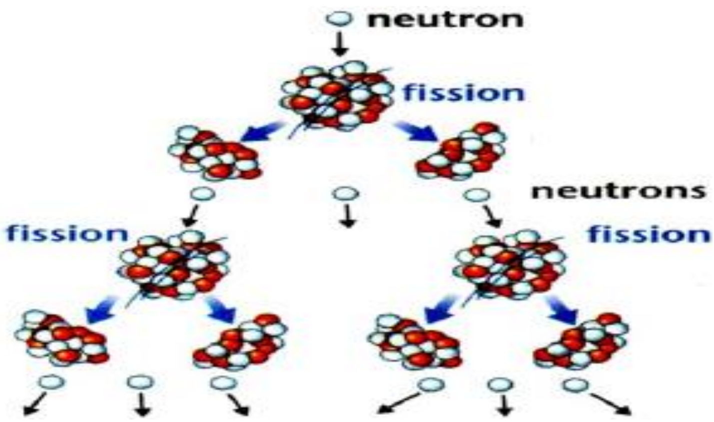
- **Nuclear fission**

Is the process of breaking large atomic nuclei ($\boldsymbol{A}>\mathbf{200}$) into smaller atomic nuclei ($\mathbf{72}<\boldsymbol{A}<\mathbf{162}$) to release a large amount of energy , which is accompanied by the emission of neutrons and gamma rays



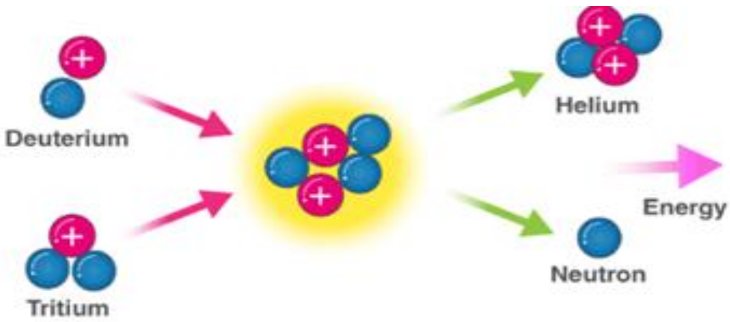
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{91}_{36}Kr + ^{142}_{56}Ba + 3^{1}_{0}n + E$$

The neutrons, can meet other uranium nuclei: we then obtain a chain reaction.



- **Nuclear Fusion**

Two light nuclei combine into a heavier nucleus, with the release of considerable energy. Subatomic particles such as neutrons or protons are also formed as products in these nuclear reactions.



$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + 2^{1}_{0}n$$

- **Nuclear transmutation**

These reactions produce nuclides with a mass number equal or very close to that of the initial nuclide. Nuclides forms are stable or radioactive.

Examples:

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

3.4 Radioactive decay law

When an individual nucleus transforms into another with the emission of radiation, the nucleus is said to decay.

The decay rate is proportional to the number of original (undecayed) nuclei **N** in a substance. The number of nuclei lost to decay, **−dN** in time interval **dt**, is written:

$$-\frac{dN}{dt} = \lambda N \quad \text{Can be rewritten as} \quad \frac{dN}{N} = -\lambda dt.$$

Where λ is called the decay constant.

Integrating both sides of the equation, and defining **N_0** to be the number of nuclei at **t=0** , we obtain

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_0^t \lambda dt \qquad \text{This gives us} \qquad \ln \frac{N}{N_0} = -\lambda t.$$

Taking the left and right sides of Equation as a power of **e** , we have the radioactive decay law.

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

The total number of nuclei drops very rapidly at first, and then more slowly (Figure 3.3).

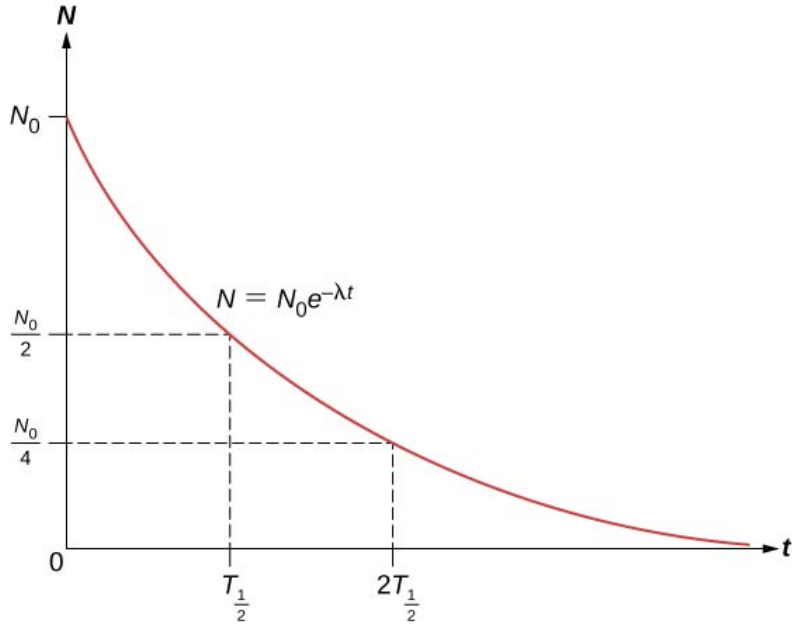


Figure 3.3 : A plot of the radioactive decay law demonstrates that the number of nuclei remaining in a decay sample drops dramatically during the first moments of decay

- **The half-life ($T_{1/2}$)**

The half-life ($T_{1/2}$) of a radioactive substance is defined as the time for half of the original nuclei to decay (or the time at which half of the original nuclei remain). The half-lives of unstable isotopes are shown in the chart of nuclides. The number of radioactive nuclei remaining after an integer (n) number of half-lives is therefore.

$$N = \frac{N_0}{2^n}$$

If the decay constant (λ) is large, the half-life is small, and vice versa. To determine the relationship between these quantities, note that when $t=T_{1/2}$, then $N=N_0/2$

can be rewritten as $\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$

Dividing both sides by N_0 and taking the natural logarithm yields

$\ln\frac{1}{2} = \ln e^{-\lambda T_{1/2}}$ which reduces to $\lambda = \frac{0.693}{T_{1/2}}$

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❖ **Activity (A)**

The activity represents the number of disintegrations per second.

$$A = -\frac{dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t}$$

Defining the initial activity as **$A_0 = \lambda N_0$**, we have:

$$A = A_0 e^{-\lambda t}.$$

The relationship between disintegration and mass

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

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

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

The activity A of a radioactive substance decreases exponentially with time.

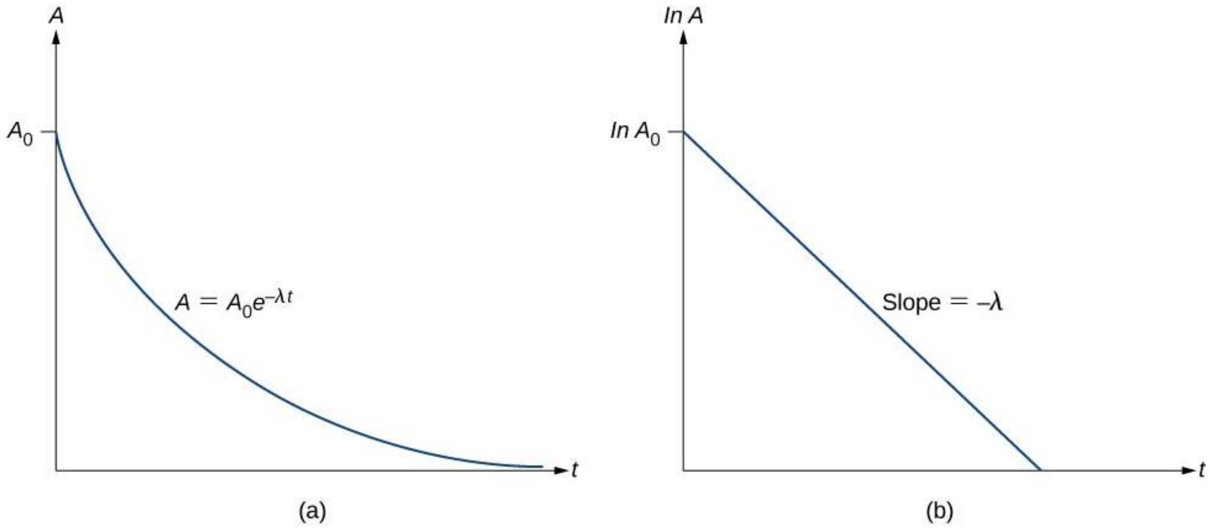

Figure 3.4: (a) A plot of the activity as a function of time (b) If we measure the activity at different times, we can plot \ln A versus t, and obtain a straight line.

❖ **Units of measurement of radioactivity**

The amount of radioactivity is reported in becquerel (Bq), which is the international unit, or the curie (Ci), which is the unit used in the United States.

1 Bq = 1 dps (decays per second)

1Ci (curie) **= 3,7 · 10^{10} Bq=3.7 x 10^{10} dps = 2 ,22 x 10 ^{12} dpm** (decays per minute)

3.5 Applications of radioactivity

- Radioactive isotopes are effective tracers because their radioactivity is easy to detect.
- Many diseases such as cancer are cured by radio therapy.
- Sterilization of medical instruments.
- Food irradiation: some radioactive substances can be used to kill microorganisms on a variety of foodstuffs, which extends the shelf life of these products. Produce such as tomatoes, mushrooms, and berries are irradiated with the emissions from cobalt-60 or cesium-137. This exposure kills a lot of the bacteria that cause spoilage, so the produce stays fresh longer. Eggs and some meat, such as beef, pork, and poultry, can also be irradiated. Irradiation of food does not make the food itself radioactive.
- Scientific use: Alpha particles emitted from the radio isotopes are used for nuclear reactions.
- Industrial use: Radio isotopes are used as fuel for atomic energy reactors.