Section 10.2

1 FOCUS

Objectives

10.2.1 **Define** half-life, and **relate** half-life to the age of a radioactive sample.

10.2.2 **Compare** and **contrast** nuclear reaction rates with chemical reaction rates.

10.2.3 **Describe** how radioisotopes are used to estimate the age of materials.

Reading Focus

Build Vocabulary L2

Paraphrase Have students write a definition of *half-life* in their own words. After students read the section, ask them to draw a diagram that illustrates the definition.

Reading Strategy L2

a. Carbon-14
b. 50,000

2 INSTRUCT

Build Science Skills L2

Drawing Conclusions Ask students to look at Figure 8. Tell them that if the object is made of an organic (once-living) material, the object's carbon-14 content can be used to determine its age. Ask, **The tools shown in the photo are made of stone. Do you think the stone tools contain carbon-14?** *(No, stone is not an organic material.)* **The caption states that the objects are estimated to be 15,000 years old. If the stone tools were not used to determine this age, then what was?** *(The people who made the stone tools also made and used other, organic-based objects. These objects, perhaps made of cloth or wood, were used to determine the age.)*
Logical

10.2 Rates of Nuclear Decay

Reading Focus

Key Concepts

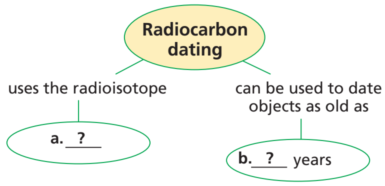
- How do nuclear decay rates differ from chemical reaction rates?
- How do scientists determine the age of an object that contains carbon-14?

Vocabulary

- half-life

Reading Strategy

Identifying Details Copy the concept map below. As you read, complete it to identify details about radiocarbon dating.



A well-known theory is that early Americans were people from Siberia who crossed the Bering Strait into Alaska about 13,000 years ago. However, this theory has been challenged by recent scientific discoveries. In the 1990s, archaeologists working at a site in Cactus Hill, Virginia, found stone tools, charcoal, and animal bones that were at least 15,000 years old. Some of the artifacts were as much as 17,000 years old. The age of these artifacts suggests that the first Americans reached the continent much earlier than formerly thought. Some archaeologists have since revised their theories on the origin of America's earliest ancestors. One possible explanation is that the first Americans were people from Europe who crossed the Atlantic Ocean by using boats.

Figure 8 shows some of the artifacts from the Cactus Hill site. They certainly look very old, but the archaeologists needed to find out *how* old. One clue that can reveal the age of an object is how many radioactive nuclei it contains. Because most materials contain at least trace amounts of radioisotopes, scientists can estimate how old they are based on rates of nuclear decay.

Figure 8 These stone tools from the archaeological site in Cactus Hill, Virginia, are at least 15,000 years old. Scientists estimated the age of the site based on rates of nuclear decay.

Section Resources

Print
- ***Laboratory Manual,*** Investigation 10A
- ***Reading and Study Workbook With Math Support,*** Section 10.2
- ***Transparencies,*** Section 10.2

Technology
- ***Interactive Textbook,*** Section 10.2
- ***Presentation Pro CD-ROM,*** Section 10.2
- ***Go Online,*** NSTA SciLinks, Half-Life

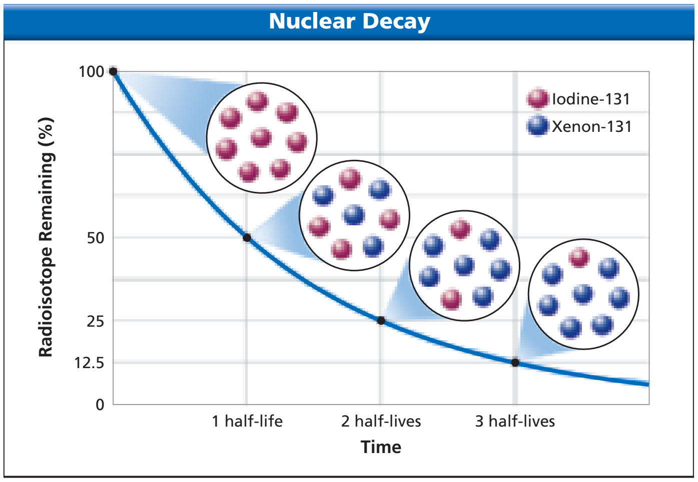


Figure 9 The half-life for the beta decay of iodine-131 is 8.07 days. After one half-life (8.07 days), half of a sample of iodine-131 will have decayed into xenon-131. After two half-lives (16.14 days), three quarters of the sample will have decayed.

Half-life

A nuclear decay rate describes how fast nuclear changes take place in a radioactive substance. Every radioisotope decays at a specific rate that can be expressed as a half-life. A **half-life** is the time required for one half of a sample of a radioisotope to decay. After one half-life, half of the atoms in a radioactive sample have decayed, while the other half remain unchanged. After two half-lives, half of the remaining half decays, leaving one quarter of the original sample unchanged. Figure 9 illustrates the nuclear decay rate of iodine-131. Iodine-131 has a half-life of 8.07 days. After two half-lives, or 16.14 days, the fraction of iodine-131 remaining is one quarter. After three half-lives, or 24.21 days, the fraction of iodine-131 remaining is one half of one quarter, or one eighth.

Half-lives can vary from fractions of a second to billions of years. Figure 10 lists the half-lives of some common radioisotopes. Uranium-238, for instance, has a half-life of 4.5 billion years. This means that in 4.5 billion years, there will be half as much uranium-238 on Earth as there is today. You could also say that 4.5 billion years ago, there was twice as much uranium-238 on Earth as there is today. **Unlike chemical reaction rates, which vary with the conditions of a reaction, nuclear decay rates are constant.** Regardless of the temperature, pressure, or surface area of a uranium-238 sample, its half-life is still 4.5 billion years.

Reading Checkpoint *What is a half-life?*

Figure 10 Nuclear decay rates are constant. A given radioisotope decays at a specific rate, or half-life. **Calculating** ***What isotope is produced by the nuclear decay of radon-222?***

Half-Lives and Radiation of Selected Radioisotopes

Isotope	Half-life	Nuclear Radiation Emitted
Radon-222	3.82 days	α
Iodine-131	8.07 days	β
Thorium-234	24.1 days	β, γ
Radium-226	1620 years	α, γ
Carbon-14	5730 years	β
Thorium-230	75,200 years	α, γ
Uranium-235	7.04×10^8 years	α, γ
Potassium-40	1.28×10^9 years	β, γ
Uranium-238	4.47×10^9 years	α

Half-Life

Use Visuals L1

Figure 9 Ask, **What happens to the amount of iodine-131 at the end of the first half-life?** *(Half of the iodine-131 atoms change into xenon-131 atoms.)* **Look at the line on the graph. Why is the line curved and not straight?** *(After each half-life, half of the remaining atoms have decayed. After one half-life, one half of the original atoms remain; after two half-lives, a fourth of the original atoms remain; and so on. After* n *half-lives,* $(\frac{1}{2})^n$ *of the original atoms remain. A graph of this relationship is a curve, not a straight line.)* **Visual**

Teacher Demo

Predicting Decay L2

Purpose Students learn that it is not possible to predict which atom decays in a radioactive sample.

Materials hot plate, 250-mL or 500-mL beaker, glass plate, popcorn, cooking oil

Procedure Place the beaker on the hot plate. Pour a small amount of cooking oil into the beaker and add popcorn to form a single layer 1 kernel thick. Put the glass plate on top of the beaker. Tell students that each kernel represents an atom that will decay. Explain to students that it is not possible to accurately predict which kernel will pop first. Tell students that when radioisotopes decay, they decay throughout the sample rather than in one particular area.

Safety Caution students to stand at a safe distance when you heat the cooking oil and pop the corn. Remind students never to eat anything in a laboratory.

Expected Outcome There will be no observable pattern to the order in which the kernels pop.
Visual, Logical

Customize for for Inclusion Students

Visually Impaired
Give students 75 metal washers. Have the students count out 40 washers and line them up in a single row. Explain that after the first half-life of a radioisotope, half of the atoms decay. Next, have them count out 20 washers and put them in a single row next to the first row of washers. Have them repeat this again for the second half-life with 10 washers, and then count out 5 washers for the third half-life. With all the rows even at the left, the students should be able to determine the shape of the "graph" by touching the right edge of each row. Inform students that in reality, exactly half of the particles do not decay each half-life, but that this process averages out to the half-life rate over a long period of time. However, reinforce that the general shape of the "graph" is accurate.

Answer to . . .

Figure 10 *Polonium-218. The equation is:*

$${}^{222}_{86}\text{Rn} \longrightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\text{He}$$

Reading Checkpoint *A half-life is the time required for one half of a sample of a radioisotope to decay.*

Quick Lab

Modeling Half-Life

L2

Objective
After completing this activity, students will be able to
- analyze data to calculate the "half-life" of a model radioactive element.

Address Misconceptions

Students may think that a half-life is half the time it takes for a radioactive substance to decay completely. This lab can help dispel this misconception.

Skills Focus **Analyzing Data, Calculating, Using Graphs**

Prep Time 20 minutes

Materials 100 1-cm squares of wallpaper, large plastic bag, graph paper

Advance Prep Use a paper cutter to cut up the wallpaper quickly.

Class Time 20 minutes

Teaching Tips
- Students can cut up the paper squares themselves.
- Explain to students that, on average, half the remaining squares will be removed each time Step 4 is repeated.
- Ask students: **How does this lab model radioactive decay?** *(Like the wallpaper squares, half the radioactive element decays during each half-life.)*

Expected Outcome Students will need to spill and remove paper squares six to nine times to remove all of the squares.

Analyze and Conclude
1. On average, half the squares will be removed in one spill and three-fourths of the squares will be removed in two spills.
2. Students' graphs should reflect the information in their data tables.
3. One year
Visual, Logical

Go Online NSTA SciLinks

Download a worksheet on half-life for students to complete, and find additional teacher support from NSTA SciLinks.

Quick Lab

Modeling Half-Life

Procedure

1. Put 100 1-cm squares of wallpaper in a large plastic bag. Construct a data table with 2 columns and 9 blank rows. Label the columns Spill Number and Number of Squares Returned.
2. Close the bag and shake it to mix up the squares. Then, spill them onto a flat surface.
3. Remove the squares that are face-side up. Record the number of squares remaining and return them to the bag.
4. Repeat Steps 2 and 3 until there are no squares left to put back into the bag.

Analyze and Conclude

1. **Analyzing Data** How many spills were required to remove half of the squares? To remove three fourths of the squares?
2. **Using Graphs** Graph your results. Plot spill number on the horizontal axis and the number of squares remaining on the vertical axis.
3. **Using Models** If each spill represents one year, what is the half-life of the squares?

Suppose you have a one-gram sample of iridium-182, which undergoes beta decay to form osmium-182. The half-life of iridium-182 is 15 minutes. After 45 minutes, how much iridium-182 will remain in the sample? To solve this problem, you first need to calculate how many half-lives will elapse during the total time of decay.

$$\text{Half-lives elapsed} = \frac{\text{Total time of decay}}{\text{Half-life}} = \frac{45 \text{ min}}{15 \text{ min}} = 3$$

After three half-lives, the amount of iridium-182 has been reduced by half three times.

$$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$$

So after 45 minutes, $\frac{1}{8} \times 1$ gram, or 0.125 gram, of iridium-182 remains while 0.875 gram of the sample has decayed into osmium-182.

Radioactive Dating

Now suppose you have a sample that was originally iridium-182, but three quarters of it have since decayed into osmium-182. Based on the fraction of iridium-182 left (one quarter), you can calculate the age of the sample to be two half-lives, or 30 minutes old.

The artifacts from Cactus Hill were dated by measuring levels of carbon-14, which has a half-life of 5730 years. Carbon-14 is formed in the upper atmosphere when neutrons produced by cosmic rays collide with nitrogen-14 atoms. The radioactive carbon-14 undergoes beta decay to form nitrogen-14.

$$^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + ^{0}_{-1}\text{e}$$

Go Online NSTA SciLinks

For: Links on half-life
Visit: www.SciLinks.org
Web Code: ccn-1102

Facts and Figures

Radiocarbon Dating An American chemist, Dr. Willard F. Libby, developed this technique in the late 1940s. Radiocarbon dating is used to date once-living materials. The date when the organism died is the date when it stopped absorbing carbon-14.

Radiocarbon dating cannot be used to date the remains of organisms that died after the 1940s. Starting in the 1940s, the testing of nuclear bombs and use of nuclear reactors has dramatically increased the amount of carbon-14 and other radioisotopes in the environment.

Carbon reacts with oxygen in the atmosphere and forms carbon dioxide. As plants absorb carbon dioxide during photosynthesis, they maintain the same ratio of carbon-14 to carbon-12 as in the atmosphere. Likewise, animals have the same ratio of carbon isotopes as the plants they eat. When a plant or animal dies, however, it can no longer absorb carbon. From this point on, the organism's carbon-14 levels decrease as the radioactive carbon decays. **In radiocarbon dating, the age of an object is determined by comparing the object's carbon-14 levels with carbon-14 levels in the atmosphere.** For example, if the ratio of carbon-14 to carbon-12 in a fossil is half the ratio in the atmosphere, then the organism lived about 5730 years ago.

Because atmospheric carbon-14 levels can change over time, the calculated age of the fossil is not totally accurate. To get a more accurate radiocarbon date, scientists compare the carbon-14 levels in a sample to carbon-14 levels in objects of known age. Such objects might include trees (which can be dated by counting tree rings) or artifacts from a specific historical period.

Radiocarbon dating can be used to date any carbon-containing object less than 50,000 years old, such as the artifact in Figure 11. Objects older than 50,000 years contain too little carbon-14 to be measurable. To date objects thought to be older than 50,000 years, scientists measure the amounts of radioisotopes with longer half-lives than carbon-14. Geologists, for instance, use the half-lives of potassium-40, uranium-235, and uranium-238 to date rock formations. The older the rock, the lower are the levels of the radioisotope present.

Figure 11 Radiocarbon dating has helped archaeologists learn more about ancient civilizations. Excavations in Abydos, a major archaeological site of ancient Egypt, have unearthed fascinating artifacts. This mummy case, containing the remains of a cat, is 1900 years old.

Section 10.2 Assessment

Reviewing Concepts

1. How are nuclear decay rates different from chemical reaction rates?
2. How can scientists determine the age of an object that contains carbon-14?
3. If a radioactive sample has decayed until only one eighth of the original sample remains unchanged, how many half-lives have elapsed?
4. What type of nuclear radiation is emitted when carbon-14 decays?

Critical Thinking

5. **Predicting** Can radiocarbon dating be used to determine the age of dinosaur fossils? Explain. (*Hint:* Dinosaurs roamed Earth more than 65 million years ago.)
6. **Inferring** All of the isotopes of radon have half-lives shorter than four days, yet radon is still found in nature. Explain why all the radon has not already decayed.
7. **Calculating** A certain isotope of technetium has a half-life of six hours. If it is given to a patient as part of a medical procedure, what fraction of the radioisotope remains in the body after one day?

Writing in Science

Explanatory Paragraph Archaeology is the study of past cultures. Explain how a concept in chemistry led to advances in archaeology.

Radioactive Dating

Build Science Skills L2

Measuring Ask students to choose a radioactive isotope for dating a hypothetical fossil. Tell students that archaeologists hypothesize that the fossil is about 20,000 years old. Have students look at the half-lives of radioisotopes in this section. Ask, **Which isotope would you recommend that the scientists first try?** *(Carbon-14)* **Why would that isotope be a good choice?** *(It is a good choice because the half-life of carbon-14 is 5370 years. The half-life of radium-226, at 1620 years, is too short. The half-life of thorium-230 is 75,200 years, which is too long. Using either of these could result in a less accurate measurement.)*
Logical, Verbal

3 ASSESS

Evaluate Understanding L2

Randomly ask students to determine the number of particles present after one, two, or three half-lives have passed from a specified initial number of particles.

Reteach L1

Use Figure 10 to review how different radioisotopes may be used to date objects of different ages. Emphasize that some radioisotopes with shorter half-lives are useful for dating young objects while radioisotopes with long half-lives are useful for dating old objects.

Interactive Textbook If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 10.2.

Writing in Science

Half-life is a concept in nuclear chemistry that has led to profound advances in archaeology, the study of past cultures. A half-life is the time required for one half of a sample of a radioisotope to decay. Using radioisotopes such as carbon-14, scientists have been able to accurately date fossils and archaeological sites up to 50,000 years old.

Section 10.2 Assessment

1. Unlike chemical reaction rates, nuclear decay rates are constant.
2. The age of an object is determined by comparing the object's carbon-14 levels with carbon-14 levels in the atmosphere.
3. Three half-lives ($\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$) have elapsed.
4. When a carbon-14 nucleus decays, it emits a beta particle.
5. Dinosaur fossils, about 65 million years old, are too old to be radiocarbon dated. Radiocarbon dating can only be used to date objects less than 50,000 years old.
6. Radon isotopes are still found in nature because they are continually formed by the decay of longer-lived radioisotopes.
7. Assuming the technetium is eliminated only by radioactive decay, then Half-Lives elapsed = Total time of decay/Half-Life = 24 hours/6 hours = 4. After four half-lives, the amount has been reduced by half four times. $(\frac{1}{2})^4 = \frac{1}{16}$

Nuclear Chemistry 301

issues in SCIENCE

Should Radon Testing in Schools Be Mandatory? L2

Background

Prior to 1984, radon gas was considered a health risk only for workers in uranium mines. Then, in 1984, a nuclear engineer set off an alarm while passing through a radiation monitor at the Limerick Nuclear Power Plant. The engineer, Stan Watras, was leaving work at the time. Since there was no nuclear fuel on site, there was no major source of radiation contamination at the plant. The Health Physics staff at the plant determined that the source of the radiation was Mr. Watras's house in Boyertown, Pennsylvania. The staff took remedial actions to fix Mr. Watras' home. Mr. Watras and his family still live in the house today.

The Watras case put radon testing in the national spotlight. In October of 1988, Congress passed legislation that established a national goal that indoor radon levels not exceed ambient outdoor radon levels (0.2–0.7 pCi/L). A picocurie (Ci) is a unit of radioactivity equal to 0.037 disintegrations per second. The law set aside funds for states to initiate radon testing in schools and workplaces.

Answers

1. The issue that needs to be resolved is whether indoor radon poses a health risk serious enough in schools to warrant mandatory testing.
2. Two reasons why radon testing should be mandatory in all schools is that radon is the second leading cause of lung cancer in the United States and that many classrooms are above the EPA's action level of 4 pCi/L.
3. Answers will vary based on which arguments students choose.

Go Online PHSchool.com

Have students further research issues related to this topic.

issues in SCIENCE

Should Radon Testing in Schools Be Mandatory?

Radon (Rn) is a radioactive element that forms from the nuclear decay of uranium in rocks and soil. A colorless, odorless gas, radon can enter buildings through drains, cracks in the floors and walls, and even the water supply. Indoor radon levels tend to be highest in places that are close to the soil and have little ventilation, such as basements or crawl spaces.

When a person inhales radon-contaminated air, the lungs trap radioactive particles. As these particles decay, radiation is released into the lung tissue. Over time, repeated exposure to high radon levels can result in lung cancer.

The Environmental Protection Agency (EPA) identifies 4 picocuries per liter (pCi/L) of air as the national "action level" for radon. (A picocurie is a unit of radioactivity.) If an indoor space has a radon level of 4 pCi/L or higher, the EPA recommends that steps be taken to reduce it. Such steps might include installing a ventilation system and sealing cracks in the building's foundation

The Viewpoints

Radon Testing in Schools Should Be Mandatory

The EPA estimates that indoor radon exposure contributes to 21,000 lung cancer deaths in the United States each year. After smoking, radon is the second-leading cause of lung cancer.

Students and teachers spend extended periods of time indoors at school. A nationwide survey of radon levels in schools found that nearly one in five schools has at least one classroom with radon exceeding the EPA's action level of 4 pCi/L.

Indoor radon can be easily tested. If elevated radon levels are found, they can be reduced using proven techniques. But without mandatory testing, school administrators may not be aware of the potential risk of radon exposure in their schools.

Radon Testing in Schools Should Not Be Mandatory

The EPA's radon guidelines are based mainly on studies of workers in uranium mines. Radon levels in these mines were far greater than those found in homes or schools. In addition, the miners engaged in tiring labor, resulting in heavy breathing of the surrounding air. Lastly, most of the miners were smokers. The data from these studies are appropriate for predicting the risk of radon exposure for uranium miners—but not for the general public.

The EPA's action level of 4 pCi/L is not universally accepted. In Canada and Europe, for example, radon guidelines are much less strict. Until scientists gather more data about the risk of residential radon exposures, radon testing in schools should not be mandatory.

Research and Decide

1. **Defining the Issue** In your own words, explain the issue that needs to be resolved about indoor radon.
2. **Analyzing the Viewpoints** List two arguments of those who think that radon testing should be mandatory in schools. List two arguments of those who think that radon testing should not be mandatory in schools.
3. **Forming Your Opinion** Should there be mandatory radon testing in schools? Which argument did you find more convincing?

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