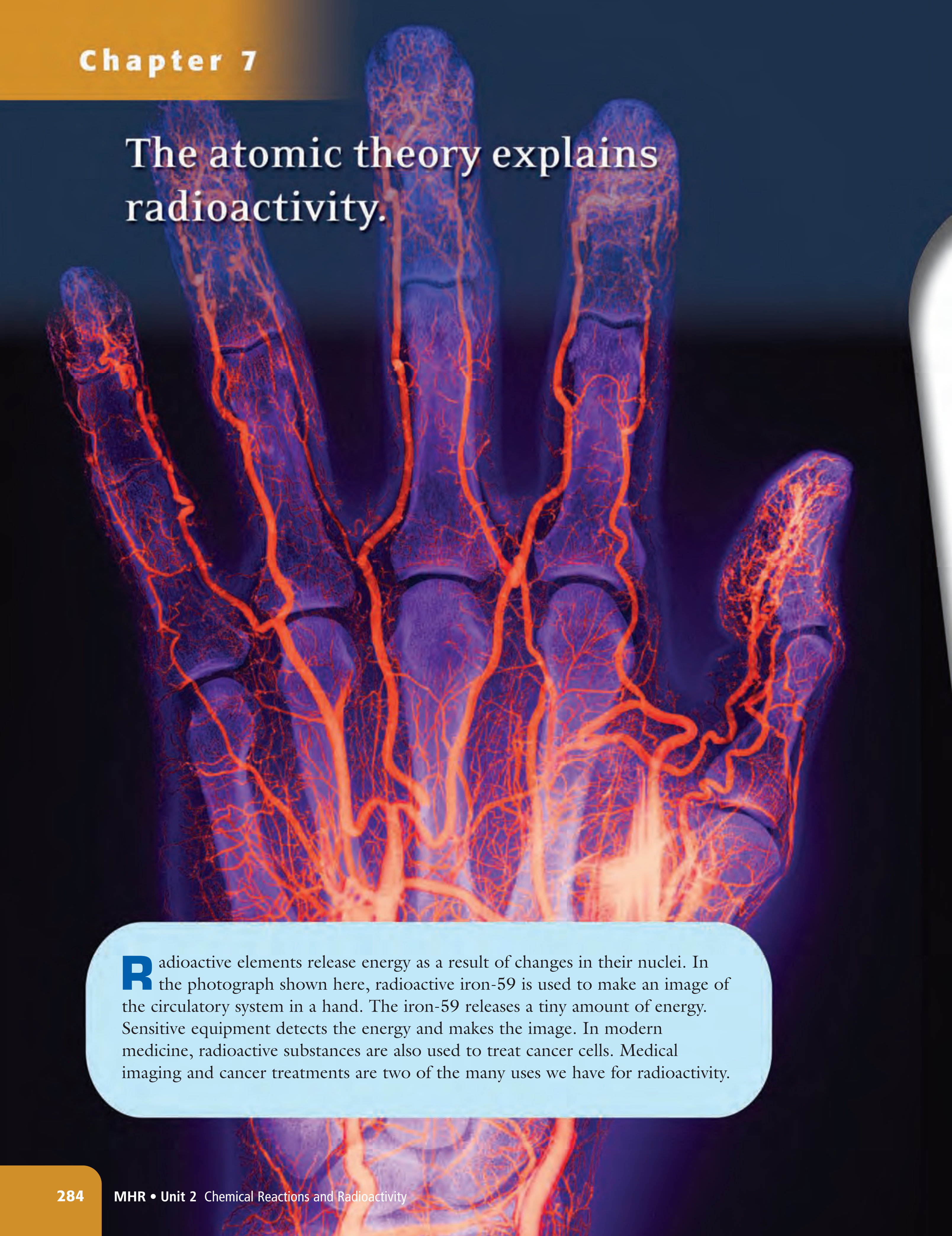
Chapter 7

The atomic theory explains radioactivity.



Radioactive elements release energy as a result of changes in their nuclei. In the photograph shown here, radioactive iron-59 is used to make an image of the circulatory system in a hand. The iron-59 releases a tiny amount of energy. Sensitive equipment detects the energy and makes the image. In modern medicine, radioactive substances are also used to treat cancer cells. Medical imaging and cancer treatments are two of the many uses we have for radioactivity.

What You Will Learn

In this chapter, you will
- **define** isotopes in terms of atomic number and mass number
- **relate** radioactive decay to changes in the nucleus
- **explain** half-life using rates of radioactive decay
- **compare** fission and fusion
- **illustrate** radioactive decay, fission, and fusion using nuclear equations

Why It Is Important

Our understanding of the uses and effects of nuclear reactions continues to grow. Issues related to the production and use of nuclear energy are frequent topics in news, international politics, industry, and the diagnosis and treatment of disease.

Skills You Will Use

In this chapter, you will
- **model** changes in isotopes during radioactive decay, fission, and fusion
- **write** nuclear equations
- **model** and **graph** a half-life curve for a radioisotope
- **interpret** information related to absolute dating using isotopes, such as carbon-14

FOLDABLES™
Reading & Study Skills

Shutter Fold

STEP 1 Begin as if you were going to make a hamburger but instead of creasing the paper, pinch it to show the midpoint.

STEP 2 **Fold** the outer edges of the paper to meet at the pinch, or mid-point, forming a shutter fold.

Vocabulary Book

STEP 1 **Fold** a sheet of notebook paper in half like a hotdog.

STEP 2 On one side, **cut** every third line. This results in ten tabs on wide ruled notebook paper and twelve tabs on college ruled.

STEP 3 **Label** the tabs and **record** information beneath.

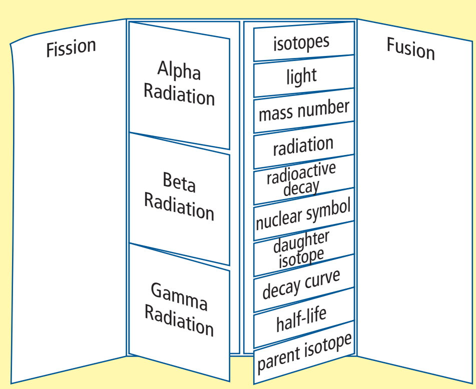
Three-tab Book

STEP 1 **Fold** a sheet of paper like a hot dog.

STEP 2 With the paper horizontal, and the fold of the hot dog up, **fold** the right side toward the center, trying to cover one half of the paper.

STEP 3 **Fold** the left side over the right side to make a book with three folds.

STEP 4 **Open** the folded book. Place your hands between the two thicknesses of paper and **cut** up the two valleys on one side only. This will form three tabs.



7.1 Atomic Theory, Isotopes, and Radioactive Decay

Radiation refers to high-energy rays and particles emitted by radioactive sources. Isotopes are atoms of the same element that differ in the number of neutrons in the nucleus. Radioisotopes are natural or human-made isotopes that decay into other isotopes, releasing radiation. The three major types of radiation are alpha particles, beta particles, and gamma rays. A nuclear reaction occurs when the number of neutrons or protons in a nucleus changes, or when radiation is released from the nucleus. Radioactivity results when the nucleus of an atom decays. If the atom emits one or more protons as it decays, the atom changes into an atom of another element.

Words to Know

alpha particle
beta particle
gamma radiation
isotopes
light
mass number
radiation
radioactive decay

Did You Know?

Trace amounts of radiation from the following sources can be found in food and water that we consume.

- radioactive substances in Earth's crust
- radioactive gas released from Earth's crust
- cosmic rays from outer space that bombard Earth

Imagine you discover that a certain type of rock emits invisible high-energy rays. Then, on further investigation, you find that several other types of rocks also emit high-energy rays. Suppose that with more investigation you discover that high-energy rays are emitted by the ground, by buildings, by humans, and even by the air around you. What explanation could you offer for the source of this energy?

Radioactivity is the release of high-energy particles and rays of energy from a substance as a result of changes in the nuclei of its atoms. We can use radioactivity to improve our lives, such as through medical diagnoses and treatments and by generating electricity.

The stream of high-energy, fast-moving particles or waves that is found in our environment is called **natural background radiation**. Background radiation has the potential to interact with an atom and turn it into an ion.

Radiation refers to high-energy rays and particles emitted by radioactive sources. Radiation includes radio waves, microwaves, infrared rays, visible light, and ultraviolet rays (Figure 7.1). Although most forms of radiation are invisible to the human eye, they are present all around us all the time. **Light** is one form of radiation that is visible to humans.

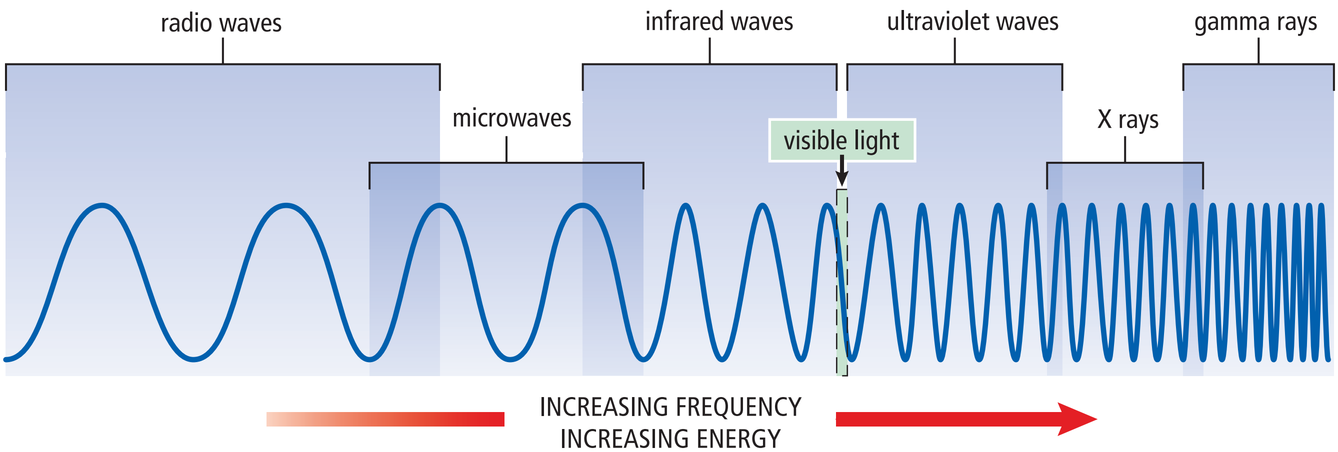


Figure 7.1 The electromagnetic spectrum

7-1A Detecting Radiation

Find Out ACTIVITY

Teacher Demonstration

Many common materials have a small degree of radioactivity. How is radiation measured? In this activity, your teacher will use an instrument known as a Geiger-Müller counter (GM counter) to detect the radiation in several samples and in your classroom.

Materials

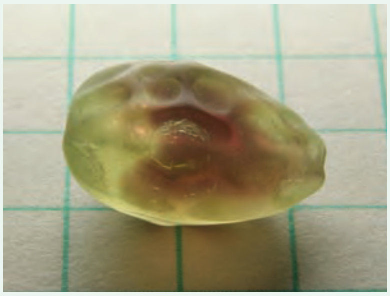
- Geiger-Müller counter
- slightly radioactive materials, which may include Vaseline glass bead, salt substitute (contains potassium), old radium-style watch (1950s era)
- sheets of paper, aluminum foil, lead

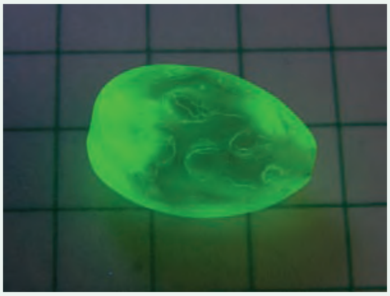
What to Do

1. Design a two-column table that you can use to record your observations. Give your table a title.
2. Your teacher will use the GM counter to measure a selection of radioactive materials and materials that may shield the radiation. Record your observations of each material tested.

What Did You Find Out?

1. How could you demonstrate that a natural level of background radiation exists in your home?
2. Which kinds of materials are effective in shielding radiation from the samples you examined?





Vaseline glass contains a small amount of uranium oxide, making it slightly radioactive.

Searching for Invisible Rays

In 1895, German physicist Wilhelm Roentgen (1845–1923) discovered that an unknown kind of energy was emitted from certain materials when he bombarded them with electrons. These invisible rays could darken photographic film, just like visible light rays could. He called the newly discovered energy X rays, where X stood for "unknown."

Roentgen's work led to the discovery of radioactivity by a French physicist who found himself in the right place at the right time, with a prepared mind. The scientist's name was Henri Becquerel (1852–1908). Becquerel discovered by chance that uranium salts emitted rays that darkened photographic plates (Figure 7.2). This surprised Becquerel because, up to this point, scientists had found evidence of the high-energy rays only when they first directed some sort of radiation onto the material.

Word Connect

The word "radiation" comes from the word radiate, which means to spread out in all directions from a central point. The combining form "radio-" is related to radiant energy.

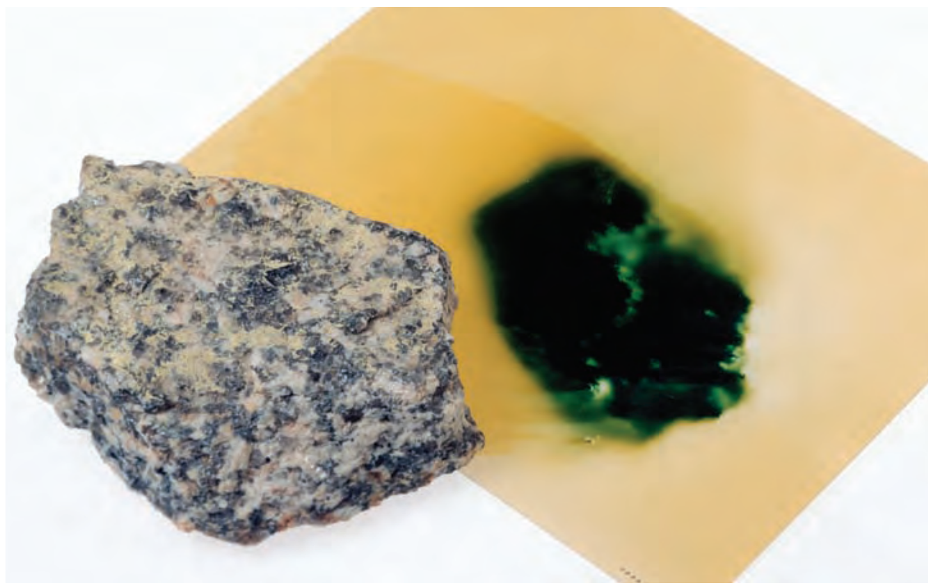


Figure 7.2 A rock containing uranium salts causes photographic film to be exposed. This is evidence that the rock is radioactive. In this example, the radioactivity is coming from the uranium atoms in the rock.

Figure 7.3 Marie Curie is considered one of the greatest scientists in history.

Chemist Marie Curie (1867–1934) (Figure 7.3) and her husband Pierre Curie (1859–1906) used Becquerel's mineral sample and isolated the components emitting the rays. They concluded that the darkening of the photographic plates was due to rays emitted from the uranium atoms present in the mineral sample. Marie Curie called this process radioactivity. Figure 7.4 on the next page shows the darkening of photographic film that is exposed to radiation emitted by radium salts.

The work of Marie and Pierre Curie was extremely important in explaining radioactivity and developing the field of nuclear chemistry. In 1898, the Curies identified two new elements, polonium and radium. Henri Becquerel and the Curies shared the 1903 Noble Prize in physics for their work. Marie Curie also received the 1911 Nobel Prize in chemistry for her work with polonium and radium. She is one of only four people to have won two Nobel prizes.

Did You Know?

Marie Curie named polonium after her home country, Poland.

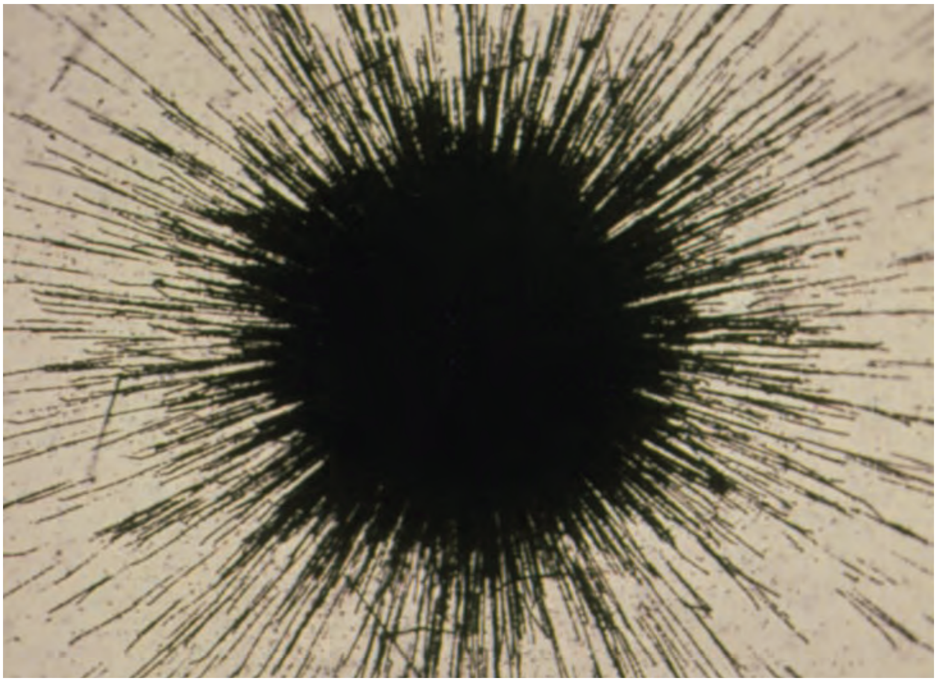


Figure 7.4 Radium salts are placed on a photographic plate. After the plate is developed, the photograph shows the dark traces left by radiation emitted by the radium salts.

Isotopes and Mass Number

Which elements are radioactive? Why are different types of radiation emitted by radioactive nuclei? To answer these questions, you need to first know about isotopes.

Isotopes are different atoms of a particular element that have the same number of protons but different numbers of neutrons. All isotopes of an element have the same atomic number (number of protons). However, since the number of neutrons differs, the mass number and atomic mass differ from one isotope to the next. The **mass number** is an integer (whole number) that represents the sum of an atom's protons and neutrons. The mass number of an isotope is found by adding the atomic number to the number of neutrons.

Mass number = atomic number + number of neutrons

Word Connect

"Isotope" comes from the Greek words *isos*, meaning equal, and *topos*, meaning place. All the isotopes for a particular element are represented by the same box or place on the periodic table. For example, chlorine-35 and chlorine-37 are both represented by the same place (atomic number 17) on the periodic table.

Number of protons and neutrons

You may remember from Chapter 4 that the atomic number is found by counting the number of protons. To find the number of neutrons of an isotope, subtract the atomic number from the mass number.

Number of neutrons = mass number − atomic number

Different isotopes of the same element have the same element symbol. For example, all isotopes of potassium have the symbol K, indicating the same number of protons, even though different numbers of neutrons can be found in the nucleus of different potassium isotopes. You can use the mass number to tell different isotopes apart.

Representing Isotopes

Chemists represent isotopes using standard atomic notation, which is a shortened form involving the chemical symbol, atomic number, and mass number. The mass number is written as a superscript (above) on the left of the symbol. The atomic number is written as a subscript (below) on the left (Figure 7.5). For example, potassium has three naturally occurring isotopes: potassium-39, potassium-40, and potassium-41 (Table 7.1). The standard atomic symbols for these three isotopes of potassium are ${}^{39}_{19}K$, ${}^{40}_{19}K$, and ${}^{41}_{19}K$. Another name for the standard atomic symbol is the **nuclear symbol**.

$${}^{39}_{19}K$$

Figure 7.5 In standard atomic notation, the mass number (39) is written above the atomic number (19).

Table 7.1 Isotopes of Potassium

	Potassium-39	Potassium-40	Potassium-41
Protons (nucleus)	19	19	19
Neutrons (nucleus)	20	21	22
Electrons (in shells)	19	19	19

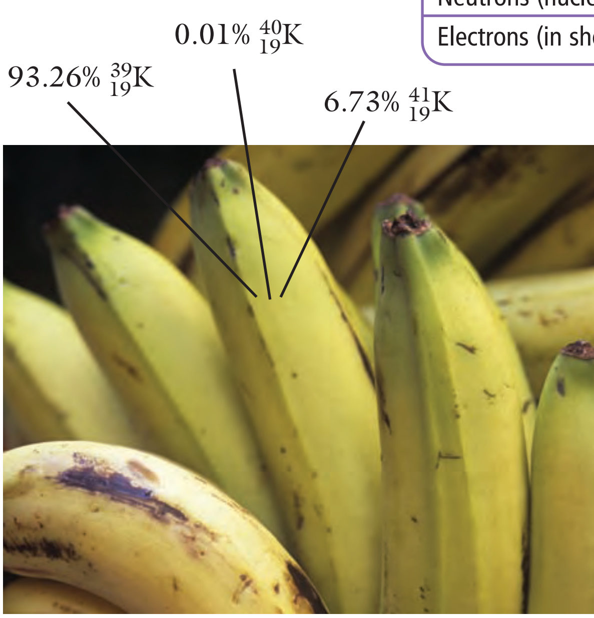


Figure 7.6 Each banana has the same relative abundance of potassium isotopes.

In nature, most elements are found as a mixture of isotopes. Usually, no matter where a sample of an element is taken from, the percentage of each isotope is constant. For example, in a banana, which is a rich source of potassium, approximately 93.26 percent of the potassium atoms will have 20 neutrons, 0.01 percent will have 21 neutrons, and 6.73 percent will have 22 neutrons (Figure 7.6). In another banana or in a totally different source of potassium, the percentage composition of the potassium isotopes will still be about the same.

Reading Check

1. Why was the discovery that uranium salts emitted radiation a surprise to scientists?
2. What did Marie Curie call the process by which some materials give off radiation such as X rays?
3. What is meant by the term "isotope"?
4. (a) What do all isotopes of the same element have in common?
   (b) How do isotopes of the same element differ?
5. What information about the nucleus of an isotope is given by its mass number?

Did You Know?

The atomic mass of an element shown in the periodic table is a decimal number. Atomic mass is an average of the masses of all the isotopes of that element.

Practice Problems

1. Copy and complete the following chart in your notebook.

Isotope	Atomic number (number of protons)	Number of Neutrons	Mass Number
neon-21			
silicon-30			
lithium-7			
	13	14	
	3	3	
	6	8	
		13	25
		10	19

2. A laboratory analyzes the composition of the two naturally occurring isotopes of bromine. One of the isotopes has an atomic number of 35 and a mass number of 81. State the following for the isotope.
   (a) number of protons
   (b) number of neutrons
   (c) name of the isotope
   (d) standard atomic notation
3. An element is analyzed and found to have a mass number of 37. An atom contains 20 neutrons in its nucleus. State the following.
   (a) number of protons
   (b) name of the isotope
   (c) standard atomic notation
4. For an isotope containing 16 protons and 17 neutrons, state the following.
   (a) atomic number
   (b) mass number
   (c) name of the isotope
   (d) standard atomic notation

Answers provided on page 592

7-1B Building Bohr Model Atoms and Ions

Think About It

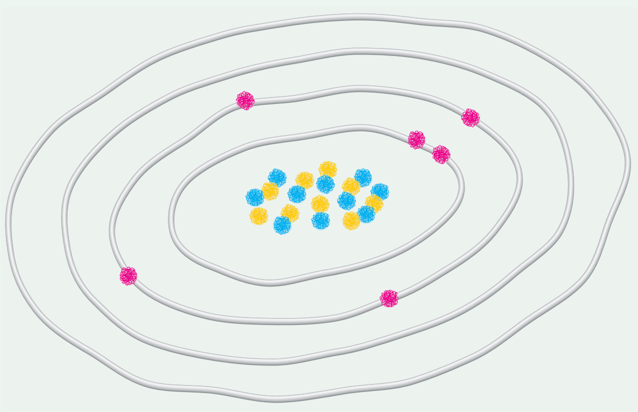
In this activity, you will construct Bohr models of atoms and ions for various isotopes. The centre of your models will represent the nucleus and the strings will represent energy shells. The fur balls are not accurate models of mass or size of subatomic particles. An electron is tiny and has approximately 0.0005 the mass of a proton.

Materials

- 20 of each of three different colours of fur balls
- 4 string loops of increasing length
- periodic table

What to Do

1. Arrange the four string loops one around the other. Decide which colours of fur balls will represent protons, neutrons, and electrons.



Arrange the loops of string around each other on a common centre.

2. Place 9 protons and 10 neutrons in the centre to represent the nucleus. You have just constructed the only stable isotope of fluorine. Complete your model by adding electrons one at a time. Place two on the inner string, paired together. Then put seven electrons on the next string, first placing an electron at each compass point and then pairing electrons. Examine your model. Record the position and number of each type of particle.
3. Build a Bohr model of neon-20 by adding to the Bohr model for fluorine-19. You will have to decide what particle(s) to add in order to make this change. Fluorine-19 and neon-20 are isotopes of different elements. Observe and record their similarities and differences.
4. Add to the Bohr model of neon-20 to create the other two stable isotopes of neon, which are neon-21 and neon-22. The models built in this step are isotopes of the same element. Observe and record their similarities and differences.
5. Build an atom of aluminum-27, showing the correct arrangement of all the subatomic particles. Then, alter the model to show an aluminum ion. The models built in this step are of the same isotope, but one is an atom and the other is an ion. Observe and record their similarities and differences.
6. Build an atom with seven protons, eight neutrons, and the correct number of electrons, arranged correctly. Use a periodic table to help you identify the element that is represented by this model. Record the element.
7. Imagine that all the protons in step 6 became neutrons and the neutrons became protons. Keep the number of electrons unchanged.
   (a) Identify the new element you have made.
   (b) Is the new element an atom or an ion? Why?
8. Construct a Bohr model for a classmate to try to identify. Do not use more than 20 of any subatomic particle. Remember that realistic nuclei with an atomic number lower than 30 have the same or nearly the same number of neutrons and protons.

What Did You Find Out?

1. Describe how to draw a Bohr model of an atom of calcium-42.
2. Explain how to modify a Bohr model of an atom of calcium-42 in order to produce a Ca^{2+} ion involving this isotope.
3. Explain how to modify a Bohr model of an atom of calcium-42 in order to produce an atom of calcium-40.
4. Explain the differences between changing an atom into an ion and changing an atom into a different isotope of the same element.
5. Explain the differences between changing an atom into a different isotope of the same element and changing an atom into an atom of a different element.

Radioactive Decay

Scientists studying radioactivity made an important discovery—that by emitting radiation, atoms of one kind of element can change into atoms of another element. This discovery was a major breakthrough, as no chemical reaction had ever resulted in the formation of new kinds of atoms.

Radioactive atoms emit radiation because their nuclei are unstable (likely to decay). Unstable atoms gain stability by losing energy, and they lose energy by emitting radiation. **Radioactive decay** is the process in which unstable nuclei lose energy by emitting radiation. Unstable radioactive atoms undergo radioactive decay until they form stable non-radioactive atoms, usually of a different element (Figure 7.7). Isotopes that are capable of radioactive decay are called **radioisotopes**.

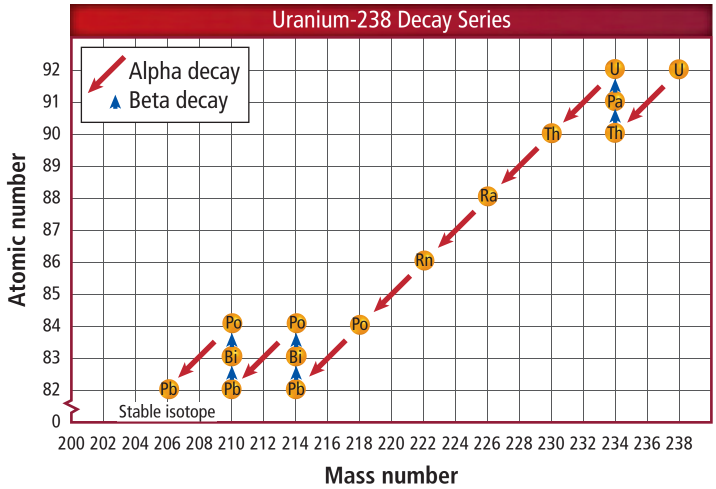


Figure 7.7 Uranium-238 undergoes 14 different radioactive decay steps before forming stable lead-206.

It is not easy to judge by looking at a nuclear symbol for an isotope whether is stable (not likely to decay) or unstable (eventually will decay and therefore is a radioisotope). For example, carbon-12 and carbon-13 are stable, while carbon-14 is not (Table 7.2). You have all three forms of carbon atoms in your body, most of which are carbon-12. Even though only 1 carbon atom in 1 trillion in your body is unstable and can therefore release radiation, this still represents a huge number of carbon-14 atoms.

Table 7.2 Isotopes of Carbon

Isotope Name	Nuclear Symbol	Mass Number (protons + neutrons)	Atomic Number (protons)	Neutrons	Percentage of a Typical Sample of Carbon Atoms
carbon-12 (stable)	$^{12}_{6}C$	12	6	6	98.9%
carbon-13 (stable)	$^{13}_{6}C$	13	6	7	1.1%
carbon-14 (unstable)	$^{14}_{6}C$	14	6	8	1 atom in 1 trillion atoms

Figure 7.8 Ernest Rutherford (1871–1937)

Three Types of Radiation

The three most common types of radiation emitted during radioactive decay were first identified by Ernest Rutherford (Figure 7.8). Rutherford later discovered the nucleus and created a model of the atom. He and his colleagues placed a radioactive source inside a lead block that allowed the radiation to pass out only through a tiny hole. From the hole, the radiation travelled through a slot between electrically charged plates that deflected any electrically charged particles (Figure 7.9). The positively charged particles were deflected toward the negative plate. Rutherford called these positively charged particles alpha particles. The negatively charged particles, called beta particles, were deflected towards the positive plate. A third type of radiation, gamma radiation, has no electric charge, and so passed right through the electric field unaffected.

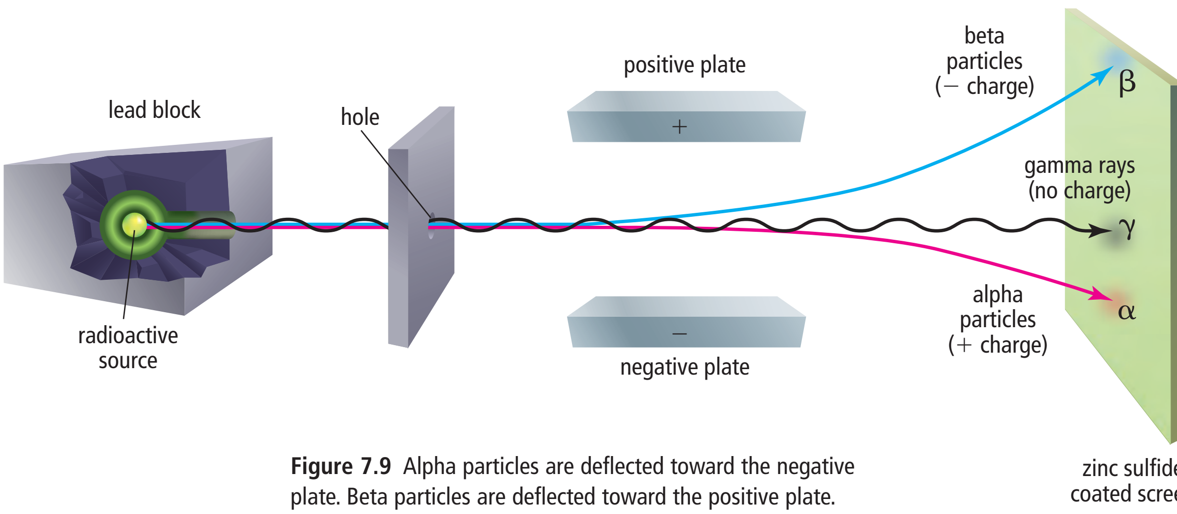


Figure 7.9 Alpha particles are deflected toward the negative plate. Beta particles are deflected toward the positive plate. Gamma radiation is not deflected by the electric field.

Did You Know?

Ernest Rutherford received a Nobel Prize for his investigations into the disintegration of the elements and the chemistry of radioactive substances. He performed many of the experiments that led to the prize while working at McGill University in Montreal. A Canadian stamp honours his work on radioactivity conducted in Canada.

Alpha Radiation

Since Rutherford's discovery, scientists have continued to study radiation. We now understand more about how radiation is emitted.

Alpha radiation is a stream of alpha particles. **Alpha particles** are positively charged atomic particles that are much more massive than either beta particles or gamma radiation. An alpha particle has the same combination of particles as the nucleus of a helium atom. We use the symbols ${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$ to represent an alpha particle. The symbols show an alpha particle has a mass number of 4 and an atomic number of 2, which means an alpha particle is composed of two protons and two neutrons. Because it has two protons, an alpha particle has an electric charge of 2+. Because of their mass and charge, alpha particles are relatively slow-moving compared with other types of radiation. Alpha particles are not very penetrating—a single sheet of paper stops alpha particles.

The emission of an alpha particle from a nucleus is a process called **alpha decay** (Figure 7.10).

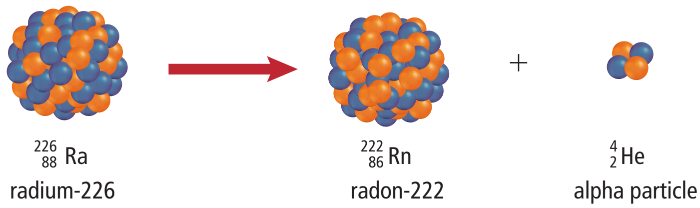


Figure 7.10 The nucleus of an atom of radium-226 contains 88 protons and 138 neutrons. A radium-226 nucleus undergoes alpha decay to form a different element, radon-222, and an alpha particle.

Word Connect

Alpha, beta, and gamma are the first three letters of the Greek alphabet. Rutherford derived the name "proton" from the Greek word *protos*, meaning first. He speculated that there might be more than one particle in the nucleus. The neutron was not discovered until 1932.

Note that the nuclear reaction in Figure 7.10 is balanced. The sum of the atomic numbers (subscripts) and the sum of the mass numbers (superscripts) on each side of the arrow are equal. Also note that, when a radioactive nucleus emits an alpha particle, the product nucleus has an atomic number that is lower by two and a mass number that is lower by four.

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$$

The equation in the example shown above can also be written as:

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

Although a helium nucleus has a 2+ charge (making it $^{4}_{2}\text{He}^{2+}$), it is common practice to omit the charge symbol when representing an alpha particle.

Practice Problems

1. Try the following alpha decay problems yourself. You can refer to the periodic table in Figure 4.3 on page 172.

(a) $^{208}_{84}\text{Po} \rightarrow$ ____ $+ {}^{4}_{2}\alpha$

(b) $^{231}_{91}\text{Pa} \rightarrow$ ____ $+ {}^{4}_{2}\text{He}$

(c) ____ $\rightarrow {}^{221}_{87}\text{Fr} + {}^{4}_{2}\alpha$

(d) ____ $\rightarrow {}^{192}_{77}\text{Ir} + {}^{4}_{2}\alpha$

(e) ____ $\rightarrow {}^{207}_{85}\text{At} + {}^{4}_{2}\text{He}$

Answers provided on page 592

Beta Radiation

A **beta particle** is an electron. We can use the symbol ${}^{0}_{-1}\beta$, or ${}^{0}_{-1}e$, to represent a beta particle. The mass of an electron is about 0.0005 the mass of a proton or a neutron, so the beta particle is assigned a mass number of zero. A beta particle has an electric charge of 1−. Because beta particles are both lightweight and fast-moving, they have a greater penetrating power than alpha particles. A thin sheet of aluminum foil can block beta particles.

Some atoms undergo beta decay. In **beta decay**, a neutron changes into a proton and an electron. During beta decay, the proton remains in the nucleus while the electron shoots out from the nucleus with a lot of energy. Since the proton remains in the nucleus, the atomic number of the element increases by one—it has become an atom of the next higher element on the periodic table. The mass number of the resulting isotope does not change because the neutron has been replaced by a proton of almost equal mass.

Example: ${}^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}\beta$

Since a beta particle is an electron that has just been ejected from a nucleus, the equation in the example shown above can also be written in the following form, which means the same thing.

Example: ${}^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e$

Did You Know?

Iodine-131 therapy is not used only for humans. Cats with thyroid cancer may receive the treatment as well.

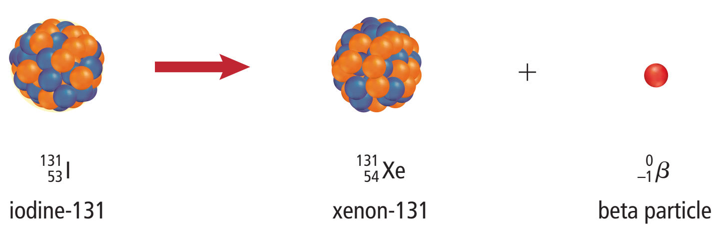


Figure 7.11 The beta particle that is emitted during beta decay has high energy and can penetrate human skin and damage cells.

Figure 7.11 shows the decay of an iodine-131 nucleus, emitting a beta particle. The mass number stays the same, but the atomic number increases by one, producing the element xenon. The iodine-131 isotope is used in the treatment of cancer of the thyroid gland, a small gland in your neck that helps control how your body uses energy (Figure 7.12).

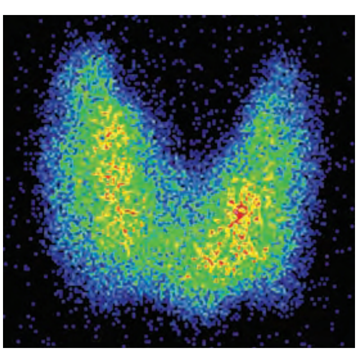


Figure 7.12 Iodine is taken up quickly by the thyroid.

Practice Problems

1. Try the following beta decay problems yourself. You can refer to the periodic table in Figure 4.3 on page 172.

(a) ${}^{14}_{6}C \rightarrow$ ____ $+ {}^{0}_{-1}\beta$

(b) ${}^{6}_{2}He \rightarrow$ ____ $+ {}^{0}_{-1}\beta$

(c) ${}^{24}_{11}Na \rightarrow$ ____ $+ {}^{0}_{-1}e$

(d) ____ $\rightarrow {}^{201}_{80}Hg + {}^{0}_{-1}\beta$

(e) ____ $\rightarrow {}^{52}_{27}Co + {}^{0}_{-1}\beta$

(f) ____ $\rightarrow {}^{42}_{20}Ca + {}^{0}_{-1}e$

Answers provided on page 592

Gamma Radiation

Gamma radiation consists of rays of high-energy, short-wavelength radiation (Figure 7.13). Gamma radiation is represented by the symbol $^{0}_{0}\gamma$. Because gamma radiation has almost no mass and no charge, the release of gamma radiation does not change the atomic number or the mass number of a nucleus.

If you turn back to Figure 7.1 on page 287, you will notice that gamma rays are the highest energy form of electromagnetic radiation. Gamma rays have much more energy than ultraviolet rays or X rays and are more dangerous than other forms of electromagnetic radiation. Gamma radiation has the greatest penetrating power of the three types of radiation. Thick blocks of dense materials, such as lead and concrete, are needed to stop gamma rays.

Gamma decay results from a redistribution of energy within the nucleus. A high-energy gamma ray is given off as the isotope falls from a high-energy state to a lower energy state. For example, high-energy nickel-60 can decay to nickel-60 by gamma decay:

$$^{60}_{28}\text{Ni}^{*} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{0}\gamma$$

The "*" means that the nickel nucleus has extra energy. This extra energy is released as a gamma ray. Many kinds of radioactive decay can release gamma rays. For example, gamma rays accompany the alpha decay of uranium-238.

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} + 2\gamma$$

The 2 in front of the γ symbol indicates that two gamma rays are emitted.

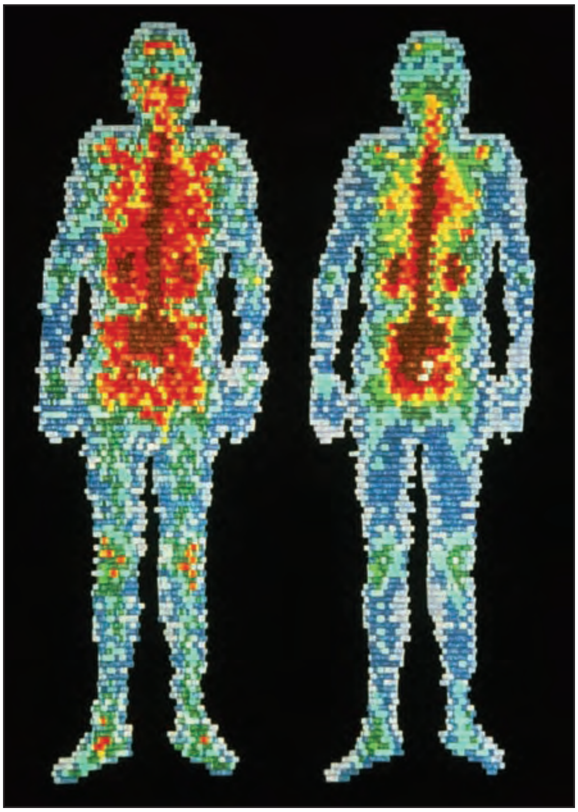


Figure 7.13 Front (right) and back views of a man injected with a radioisotope that concentrates in the bones. The scans are coloured according to the strength of the gamma radiation, ranging from blue for the lowest emission through to brown for the highest emission.

Reading Check

1. What is radioactive decay?
2. What is a radioisotope?
3. What are the names of the three main types of radiation?
4. What is the electric charge of each of the three kinds of radioactive decay?
5. List the symbols used for:
   (a) alpha radiation (two symbols)
   (b) beta radiation (two symbols)
   (c) gamma radiation

Suggested Activity

Think About It 7-1C on page 299

Radiation and Radioactive Decay Summaries

Some isotopes release alpha, beta, and gamma radiation all at once. The properties of alpha, beta, and gamma radiation are summarized below in Table 7.3. A summary of radioactive decay processes is shown below in Table 7.4.

Table 7.3 Properties of Alpha, Beta, and Gamma Radiation

Property	Alpha Radiation	Beta Radiation	Gamma Radiation
Symbol	${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$	${}^{0}_{-1}\beta$ or ${}^{0}_{-1}e$	${}^{0}_{0}\gamma$
Composition	Alpha particles	Beta particles	High-energy electromagnetic radiation
Description of radiation	Helium nuclei, ${}^{4}_{2}He$	Electrons	High energy rays
Charge	2+	1−	0
Relative penetrating power	Blocked by paper	Blocked by metal foil or concrete	Partly or completely blocked by lead

Table 7.4 Summary of Radioactive Decay Processes

	Alpha Decay	Beta Decay	Gamma Decay
Particle emitted	${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$	${}^{0}_{-1}\beta$ or ${}^{0}_{-1}e$	${}^{0}_{0}\gamma$
Change in mass number of starting nucleus	Decreases by 4	No change	No change
Change in atomic number of starting nucleus	Decreases by 2	Increases by 1	No change

Nuclear equations for radioactive decay

A **nuclear equation** is a set of symbols that indicates changes in the nuclei of atoms during a nuclear reaction. The symbols used in a nuclear equation include element symbols (including atomic number and mass number) and symbols representing neutrons and electrons. Like a chemical equation, a nuclear equation shows reactants on the left and products on the right. The reactants and products are separated by an arrow, which means produces or changes into.

You can use a nuclear equation to show changes in the nucleus due to radioactivity. When you write a nuclear equation, you need to include the mass number and the atomic number of every particle and every nucleus participating in the change. Remember the following rules when you write a nuclear equation.

1. **The sum of the mass numbers does not change.** Even when a neutron changes into a proton and an electron or when a large nucleus splits into smaller ones releasing protons ($^{1}_{1}p$) or neutrons ($^{1}_{0}n$) or gamma rays, the total number of protons plus neutrons remains the same.
2. **The sum of the charges in the nucleus does not change.** The atomic number of an element represents the total (positive) charge in a nucleus. Each nuclear symbol, including electrons and neutrons, has a number in the bottom left. The charge number does not change across a nuclear reaction.

Explore More

Some of the natural background radiation on Earth is caused by exposure to radon, a radioactive gas that seeps from Earth's crust and is present in the air we breathe. This is a problem in some British Columbia communities. Find out more about radon and its presence in our environment. Start your search at **www.bcscience10.ca**.

7-1C Modelling Radioactive Decay

Think About It

In this activity, you will compare radioactive decay to changes in the nucleus. You will build models to represent the isotopes of different elements and then model alpha, beta, and gamma decay. You do not need to show the electrons that exist in energy shells surrounding the nucleus as they do not take part in radioactive decay.

Materials

- small objects, such as foam balls, paper clips, and cloth balls to represent subatomic particles

What to Do

1. Work with a partner or in a small group to build the nuclei of three of the isotopes of carbon. They are carbon-12, carbon-13, and carbon-14. If you are not sure how many of each particle is in each nucleus, refer to Table 7.2, on page 293. Compare the three isotopes. What do they have in common? What makes them different from each other?
2. Build a model of an alpha particle. An alpha particle is made of two protons and two neutrons.
3. Select a particle to represent an electron. An electron is not composed of parts, so it should be represented by a single foam ball or other object. Represent a gamma ray with a long piece of paper with a wave drawn on it labelled "gamma ray."
4. Draw sketches to represent the following nuclear decay reactions. Discuss your sketches with other members of the class or your teacher. Make sure you can explain each part of the sketch.
   Alpha decay: $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}\alpha$
   Beta decay: $^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta$
   Gamma decay: $^{60}_{28}Ni^{*} \rightarrow ^{60}_{28}Ni + ^{0}_{0}\gamma$
5. Clean up and put away all your materials.

What Did You Find Out?

1. How is the mass number of an element determined?
2. How did you represent a large nucleus such as radium-226?
3. Why does an alpha particle have a positive charge?
4. How does beta decay result in the production of an element with one more proton than the nucleus started out with?
5. Since gamma rays are not made of matter, how can they be detected?

Wild, Weird, Wonderful

www Science

Fake Money, Real Isotopes

In law enforcement, tracking down counterfeiters, and tracing the origins of illegal substances, there is a new tool in the toolkit: isotope analysis.

Isotopes are atoms of the same element that are chemically identical but which have slightly different weights because they have different numbers of neutrons in the nucleus. For example, carbon-13 is heavier than carbon-12 but lighter than carbon-14. A device called a mass spectrometer can sort out isotopes of the same element. Investigators use a mass spectrometer to compare the amount of carbon-13 isotope to the amount of carbon-12 isotope in a sample. This ratio changes depending on the water content of the soil and the metabolism of the plant. In other words, different plants can have ratios that reflect the growth environment. The differences show up in chemicals that come from plants, such as in illicit drugs like cocaine and heroin.

Cocaine is a chemical derived from the coca plant. The coca plant gets its nutrients from the soil it is planted in. Different soil types have slightly different amounts of isotopes of elements such as carbon and nitrogen. This difference acts like a fingerprint. Investigators can analyze isotopes to determine whether the coca plant grew in Bolivia, Colombia, or Peru.

The powerful drug morphine is refined from opium, which comes from the poppy plant. Heroin is made from morphine. Analyzing the ratio of carbon-12 to carbon-13 and then comparing to data bases can determine whether the poppies grew in Asia, South America, or Mexico, for example. The rate at which plants take up isotopes changes depending on environmental conditions in different parts of the world.

Drug law enforcement officers use isotope analysis to understand where illicit drugs come from and to focus their resources appropriately. Isotope analysis is also used in other areas of law enforcement. Since explosives are made from chemicals that also contain carbon, isotope analysis can help with determining the source of materials used in explosives.

The same techniques can help trace the country of origin of counterfeit paper money, such as $100 bills. Currency paper contains cotton to give it extra strength and durability. Cotton requires water for growth; water contains oxygen. Oxygen isotopes vary in rainwater around the world. Differences in rainwater show up as differences in the cellulose molecules in the cotton. Mass spectrometer analysis can determine the part of the world the cotton used in the fake bills has come from.

Isotope analysis can be used to help identify the source of cotton (top) used in counterfeit currency or where coca plants (bottom) were grown.

Check Your Understanding

Checking Concepts

1. What did Henri Becquerel discover about radiation emitted from uranium salts?
2. Distinguish between the terms "mass number" and "atomic number."
3. How do various isotopes of an element differ?
4. How many protons and neutrons are in the nuclei of each of the following isotopes?

   (a) $^{11}_{5}B$ (e) magnesium-26

   (b) $^{20}_{10}Ne$ (f) nitrogen-15

   (c) $^{31}_{15}P$ (g) silicon-28

   (d) $^{7}_{3}Li$ (h) chlorine-37

5. What two rules relate to mass numbers and atomic numbers in a nuclear equation?
6. Explain the changes that occur in the nucleus during each of the following.
   (a) alpha decay
   (b) beta decay
   (c) gamma decay

Understanding Key Ideas

7. Give the name and nuclear symbol for each of the following.
   (a) an element with 9 protons and 10 neutrons
   (b) an element with 8 protons and 10 neutrons
   (c) an element with 26 protons and 30 neutrons
8. Explain the composition of alpha and beta particles in terms of subatomic particles.
9. How is gamma radiation different from alpha and beta radiation?
10. Draw a Bohr model showing the number of protons and neutrons and the electron arrangement (including pairs and single electrons) for these atoms.
    (a) hydrogen-1
    (b) hydrogen-2
    (c) beryllium-9
    (d) magnesium-26
    (e) sulfur-36
11. Classify each of the following as alpha, beta, or gamma decay:

    (a) $^{201}_{80}Hg \rightarrow ^{201}_{81}Tl + ^{0}_{-1}\beta$

    (b) $^{231}_{91}Pa \rightarrow ^{227}_{89}Ac + ^{4}_{2}He$

    (c) $^{225}_{89}Ac \rightarrow ^{221}_{87}Fr + ^{4}_{2}\alpha$

    (d) $^{60}_{28}Ni^{*} \rightarrow ^{60}_{28}Ni + ^{0}_{0}\gamma$

    (e) $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

    (f) $^{24}_{11}Na \rightarrow ^{24}_{12}Mg + ^{0}_{-1}e$

12. Provide the symbol for the particle or nucleus that correctly completes the equation. For alpha decay, use either $^{4}_{2}\alpha$ or $^{4}_{2}He$. For beta decay, use $^{0}_{-1}\beta$ as needed.

    (a) $^{212}_{84}Po \rightarrow ^{208}_{82}Pb +$ ____

    (b) $^{90}_{38}Sr \rightarrow ^{90}_{39}Y +$ ____

    (c) $^{239}_{93}Np \rightarrow$ ____ $+ ^{0}_{-1}\beta$

    (d) $^{144}_{60}Nd \rightarrow$ ____ $+ ^{4}_{2}\alpha$

    (e) $^{42}_{19}K^{*} \rightarrow$ ____ $+ ^{0}_{0}\gamma$

    (f) $^{146}_{62}Sm \rightarrow ^{142}_{60}Nd +$ ____

13. Complete the following radioactive decay equations.

    (a) $^{257}_{104}Rf^{*} \rightarrow$ (gamma decay)

    (b) $^{8}_{3}Li \rightarrow$ (beta decay)

    (c) $^{255}_{103}Lr \rightarrow$ (alpha decay)

    (d) $^{254}_{98}Cf^{*} \rightarrow$ (gamma decay)

    (e) $^{13}_{5}B \rightarrow$ (beta decay)

    (f) $^{233}_{91}Pa \rightarrow$ (alpha decay)

Pause and Reflect

Both radioactivity and chemical reactions involve changes in matter. What do you think are the main differences between these two kinds of changes?