

CHAPTER 3.

RADIOACTIVITY – NUCLEAR REACTIONS

Chapter contents

- 1. Natural radioactivity (α , β and γ radiation),**
- 2. Artificial radioactivity and nuclear reactions,**
- 3. Kinetics of disintegration radioactive,**
- 4. Radioactivity Applications.**

1. Introduction

In **1895**, the German physicist **Wilhelm Röntgen** observed that cathode rays caused glass and metals to emit a very unusual type of radiation. This highly energetic radiation penetrated matter, darkened covered photographic plates, and caused a variety of substances to fluoresce. Because these rays could not be deflected by a magnet, they could not contain charged particles as cathode rays do. Röntgen called them X-rays.

After that, **Antoine Becquerel (1896)**, a professor of physics in Paris, began to study the fluorescent properties of substances. He found that uranium compounds emitted high-energy rays that could not be deflected by a magnet, but these differed from X-rays in that they were generated spontaneously.

One of Becquerel's students, **Marie Curie**, suggested the term "radioactivity" to describe the spontaneous emission of particles and/or radiation. Consequently, any element that spontaneously emits radiation is said to be radioactive.

In chemical reactions, only the outer electrons of the atoms are disturbed. The nuclei of the atoms are not affected. In nuclear reactions, however, the nuclear changes that occur are independent of the atom's chemical environment. We will look at two types of nuclear reactions.

1. One type is **radioactive decay**, the process in which a nucleus spontaneously disintegrates, giving off radiation. The radiation consists of one or more of the following, depending on the nucleus: electrons, nuclear particles (such as neutrons), smaller nuclei (usually helium-4 nuclei), and electromagnetic radiation.
2. The second type of nuclear reaction is a **nuclear bombardment reaction**, a nuclear reaction in which a nucleus is bombarded, or struck, by another nucleus or by a nuclear particle. If there is sufficient energy in this collision, the nuclear particles of the reactants rearrange to give a product nucleus or nuclei.

3. Nuclear Stability

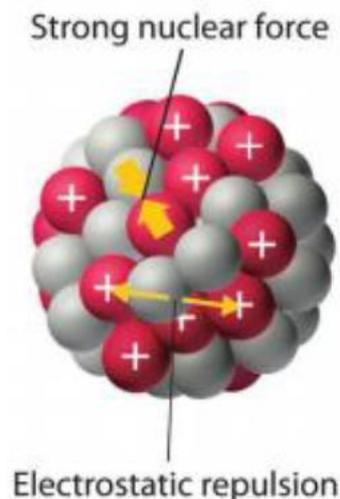
A nucleus is stable if it cannot be transformed into another configuration without adding energy from the outside. Of the thousands of nuclides that exist, about 250 are stable.

1. Stable isotopes have a neutron-to-proton ratio (n/p) less than 1.
2. All elements with $Z > 83$ are unstable and radioactive.

3. The greater the average binding energy, the more stable the element

This is because larger nuclei have more proton-proton repulsions and require larger numbers of neutrons to provide compensating strong forces to overcome these electrostatic repulsions and hold the nucleus together.

Electrostatic repulsions between positively charged protons would normally cause the nuclei of atoms (except H) to fly apart. In stable atomic nuclei, these repulsions are overcome by the strong nuclear force, a short-range but powerful attractive interaction between nucleons. If the attractive interactions due to the strong nuclear force are weaker than the electrostatic repulsions between protons, the nucleus is unstable, and it will eventually decay.



Magic Numbers

The "magic numbers" are natural occurrences in isotopes that are particularly stable. In some cases, the isotopes can consist of magic numbers for both protons and neutrons; these would be called **double magic numbers**. The magic numbers are:

1. Proton: 2, 8, 20, 28, 50, 82, 114
2. Neutron: 2, 8, 20, 28, 50, 82, 126, 184

Also, there is the concept that isotopes consisting of a combination of even-even, even-odd, odd-even, and odd-odd are all stable. There are more nuclides that have a combination of even-even than odd-odd.

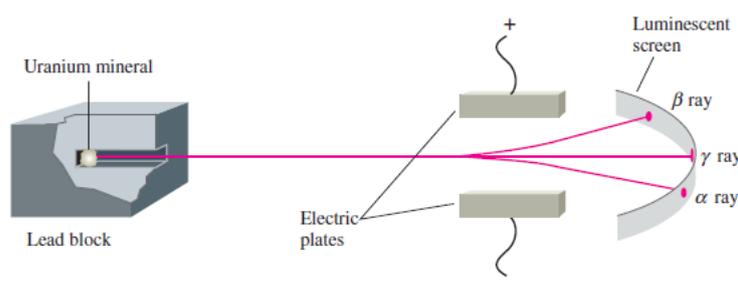
Table 1: Distribution of Stable and Unstable Isotopes based on Neutron and Proton Numbers

Proton number (Z)	Neutron Number	# of stable Isotopes
Even	Even	163
Even	Odd	53
Odd	Even	50
Odd	Odd	4

Although rare, four stable odd-odd nuclides exist: ${}^1_1\text{H}$, ${}^6_3\text{Li}$, ${}^{10}_5\text{B}$, and ${}^{14}_7\text{N}$

3. Natural radioactivity (α , β , and γ radiation)

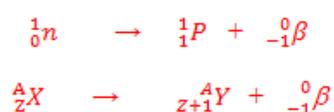
The radiation from uranium minerals was later shown to be separable by electric (and magnetic) fields into three types: alpha (α), beta (β), and gamma (γ) rays.



- Alpha rays:** bend away from a positive plate and toward a negative plate, indicating that they have a positive charge; they are now known to consist of helium-4 nuclei (nuclei with two protons and two neutrons). For energetic reasons α -decay happens only for heavy nuclides with $A > 170$ and $Z > 70$ according to:

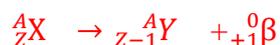
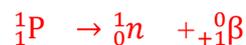


- Beta rays:** bend in the opposite direction, indicating that they have a negative charge; they are now known to consist of high-speed electrons. In a beta decay, a neutron in the nucleus changes into a proton (β -decay)



First, the emitted particles were called beta particles; later, it was shown that they were electrons. The emitted electron is not one of the orbital electrons of the atom. The new particle was called a **neutrino**.

Another beta decay process is the so-called β^+ -decay in which a **positron** is emitted. Or a proton changes into a neutron (β^+ -decay). Z and N each change by one unit, but A remains unchanged.



The positron is the **antiparticle** of the electron. The only change of an antiparticle is its charge. The β decay is only possible if the available energy is greater than 1 MeV.

3. **Gamma rays** are unaffected by electric and magnetic fields; they have been shown to be a form of electromagnetic radiation that is similar to X-rays, except they are higher in energy with shorter wavelengths.

Following alpha or beta decay, the final nucleus may be left in an **excited state**. Just as an atom does, the nucleus will reach its ground state after emitting one or more photons, known as **nuclear gamma rays**.

A sheet of paper stops comparatively massive α particles, whereas β particles easily penetrate paper but are stopped by a thin piece of lead foil. Uncharged γ rays penetrate the paper and lead foil; a much thicker piece of lead or concrete is needed to absorb them.

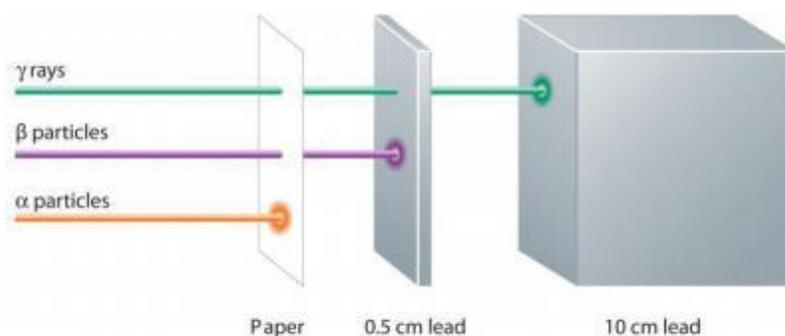


TABLE 26-3 *Common Types of Radioactive Emissions*

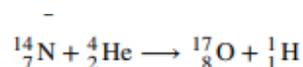
Type and Symbol ^a	Identity	Mass (amu)	Charge	Velocity	Penetration
beta (β^- , ${}_{-1}^0\beta$, ${}_{-1}^0e$)	electron	0.00055	1-	$\leq 90\%$ speed of light	low to moderate, depending on energy
positron ^b (${}_{+1}^0\beta$, ${}_{+1}^0e$)	positively charged electron	0.00055	1+	$\leq 90\%$ speed of light	low to moderate, depending on energy
alpha (α , ${}_{2}^4\alpha$, ${}_{2}^4\text{He}$)	helium nucleus	4.0026	2+	$\leq 10\%$ speed of light	low
proton (${}_{1}^1p$, ${}_{1}^1\text{H}$)	proton, hydrogen nucleus	1.0073	1+	$\leq 10\%$ speed of light	low to moderate, depending on energy
neutron (${}_{0}^1n$)	neutron	1.0087	0	$\leq 10\%$ speed of light	very high
gamma (${}_{0}^0\gamma$) ray	high-energy electromagnetic radiation such as X-rays	0	0	speed of light	high

Exercise 1.

- Write the nuclear equation for the radioactive decay of radium-226 by alpha decay to give radon-222. Aradium-226 nucleus emits one alpha particle, leaving behind a radon-222 nucleus.
- Technetium-99 is a long-lived radioactive isotope of technetium. Each nucleus decays by emitting one beta particle. What is the product nucleus?
- Calculate the number of α and β particles emitted during the decay of ${}_{93}^{273}\text{Np}$ to ${}_{87}^{221}\text{Fr}$.
- An alpha particle is accelerated to 23.1 MeV per particle. What is this energy in kJ/mol?

4. Artificial radioactivity and nuclear reactions

The first man-made nucleus was produced in Ernest Rutherford's laboratory in 1919 by a transmutation reaction, the bombardment of one type of nuclei with other nuclei or with neutrons. Rutherford bombarded nitrogen atoms with high-speed α particles from a natural radioactive isotope of radium and observed protons resulting from the reaction:



The ${}_{8}^{17}\text{O}$ and ${}_{1}^1\text{H}$ nuclei that are produced are stable, so no further (nuclear) changes occur.

Writing a nuclear equation differs somewhat from writing equations for chemical reactions. In addition to writing the symbols for various chemical elements, we must also explicitly indicate protons, neutrons, and electrons. In fact, we must show the numbers of protons and neutrons present in every species in such an equation.

The Symbols for elementary particles are as follows

${}^1_1\text{P}$ or ${}^1_1\text{H}$	${}^1_0\text{n}$	${}^{-1}_0\text{e}$ or ${}^{-1}_0\beta$	${}^{+1}_0\text{e}$ or ${}^{+1}_0\beta$	${}^4_2\text{He}$ or ${}^4_2\alpha$	${}^2_1\text{d}$
Proton	neutron	electron	positron	α particle	deuteron

The nuclear equation is not balanced in the usual chemical sense because the kinds of nuclei are not the same on both sides of the arrow. Instead, a nuclear equation is balanced when the sums of the nucleons are the same on both sides of the equation and when the sums of the charges on the nuclei and any elementary particles (protons, neutrons, and electrons) are the same on both sides.

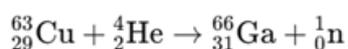
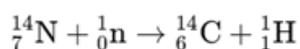
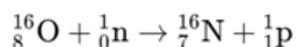
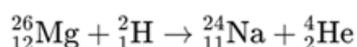
Note also that we are concerned only with charges on elementary particles and on nuclei when we write nuclear equations, not with ionic charges on atoms.

Exercise 2.

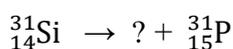
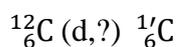
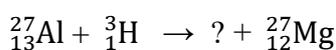
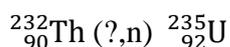
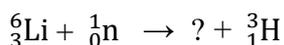
- Write the nuclear equations for the following bombardment reactions.

- a. ${}^{45}_{21}\text{Sc} (\text{n}, \alpha) {}^{42}_{19}\text{K}$; b. ${}^{63}_{29}\text{Cu} (\text{p}, \text{n}) {}^{63}_{30}\text{Zn}$
 c. ${}^{14}_6\text{C} (\beta^-) {}^{14}_7\text{N}$; d. ${}^{252}_{98}\text{Cf} (\text{n}) {}^{142}_{56}\text{Ba}, {}^{106}_{42}\text{Mo}$

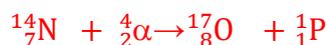
- Write the abbreviated notations for the following bombardment reactions.



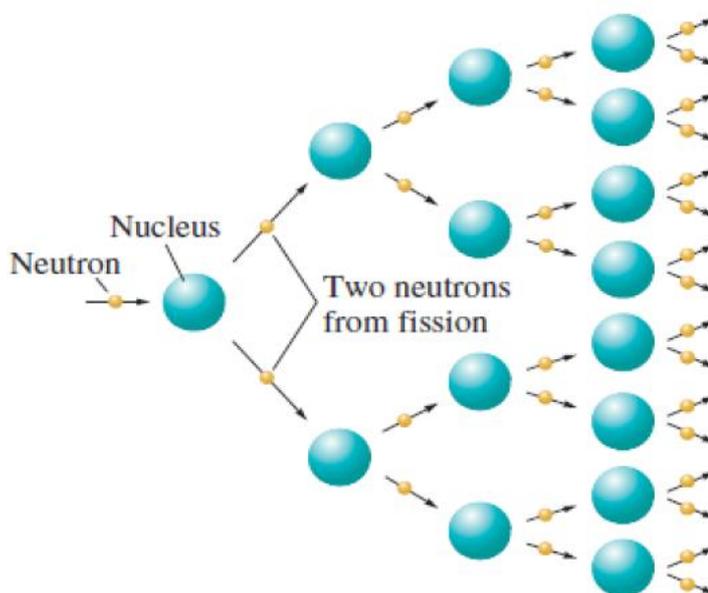
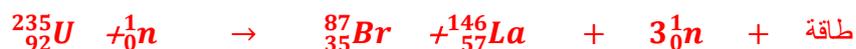
- Fill in the missing parts of the following reactions.



Transmutation is the change of one element to another by bombarding the nucleus of the element with nuclear particles or nuclei.

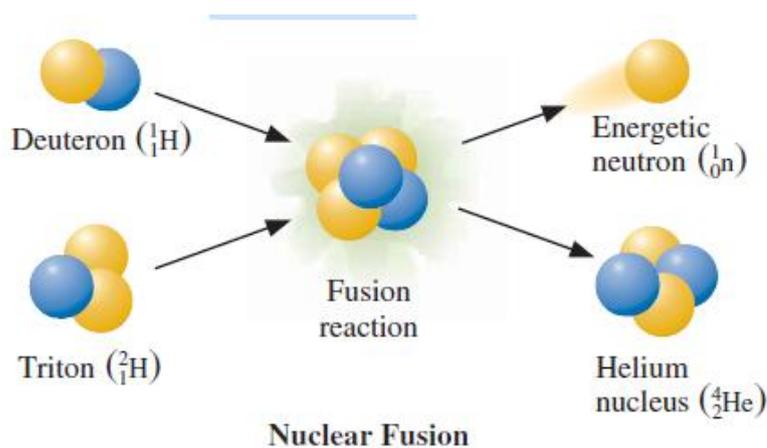


Nuclear fission is a nuclear reaction in which a heavy nucleus splits into lighter nuclei, and energy is released. For example, uranium-235 is employed in nuclear power plants to generate electricity. One way of nuclear fission of uranium is represented by the following equation:



Nuclear fusion is a nuclear reaction in which light nuclei combine to give a stable, heavier nucleus plus possibly several neutrons, and energy is released. An example of nuclear fusion is:



**Exercise 3.**

Identify each of the following reactions as fission, fusion, a transmutation, or radioactive decay.

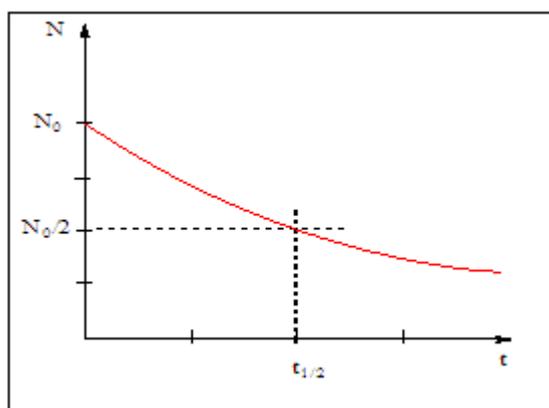
- $4 {}^1_1\text{H} \longrightarrow {}^4_2\text{He} + 2 {}^0_1\text{e}$
- ${}^{14}_6\text{C} \longrightarrow {}^{14}_7\text{N} + {}^0_{-1}\text{e}$
- ${}^1_0\text{n} + {}^{235}_{92}\text{U} \longrightarrow {}^{140}_{56}\text{Ba} + {}^{93}_{36}\text{Kr} + 3 {}^0_1\text{e}$
- ${}^{14}_7\text{N} + {}^4_2\text{He} \longrightarrow {}^{17}_8\text{O} + {}^1_1\text{H}$

5. Kinetics of radioactive disintegration

Radionuclides have different stabilities and decay at different rates. Some decay nearly completely in a fraction of a second, and others only after millions of years. The rates of all radioactive decays are independent of temperature and obey *first-order kinetics*.

The rate of a first-order process is proportional only to the concentration of one substance.

$$\frac{dN}{dt} = -\lambda N \Rightarrow \ln \frac{N_0}{N} = \lambda t \Rightarrow \mathbf{N(t) = N_0 e^{-\lambda t}}$$



Here :

- N represents the amount of decaying radionuclide of interest remaining after some time t , and
- N_0 is the amount present at the beginning of the observation.
- λ is the rate constant, which is different for each radionuclide.

Because N_0/N is a ratio, N_0 and N can represent either molar concentrations of a reactant or masses of a reactant? We can write:

$$N = \mathcal{N} \frac{m}{M} \Rightarrow m = m_0 e^{-\lambda t}$$

In nuclear chemistry, the decay rate is usually expressed in terms of the **half-life**, $t_{1/2}$, of the process. This is the amount of time required for half of the original sample to react. For a first-order process, $t_{1/2}$ is given by the equation:

$$\frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \Rightarrow t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

Exercise 4.

The decay constant for the beta decay of ${}^{99}_{43}\text{Tc}$ is 10^{-13} s^{-1} . What is the half-life of this isotope in years?

1. Activity, the Rate of Decay

The Rate of Decay means the number of decays per unit time. We define activity A to be the rate of decay expressed in decays per unit time. In equation form, this is:

$$A = \lambda N \Rightarrow A(t) = A_0 e^{-\lambda t}$$

The **Becquerel (Bq)** is the SI unit for measuring the number of nuclear disintegrations occurring per second in a sample. The **curie (Ci)** and **millicurie (mCi)** also measure disintegrations per unit time, but they are far larger units than the Becquerel and are more often used, particularly in medicine and biochemistry.

One curie is the decay rate of 1 g of radium, equal to $3.7 \times 10^{10} \text{ Bq}$:

$$1 \text{ Bq} = 1 \text{ disintegration/s} \Rightarrow 1 \text{ Ci} = 3.7 * 10^{10} \text{ Bq} = 3.7 * 10^{10} \text{ disintegrations/s}$$

Exercise 5.

A 1 mg sample of technetium-99 has an activity of 1.7×10^{-5} Ci, decaying by beta emission. What is the decay constant for ${}_{43}^{99}\text{Tc}$?

2. Decay energy

The decay energy is the energy change of a nucleus that has undergone radioactive decay. The energy difference of the reactants is often written as :

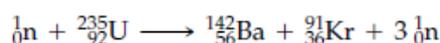
$$\Delta E = \Delta m \times C^2$$

Where :

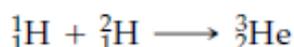
$$\Delta m = \sum \text{mass of products} - \sum \text{mass of reactants}$$

Exercise 6.

3. How much energy (in kJ/mol) is released by the fission of uranium-235 to form barium-142 and krypton-91? The atomic masses are ${}^{235}\text{U}$ (235.0439 amu), ${}^{142}\text{Ba}$ (141.9164 amu), ${}^{91}\text{Kr}$ (90.9234 amu) and n (1.00866 amu).



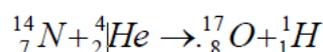
4. Calculate the amount of energy released (in kJ/mol) for the fusion reaction of 1H and 2H atoms to yield a ${}^3\text{He}$ atom.



The atomic masses are ${}^1\text{H}$ (1.007 83 amu), ${}^2\text{H}$ (2.014 10 amu), and ${}^3\text{He}$ (3.016 03 amu).

Exercise 7.

5. Does the following nuclear reaction absorb or release energy:



6. Calculate the value of this energy in megaelectron volts.

Masses are given in amuunits: ${}^{14}\text{N} = 14.00754$; ${}^4\text{He} = 4.00388$; ${}^{17}\text{O} = 17.0045$; ${}^1\text{H} = 1.00783$

7. Radioactivity Applications

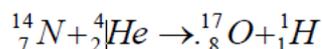
Radiometric Dating

Several radioisotopes have half-lives and other properties that make them useful for purposes of “dating” the origin of objects such as archaeological artefacts, formerly living organisms, or geological formations. This process, known as radiometric dating, has been responsible for many breakthrough scientific discoveries about the geological history of the Earth, the evolution of life, and the history of human civilisation. We will explore some of the most common types of radioactive dating and how the particular isotopes work for each type.

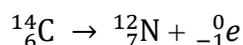
Radioactive Dating Using Carbon-14

The radioactivity of carbon-14 provides a method for dating objects that were part of a living organism. This method of radiometric dating, also known as radiocarbon dating or carbon-14 dating, is accurate for dating carbon-containing substances that are up to approximately 30,000 years old and can provide reasonably accurate dates up to a maximum of about 50,000 years old.

Naturally occurring carbon consists of three isotopes: $^{12}_6\text{C}$, which constitutes about 99% of the carbon on earth; $^{13}_6\text{C}$, about 1% of the total; and trace amounts of $^{14}_6\text{C}$. Carbon-14 forms in the upper atmosphere by the reaction of nitrogen atoms with neutrons from cosmic rays in space:



All isotopes of carbon react with oxygen to produce CO_2 molecules. The ratio of $^{14}_6\text{CO}_2$ to $^{12}_6\text{CO}_2$ depends on the ratio of $^{14}_6\text{CO}$ to $^{12}_6\text{CO}$ in the atmosphere. The natural abundance of $^{14}_6\text{CO}$ in the atmosphere is approximately 1 part per trillion; until recently, this has generally been constant over time, as seen in gas samples found trapped in ice. The incorporation of $^{14}_6\text{CO}_2$ and $^{12}_6\text{CO}_2$ into plants is a regular part of the photosynthesis process, which means that the $^{14}_6\text{C} : ^{12}_6\text{C}$ ratio found in a living plant is the same as the $^{14}_6\text{C} : ^{12}_6\text{C}$ ratio in the atmosphere. But when the plant dies, it no longer traps carbon through photosynthesis. Because $^{12}_6\text{C}$ is a stable isotope and does not undergo radioactive decay, its concentration in the plant does not change. However, carbon-14 decays by β emission with a half-life of 5730 years:



Thus, the $^{14}_6\text{C} : ^{12}_6\text{C}$ ratio gradually decreases after the plant dies. The decrease in the ratio with time provides a measure of the time that has elapsed since the death of the plant (or other organism that ate the plant).

Radioactive Dating Using Nuclides Other than Carbon-14

Radioactive dating can also use other radioactive nuclides with longer half-lives to date older events. For example, uranium-238 (which decays in a series of steps into lead-206) can be used to establish the age of rocks (and the approximate age of the oldest rocks on Earth).

Exercise 8:

An igneous rock contains 9.58×10^{-5} g of U-238 and 2.51×10^{-5} g of Pb-206, and much smaller amounts of Pb-208. Determine the approximate time at which the rock formed.

Medical Uses of Radioactivity

The origins of nuclear medicine date to 1901, when the French physician Henri Danlos first used radium in the treatment of a tuberculous skin lesion. Since that time, uses of radioactivity have become a crucial part of modern medical care, both diagnostic and therapeutic. Current nuclear techniques can be grouped into three classes: (1) in vivo procedures, (2) therapeutic procedures, and (3) imaging procedures.

Exercise 9:

The “cobalt treatments” used in medicine to arrest certain types of cancer rely on the ability of gamma rays to destroy cancerous tissues. Cobalt-60 decays with the emission of beta particles and gamma rays, with a half-life of 5.27 years.



How much of a 3.42-g sample of cobalt-60 remains after 30.0 years?