

10.3: Half-Life

Learning Outcomes

- Define half-life as it relates to radioactive nuclides and solve half-life problems.
- Describe the general process by which radioactive dating is used to determine the age of various objects.
- Calculate the time for a sample to decay.
- Complete dosage calculations based on nuclide activity.

The rate of radioactive decay is often characterized by the half-life of a radioisotope. **Half-life** ($t_{1/2}$) is the time required for one half of the nuclei in a sample of radioactive material to decay. After each half-life has passed, one half of the radioactive nuclei will have transformed into a new nuclide (see table below). The rate of decay and the half-life do not depend on the original size of the sample. They also do not depend upon environmental factors such as temperature and pressure.

Table 10.3.1

Number of Half-Lives Passed	Fraction Remaining	Percentage Remaining	Mass remaining starting with 80 g
1	1/2	50	40 g
2	1/4	25	20 g
3	1/8	12.5	10 g
4	1/16	6.25	5.0 g
5	1/32	3.125	2.5 g

As an example, iodine-131 is a radioisotope with a half-life of 8 days. It decays by beta particle emission into xenon-131.



After eight days have passed, half of the atoms of any sample of iodine-131 will have decayed, and the sample will now be 50% iodine-131 and 50% xenon-131. After another eight days pass (a total of 16 days or 2 half-lives), the sample will be 25% iodine-131 and 75% xenon-131. This continues until the entire sample of iodine-131 has completely decayed (see figure below).

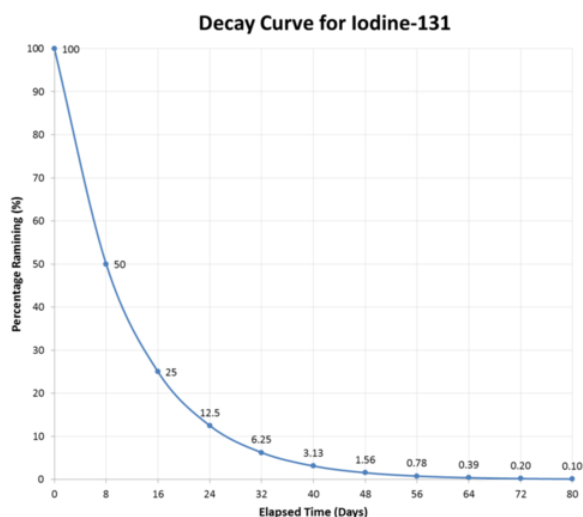


Figure 10.3.1: The half-life of iodine-131 is eight days. Half of a given sample of iodine-131 decays after each eight-day time period elapses.

Half-lives have a very wide range, from billions of years to fractions of a second. Listed below (see table below) are the half-lives of some common and important radioisotopes. Those with half-lives on the scale of hours or days are the ones most suitable for use in medical treatment.

Table 10.3.2

Nuclide	Half-Life ($t_{1/2}$)	Decay Mode
Carbon-14	5730 years	β^-
Cobalt-60	5.27 years	β^-
Francium-220	27.5 seconds	α
Hydrogen-3	12.26 years	β^-
Iodine-131	8.07 days	β^-
Nitrogen-16	7.2 seconds	β^-
Phosphorus-32	14.3 days	β^-
Plutonium-239	24,100 years	α
Potassium-40	1.28×10^9 years	β^- and e^- capture
Radium-226	1600 years	α
Radon-222	3.82 days	α
Strontium-90	28.1 days	β^-
Technetium-99	2.13×10^5 years	β^-
Thorium-234	24.1 days	β^-
Uranium-235	7.04×10^8 years	α
Uranium-238	4.47×10^9 years	α

The following example illustrates how to use the half-life of a sample to determine the amount of radioisotope that remains after a certain period of time has passed.

Example 10.3.1: Strontium-90

Strontium-90 has a half-life of 28.1 days. If you start with a 5.00 mg sample of the isotope, how much remains after 140.5 days have passed?

Solution

Step 1: List the known values and plan the problem.

Known

- Original mass = 5.00 mg
- $t_{1/2}$ = 28.1 days
- Time elapsed = 140.5 days

Unknown

- Final mass of Sr-90 = ? mg

First, find the number of half-lives that have passed by dividing the time elapsed by the half-life. Then, reduce the amount of Sr-90 by half, once for each half-life.

Step 2: Solve.

Number of half-lives, days, mass

0 half-lives, 0 days, 5.00 mg

1 half-life, 28.1 days, 2.50 mg

2 half-lives, 56.2 days, 1.25 mg
 3 half-lives, 84.3 days, 0.613 mg
 4 half-lives, 112.4 days, 0.313 mg
 5 half-lives, 140.5 days, 0.156 mg

Step 3: Think about your result.

According to the data above, the passage of 5 half-lives means 0.156 mg of the original Sr-90 remains. The remaining 4.844 mg has decayed by beta particle emission to yttrium-90.

Radioactive Dating

Radioactive dating is a process by which the approximate age of an object is determined through the use of certain radioactive nuclides. For example, carbon-14 has a half-life of 5,730 years and is used to measure the age of organic material. The ratio of carbon-14 to carbon-12 in living things remains constant while the organism is alive because fresh carbon-14 is entering the organism whenever it consumes nutrients. When the organism dies, this consumption stops, and no new carbon-14 is added to the organism. As time goes by, the ratio of carbon-14 to carbon-12 in the organism gradually declines, because carbon-14 radioactively decays while carbon-12 is stable. Analysis of this ratio allows archaeologists to estimate the age of organisms that were alive many thousands of years ago. Carbon dating is effective until about 50,000 years. The ages of many rocks and minerals are far greater than the ages of fossils. Uranium-containing minerals that have been analyzed in a similar way have allowed scientists to determine that the Earth is over 4 billion years old.

Decay Series

In many instances, the decay of an unstable radioactive nuclide simply produces another radioactive nuclide. It may take several successive steps to reach a nuclide that is stable. A **decay series** is a sequence of successive radioactive decays that proceeds until a stable nuclide is reached. The terms reactant and product are generally not used for nuclear reactions. Instead, the terms parent and daughter nuclide are used to refer to the starting and ending isotopes in a decay process. The figure below shows the decay series for uranium-238.

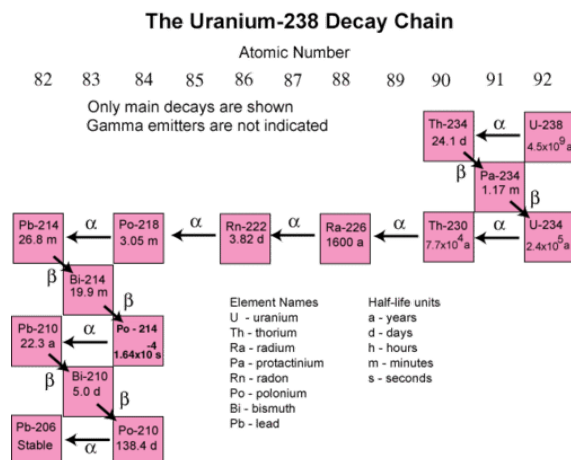


Figure 10.3.2: The decay of uranium-238 proceeds along many steps until a stable nuclide, lead-206, is reached. Each decay has its own characteristic half-life.

In the first step, uranium-238 decays by alpha emission to thorium-234 with a half-life of 4.5×10^9 years. This decreases its atomic number by two. The thorium-234 rapidly decays by beta emission to protactinium-234 ($t_{1/2} = 24.1$ days). The atomic number increases by one. This continues for many more steps until eventually the series ends with the formation of the stable isotope lead-206.

Artificial Transmutation

As we have seen, transmutation occurs when atoms of one element spontaneously decay and are converted to atoms of another element. **Artificial transmutation** is the bombardment of stable nuclei with charged or uncharged particles in order to cause a nuclear reaction. The bombarding particles can be protons, neutrons, alpha particles, or larger atoms. Ernest Rutherford performed

some of the earliest bombardments, including the bombardment of nitrogen gas with alpha particles to produce the unstable fluorine-18 isotope.



Fluorine-18 quickly decays to the stable nuclide oxygen-17 by releasing a proton.



When beryllium-9 is bombarded with alpha particles, carbon-12 is produced with the release of a neutron.



Transuranium Elements

Many, many radioisotopes that do not occur naturally have been generated by artificial transmutation. The elements technetium and promethium have been produced, since these elements no longer occur in nature. All of their isotopes are radioactive and have half-lives short enough that any amount of the elements that once existed have long since disappeared through natural decay. The **transuranium elements** are elements with atomic numbers greater than 92. All isotopes of these elements are radioactive and none occur naturally.

Dosing

Half-life calculations can be based on mass, percent remaining, or dose. Regardless of which one, the concept is still the same. Understanding the radioactivity and half-life of a sample is important for calculating the correct dose for a patient and determining the levels and duration of radioactive emission from a patient after treatment is received.

Frequently, dosages for radioactive isotopes are given the activity in volume. For example, the concentration of I-137 is given as $50 \mu\text{Ci/mL}$ (microCurie per milliliter). This relationship can be used to calculate the volume needed for a particular dose. For example, a patient needs $125 \mu\text{Ci}$ of I-137. What volume of a $50 \mu\text{Ci}$ per 10 mL solution should be given?

$$125 \mu\text{Ci} \left(\frac{10 \text{ mL}}{50 \mu\text{Ci}} \right) = 25 \text{ mL} \quad (10.3.5)$$

Example 10.3.2

A patient is given I-131 to treat thyroid cancer. The patient receives 5.50 mL of a solution containing 50 mCi (milliCurie) in 2 mL (assume concentration is an exact number). What does (in mCi) is given to the patient? What will be the activity in mCi after 24.21 days given that the half-life of I-131 is 8.07 days?

Solution

The first part of the problem is to find the dose given to the patient. We are given the volume and the concentration (in units of radioactivity over volume).

$$5.50 \text{ mL solution} \left(\frac{50 \text{ mCi}}{2 \text{ mL}} \right) = 138 \text{ mCi} \quad (10.3.6)$$

The patient is given a dose of 138 mCi

Now, we need to find the activity after 24.21 days have passed. After one half-life (8.07 days), the sample will have half as much activity ($138/2 = 69.0 \text{ mCi}$) After two half-lives (total of 16.14 days), the sample will have half as much activity as after the first half-life ($69.0/2 = 34.5 \text{ mCi}$) After three half-lives (total of 24.21 days), the sample will have half as much activity as after the second half-life ($34.5/2 = 17.3 \text{ mCi}$) Therefore, after 24.21 days (3 half-lives), the radioactivity will be 17.3 mCi

Contributors and Attributions

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