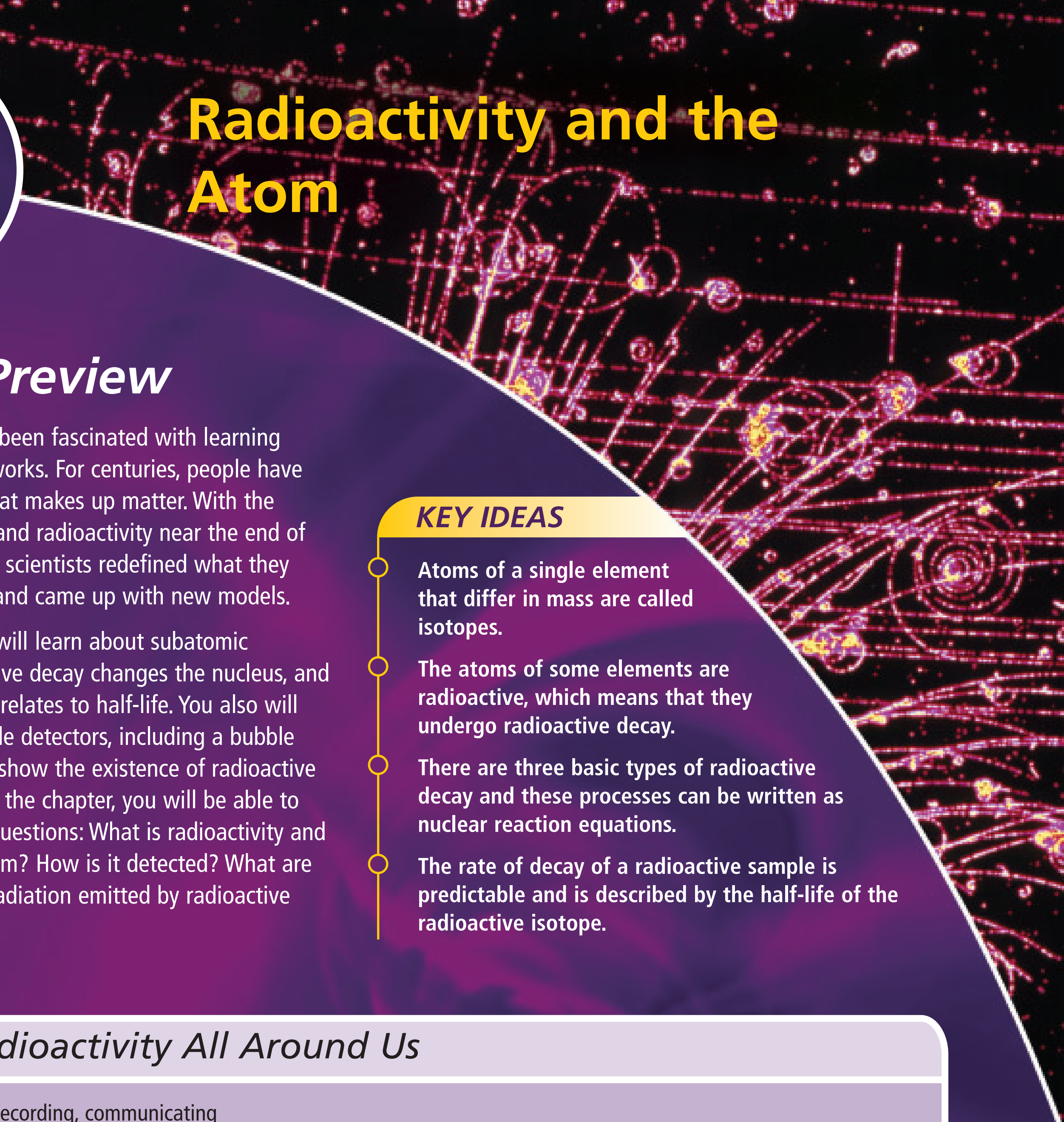
CHAPTER 10

Radioactivity and the Atom



Chapter Preview

Scientists have always been fascinated with learning about how the world works. For centuries, people have tried to understand what makes up matter. With the discovery of the X-ray and radioactivity near the end of the nineteenth century, scientists redefined what they knew about the atom and came up with new models.

In this chapter, you will learn about subatomic particles, how radioactive decay changes the nucleus, and how radioactive decay relates to half-life. You also will learn about how particle detectors, including a bubble chamber, were able to show the existence of radioactive particles. By the end of the chapter, you will be able to answer the following questions: What is radioactivity and where does it come from? How is it detected? What are the different types of radiation emitted by radioactive atoms?

KEY IDEAS

- **Atoms of a single element that differ in mass are called isotopes.**
- **The atoms of some elements are radioactive, which means that they undergo radioactive decay.**
- **There are three basic types of radioactive decay and these processes can be written as nuclear reaction equations.**
- **The rate of decay of a radioactive sample is predictable and is described by the half-life of the radioactive isotope.**

TRY THIS: Radioactivity All Around Us

Skills Focus: observing, recording, communicating

In this activity, you will observe some sources of nuclear radiation in your environment. Since nuclear radiation is invisible, your teacher will use a Geiger counter to detect radiation given off from some samples.

Materials: Geiger counter, glass crystal, pottery, smoke detector, wristwatch

1. Copy Table 1 into your notebook and list all your samples.

Table 1

Sample	Counts per minute
background	
glass crystal	

2. Turn on the Geiger counter without any of the samples placed near it and see how many counts there are in one minute. Record this number as the background radiation.
3. As your teacher places the samples in front of the Geiger counter, record the counts per minute for each sample.

A. Which sample had the highest number of counts per minute? Which had the lowest?

B. Would it be more accurate to record the number of counts per hour instead of counts per minute? Why or why not?

10.1 Radioactivity and Its History

Around the late 1800s, scientists determined that there were different types of radiation in addition to visible light. Electric currents produced some types of radiation while others seemed to be produced directly by matter. Each type of radiation had different properties. Some radiation had mass whereas others did not. Electrically, different types of radiation were positive, negative, or neutral.

The history of radioactivity involved the work of many people over a relatively short amount of time (Figure 1). Some discoveries were serendipitous, or accidental, while others required dedication and determination. For the purposes of this chapter, the history of radioactivity begins with the detection of cathode rays.

STUDY TIP

Study cards are an effective way to study for multiple-choice exams. On the front of the card, write the name of the scientist. On the back of the card, write how the scientist's discovery contributed to the understanding of radioactivity and the atom.

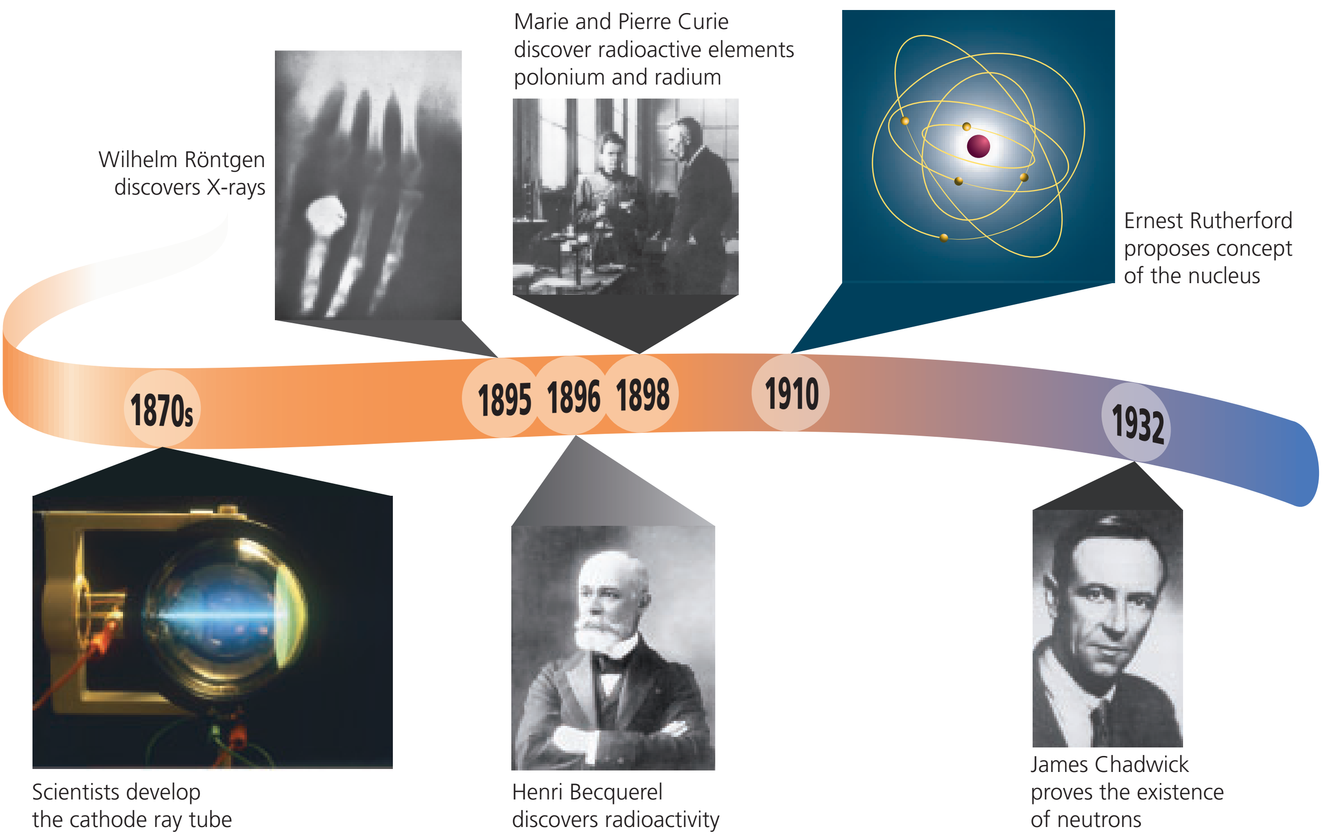


Figure 1 A brief history timeline of radioactivity and nuclear physics

Cathode Rays

In Grade 9 you learned about conductors and insulators when you studied electricity. During the middle to late 1800s, scientists believed that all gases were very poor conductors of electricity and, therefore, were insulators. However, scientists found that when most of the air inside a glass tube was removed by a vacuum pump, and a high voltage was applied to two electrodes inside the tube, a small electric current would pass through the remaining gas.

The current produces a beam, or ray, from the negative electrode (called the cathode) that goes to the positive electrode (called the anode) and causes the fluorescent screen at the end of the glass vacuum tube to glow. Since the beam comes from the cathode, the beam was said to be made of cathode rays, and the tube was called a cathode ray tube, or CRT (Figure 2).

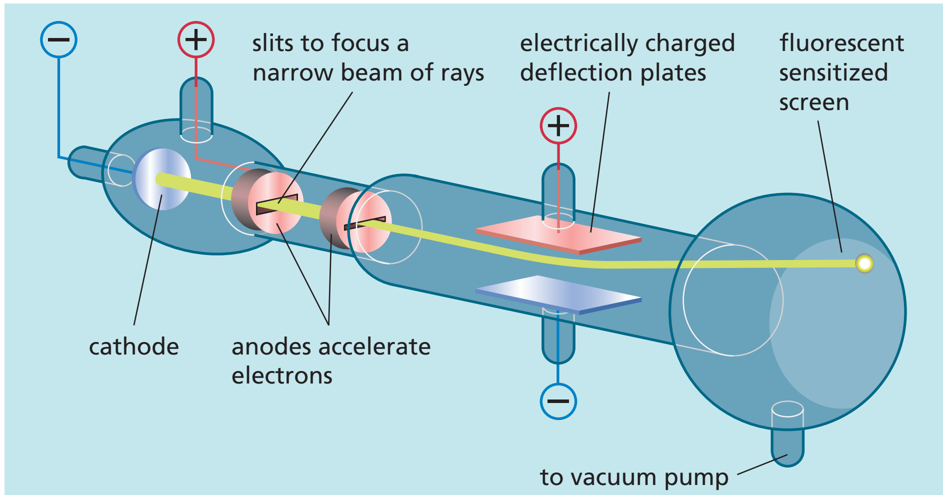


Figure 2 A cathode ray tube is used to show that electricity can be conducted in a gas under low pressure in a vacuum tube.

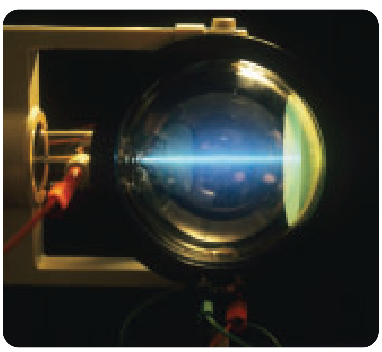


Figure 3 A Crookes tube

To learn more about how charged plates and a magnetic field can affect cathode rays view the animation at **www.science.nelson.com**

A Crookes tube (Figure 3) is a type of cathode ray tube. It is made from a glass cylinder with a partial vacuum inside. The tube contains a metal plate bent at right angles. It has a slit at one end and the visible surface is coated with a fluorescent material that glows when struck by the cathode rays. There are two electric terminals inside the tube that are connected to high voltage. The glow of fluorescence down the middle of the metal plate indicates that the cathode is emitting a beam of particles that is striking the plate.

Cathode rays can be deflected by electric charges and by magnets. The direction of the deflection of the cathode rays showed that they had a negative charge. When scientists placed a small paddle wheel inside the cathode ray tube, the cathode rays turned the wheel, which showed that the cathode rays behaved like particles. In 1897, Sir J.J. Thomson identified the negatively charged particles of the cathode ray as electrons.

Cathode ray tubes were used both in science and society. Prior to the development of liquid crystal screens and plasma screens, a cathode ray tube was the basic component of a television.

X-Rays

In 1895, Wilhelm Röntgen was experimenting with a cathode ray tube to investigate the secondary emissions caused by cathode rays. He covered a cathode ray tube with thick black paper, allowed cathode rays to strike a metal plate, and observed the emissions outside the tube (Figure 4). He discovered that the rays outside the tube caused fluorescent minerals to glow and also exposed photographic film. Since the rays that he discovered had no name, he called them X-rays. (“X” is used to refer to an unknown.)

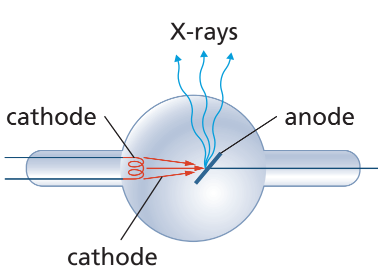


Figure 4 A simple X-ray tube

Röntgen found that X-rays were able to penetrate some materials, such as paper and skin, but not others, such as bone and metal. Röntgen took the first X-ray image (Figure 5). He received the first Nobel Prize in Physics in 1901 for his discovery.

Further investigations revealed that X-rays were actually a high-energy component of the electromagnetic spectrum. You may remember that the electromagnetic spectrum goes from low-energy radio waves to high-energy gamma rays (Figure 6).

In a cathode tube, the electrons are accelerated from the negative cathode to the positive anode and given a high speed. In fact, X-rays are produced by converting the kinetic energy of the high-speed electrons directly into electromagnetic radiation when they strike the metal plate.

Although you may think that X-rays are only used to take pictures of broken bones or cavities in teeth, X-rays also play an important role in the diagnosis and treatment of various diseases. Doctors use CAT (computerized axial tomography) scans, or multiple X-rays, to film slices of the body so that they can detect abnormal tissue or cancerous growths. Mammograms are used to detect breast cancer. High-energy X-rays are used to kill or shrink cancer cells.

Figure 5 Röntgen took the first X-ray of his wife's hand. Since X-rays cannot penetrate bones or metal, you can see the bones of her fingers as well as her wedding ring.

The Discovery of Radioactivity

At the same time Röntgen was experimenting with cathode rays, Henri Becquerel was experimenting with fluorescent minerals, some containing uranium. He thought the minerals might produce X-rays when exposed to sunlight. He put samples of the minerals on photographic film. When he developed the film, it showed an image of the shape of the sample.

Since Becquerel thought that the Sun was giving the minerals energy, his experiments were delayed by cloudy days, and he stored the samples and film in a drawer. One cloudy day, after storing the uranium sample on unexposed film, he decided to develop the film anyway, expecting to see nothing. To his surprise, the film showed a strong image of the shape of the mineral.

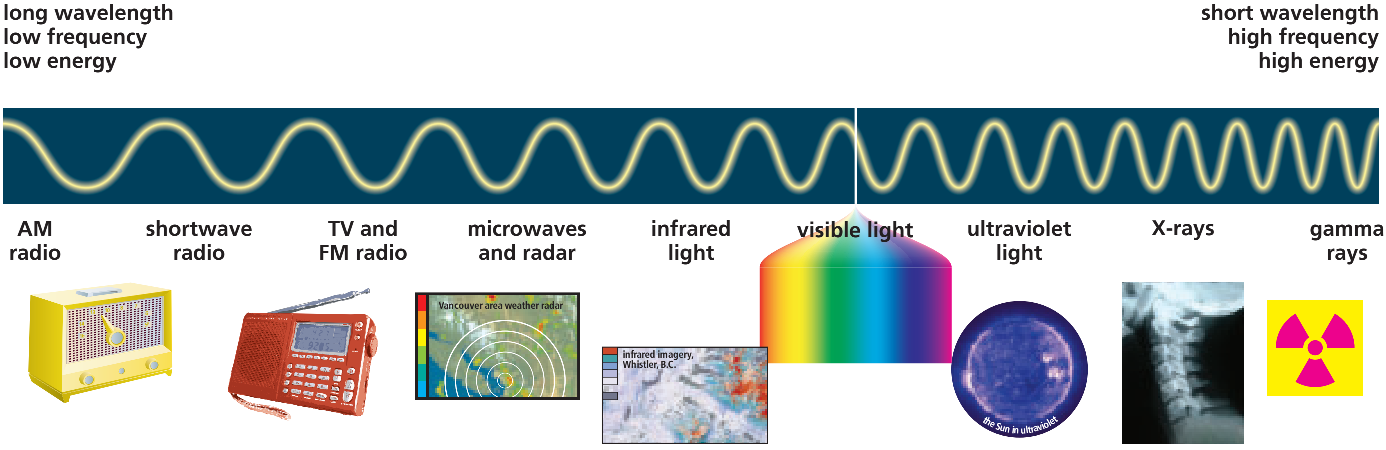


Figure 6 The electromagnetic spectrum

He concluded that the mineral did not need the Sun's energy. Since further study of the emissions produced by the uranium showed that they were deflected by electric charges and magnets and, therefore, had an electric charge, the emissions were not X-rays. The emissions became known, for a time, as Becquerel rays.

After Becquerel's discovery, Marie Curie and her husband Pierre Curie (Figure 7) began to analyze uranium to see what caused it to produce Becquerel rays. They determined that it was the uranium itself that was the source of the emissions. Marie Curie also investigated other elements to see if they emitted Becquerel rays. She found that other elements, such as thorium, also produced similar emissions. The Curies determined that the strength of the emissions produced by a compound depended only on the amount of uranium or thorium in the compound. During their study of uranium (pitchblende), Marie and Pierre Curie discovered two entirely new elements, radium and polonium.

Did You KNOW?

Facts about Marie

Marie Curie was born Maria Sklodowska in Warsaw, Poland in 1867. When she was 24 years old, she moved to Paris to study physics. She met her future husband, Pierre, at the university and they teamed up to conduct research into radioactive substances. She was so intrigued by radioactive isotopes that not only did she keep a sample of radium on her bedside table (because she liked the glow), but she also carried test tubes of radioactive isotopes in her pocket. She died in 1934 from leukemia caused from prolonged exposure to radiation.

Figure 7 In 1903, Marie and Pierre Curie shared the Nobel Prize in Physics with Henri Becquerel for their research on radiation. In 1911, Marie was awarded the Nobel Prize in Chemistry, the first person to ever win two Nobel Prizes in different fields.

Other scientists joined the investigation to learn about Becquerel rays. They found that physical factors, such as pressure and temperature, and chemical changes had no effect on the amount of radiation emitted from the nucleus of an atom. Scientists concluded that the radiation came from the core of the atom. Marie Curie coined the term **radioactivity** for the spontaneous emission of radiation from the nucleus of an atom.

10.1

CHECK YOUR Understanding

1. As the frequency of an electromagnetic radiation increases, what happens to the wavelength?
2. X-rays and visible light are both part of the electromagnetic spectrum. Identify whether the following descriptions apply to X-rays or to visible light:
   (a) the longest wavelength
   (b) the highest frequency
   (c) the lowest energy
3. Are gases insulators or conductors of electricity? Explain your answer.
4. What type of electromagnetic radiation is emitted by the nucleus of an atom?
5. Figure 8 shows a Crookes tube with a cathode ray inside. There are metal plates above and below the tube. One plate has a positive electric charge and the other has a negative electric charge. Copy the diagram into your notebook. The green line on the screen inside the tube shows the cathode ray. Label the direction of the cathode ray on your diagram. Indicate on your diagram which plate is positive and which is negative. Explain how you know the charges of the plates.

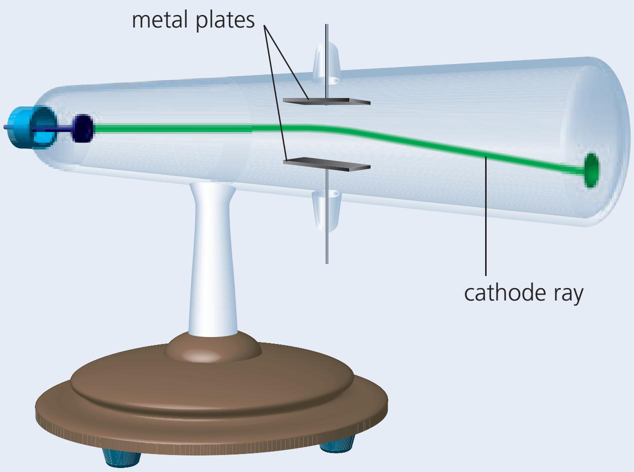


Figure 8

6. When cathode rays were first discovered, scientists thought they were radiation in the form of waves. Describe an experiment that showed that cathode rays behaved like particles.
7. It is recommended that students be at least 3 m away from an operating Crookes tube. Why should students do this?
8. When a high-speed electron strikes a metal plate inside a vacuum tube, an X-ray is produced.
   (a) What happens to the electron? Does the electron cease to exist?
   (b) The X-ray has energy. Where did the energy come from?
9. List the similarities and differences between visible light and X-rays.
10. Describe how X-rays are used to create images of broken bones (Figure 9).

Figure 9

11. What two elements were discovered by Marie and Pierre Curie?
12. Write your own definition of the word "radioactivity."
13. List three physical factors that have no effect on the amount of radiation emitted by a radioactive source.

10.2 Radioactivity and the Nucleus

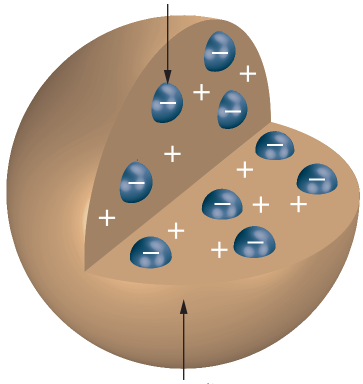


Figure 1 Thomson's model of the atom, called the "raisin bun model," was that an atom consisted of matter that had a positive charge (the bun part) with negatively charged particles (the raisins) inside.

The development of an accurate model of the atom was an ongoing process that occurred over thousands of years and involved many different people. The different atomic models are briefly described in Chapter 6.

An understanding of radioactivity led scientists to discover more about the internal structure of atoms. Thomson's discovery of the electron identified the first internal structure of the atom (Figure 1).

The Rutherford Experiment

New Zealand physicist Ernest Rutherford and his colleagues at the University of Manchester used the newly discovered radioactivity as a means to explore the atom. They directed a stream of positively charged particles at a thin sheet of gold foil. According to the Thomson model of the atom, the positively charged particles would simply pass through the gold atoms or would be deflected by small amounts. Rutherford found that, although most of the particles went straight through the foil, some particles were deflected and some were even bounced straight back from the gold foil (Figure 2). The result was as unexpected as shooting a cannon ball at a piece of paper and having the cannon ball bounce back!

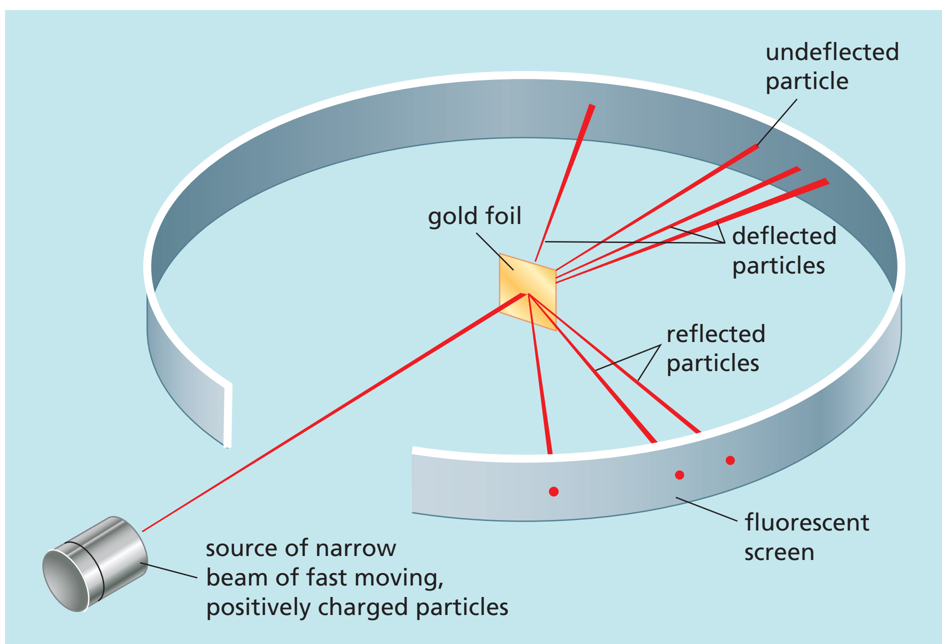


Figure 2 Rutherford's gold foil experiment used alpha particles, a type of radiation, to show that most of the atom is empty space.

To explore an interactive version of the Rutherford experiment and to test your knowledge, go to **www.science.nelson.com**

Rutherford concluded from the gold foil experiment that most of an atom is empty space, and that all of the positive charge and almost all of the mass of the atom is concentrated at the centre. This part of the atom came to be called the **nucleus**.

Once the nucleus (with its positive charge) and the electrons (with their negative charge) were known, Rutherford developed a model of the atom that resembled the solar system and became known as the planetary model (Figure 3). In the planetary model, the nucleus is the Sun, and the electrons are the planets orbiting the Sun. The electric force between the positive nucleus and the negative electrons holds the electrons in their orbits, just as the force of gravity holds the planets in their orbits about the Sun.

The planetary model of the atom suffered from some problems. Electrons in an orbit are accelerated, and accelerated charges always emit energy in the form of light. However, electrons orbiting the nucleus do not continuously give off energy. Niels Bohr proposed a solution: electrons exist in specific orbits. Each orbit can accommodate a specific number of electrons. For further information on Bohr's theory, refer to Section 6.2.

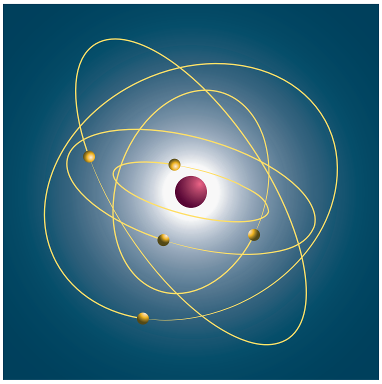


Figure 3 Rutherford's planetary model of the atom

Protons, Neutrons, and Isotopes

Although Rutherford discovered the nucleus almost one hundred years ago, it was not well understood. In 1918, through experiments, Rutherford became convinced that the hydrogen nucleus was an elementary particle, and named it the **proton**. The proton had a charge equal, but opposite, to the electron and a mass about 1800 times greater than the electron. GO

In 1932, British physicist James Chadwick discovered that atomic nuclei contained neutral particles that he called **neutrons**. The neutron has no electric charge and is similar in mass to a proton. Since it is neutral, it was difficult to detect. However, unlike protons and electrons, when the neutron is outside a nucleus, it is not stable.

To review the particles that make up an atom, go to **www.science.nelson.com** GO

Based on the development of the atomic theory over the years, there are several things that we know: everything is made of atoms; an atom is the smallest piece of an element; the Periodic Table lists all of the elements; and each element has a different number of protons. The atomic number is the number of protons in the nucleus. The mass of the atom comes from the protons and neutrons in the nucleus since the electrons have very little mass. The mass number of an atom is the sum of the number of protons and the number of neutrons. Figure 4 shows the standard notation for carbon.

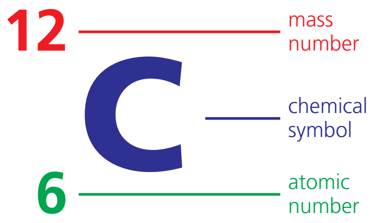


Figure 4 The atomic number of carbon means that it has six protons. The mass number means that the sum of protons and neutrons is 12. Therefore, we know that carbon has 6 neutrons.

Isotopes are atoms of the same element that have different mass numbers. That means that they have the same number of protons, but a different number of neutrons. Since the electrons in an atom are responsible for the chemical properties of an element, isotopes of an element share almost identical chemical properties. However, the physical properties can be very different. For example, carbon has three important isotopes, all with six protons. The most common isotope of carbon (about 99 % of all carbon atoms) has six protons and six neutrons for a mass number of 12. This isotope is called carbon-12. A very small amount of all natural carbon, about 1 %, has six protons and seven neutrons for a mass number of 13. This isotope is called carbon-13. Carbon-14 is a radioactive isotope that is constantly created by the action of cosmic rays in the upper atmosphere. How many neutrons does it have?

Did You KNOW?

Why the Nuclei of Atoms Do Not Fly Apart

We know that the nucleus of an atom has protons, all with a positive charge, tightly packed together. But we also know that like charges repel. So why do nuclei with more than one proton not fly apart because of repulsion? A strong nuclear force—an attractive force acting between protons and neutrons over very short distances—holds the nucleus together. As the number of protons increases, the repulsion increases. However, because there are also more neutrons in the nucleus, the strong nuclear force increases to keep the nucleus together.

LEARNING TIP

Check your understanding of the three isotopes of hydrogen by explaining Table 1 to a partner.

Figure 5 shows the different ways to express the names of the three isotopes of carbon.

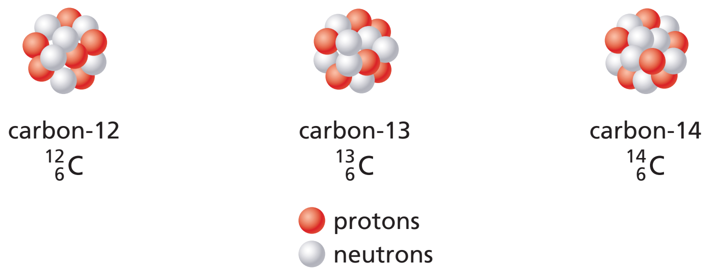


Figure 5 The three isotopes of carbon. Carbon-12 is stable, but carbon-14 is radioactive.

The isotopes of all other elements are written in a similar manner. However, hydrogen is an exception. Hydrogen has three isotopes and they each have their own name. Table 1 shows the isotopes of hydrogen.

Table 1 Isotopes of Hydrogen

Name	Symbol	Comment
hydrogen	$^{1}_{1}H$	• one proton, no neutrons • most common form of hydrogen (99.985 %)
deuterium	$^{2}_{1}H$	• one proton, one neutron • approximately 0.015 % of all hydrogen
tritium	$^{3}_{1}H$	• one proton, two neutrons • radioactive • trace amounts

The names and symbols give us information about isotopes. For example, given an isotope's name, we can determine the number of protons and neutrons it has.

SAMPLE PROBLEM

Determine the Number of Protons and Neutrons

Write the symbol for silver-107. How many protons and neutrons does it have?

Solution

The symbol is $^{107}_{47}Ag$. From the Periodic Table, we know that silver has 47 protons. Since $107 - 47 = 60$, we know that there are 60 neutrons.

Practice

Write the symbol for beryllium-9. How many protons and neutrons does it have?

10.2 CHECK YOUR Understanding

1. In Thomson's raisin bun model of the atom, what do the raisins and the bun represent?
2. Thomson assumed that the amount of positive charge and negative charge in an atom was equal. Was this a reasonable assumption? Give reasons to support your answer.
3. Figure 6 shows a diagram of Rutherford's gold foil experiment. Explain what is happening in the diagram. How did the experiment prove that the nucleus is very small and that it is positive?

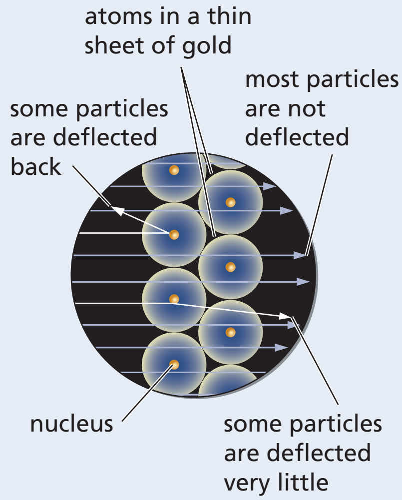


Figure 6

4. In the planetary model of the atom, what do the Sun and the planets represent? The force of gravity holds the solar system together. According to the planetary model of the atom, what holds the atom together?
5. What is the difference between a hydrogen atom and a proton?
6. The mass of an electron is 9.11×10^{-31} kg and the mass of a proton is 1.67×10^{-27} kg. How many electrons does it take to equal the mass of one proton?
7. The neutron was discovered long after electrons and protons. Why was it so difficult to discover?
8. How is a neutron different from both a proton and an electron?
9. Explain the difference between the atomic number and the mass number.
10. Write a definition of an isotope in your own words.
11. Draw a diagram of an oxygen-18 atom. Label the protons, neutrons, and electrons.
12. Chlorine occurs naturally as either chlorine-35 or chlorine-37. What is the difference between the two isotopes?
13. Copy Table 2 into your notebook and complete the missing information. The first row has been completed for you.

Table 2 Isotopes of Elements

Isotope name	Symbol	Number of protons	Number of neutrons
astatine-211	$^{211}_{85}At$	85	126
		92	143
magnesium-25			
	$^{209}_{86}Rn$		
		17	20
deuterium			
	$^{30}_{14}Si$		
palladium-102			
		53	74
tantalum-180			
	$^{182}_{74}W$		

14. Why do different isotopes of an element have the same chemical properties?

10.3 Radioactive Decay

10A Investigation

Penetrating Ability of Nuclear Radiation

To perform this investigation, turn to page 298.

In this investigation, you will look at radioactive decay.

Henri Becquerel, and Pierre and Marie Curie found that uranium, radium, and polonium were radioactive. We now know that there are other naturally occurring radioactive elements including astatine, radon, and francium. The nuclei of some isotopes are unstable and emit radiation. Such isotopes are called radioactive isotopes, or radioisotopes. An unstable nucleus that emits radiation is undergoing **radioactive decay**. There are three main types of radioactive decay: alpha decay, beta decay, and gamma decay. Table 1 and Figure 1 summarize their characteristics. 10A Investigation

Table 1 Three Main Types of Radioactive Decay

Method of decay	Radiation	Radiation symbol	Electric charge	Mass (electron = 1)	What is it?	Characteristics
alpha decay	alpha particle	α	+2	7000	a helium nucleus $^{4}_{2}He$	• slow moving • can only penetrate a piece of paper or skin
beta decay	beta particle	β	−1	1	an electron $^{0}_{-1}e$	• can only penetrate a few sheets of aluminum foil
gamma decay	gamma rays	γ	0	0	energetic "light" $^{0}_{0}\gamma$	• can only penetrate a few centimetres of lead

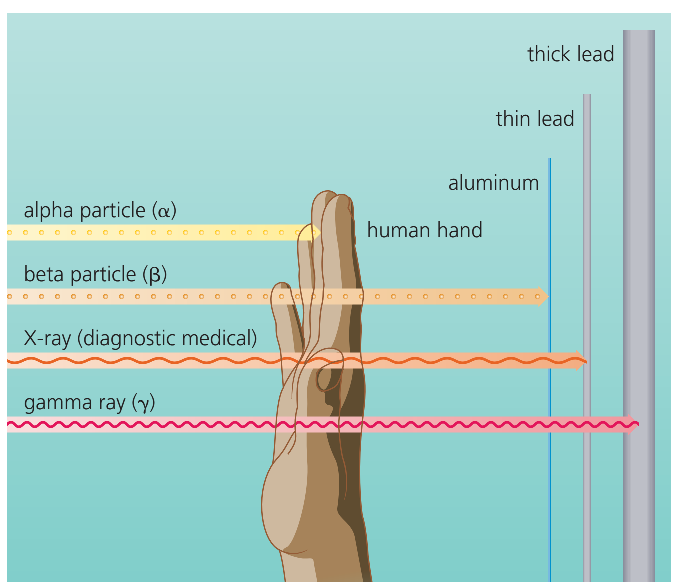


Figure 1 The penetrating ability of radiation. This is a measure of how much material is required to stop most, but not all, of the radiation going through the material.

In alpha and beta decays, the nucleus emits a particle and changes its identity. In other words, the atom has changed from one element to another. This is called transmutation. Transmutation changes a **parent nucleus** into a **daughter nucleus**. In gamma decay, the charge of the nucleus does not change, it just loses some energy. GO

To learn more about radioactive decay, go to www.science.nelson.com GO

Alpha Decay

Alpha decay occurs when a radioactive atom emits an **alpha particle**, α, which consists of two protons and two neutrons bound together into a particle identical to a helium nucleus, ${}^{4}_{2}\mathrm{He}$. For example, the isotope polonium-210, the radioactive element discovered by Marie Curie, undergoes radioactive decay by emitting a helium nucleus. During the decay, the polonium-210 is changed into lead-206 (Figure 2). In this case, polonium-210 is the parent nucleus and lead-206 is the daughter nucleus. The process can be written as a nuclear reaction equation:

$$ {}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He} $$

LEARNING TIP

Active readers adjust their reading to fit the difficulty of the text. If you find the text difficult to understand, go back and forth between the text and the diagram. Read more slowly, and reread.

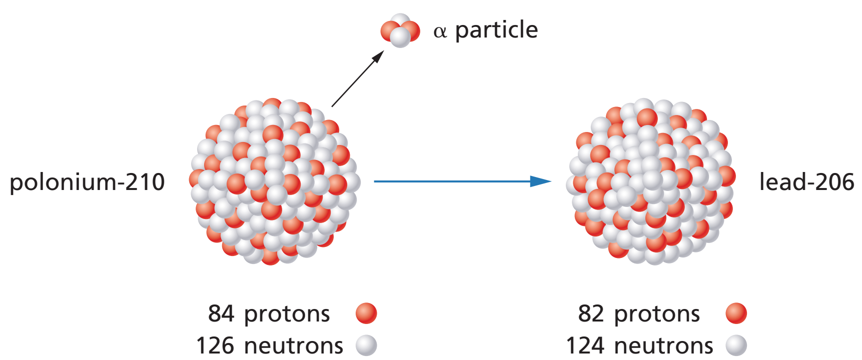


Figure 2 The alpha decay of polonium-210

After the alpha particle (remember, this is really a helium nucleus) has been emitted, it will slow down by crashing into surrounding atoms and eventually acquire two electrons to become a helium atom. Until the alpha particle becomes a stable helium atom, it moves around and collides with other atoms.

There are basically two rules for writing balanced nuclear equations: conservation of electric charge (atomic number) and conservation of the total number of protons and neutrons (mass number). The conservation of electric charge means that the amount of charge on the left-hand side of the arrow—in this case, $+84$—must equal the total charge on the right-hand side of the arrow—in this case, $82 + 2 = 84$. The mass number on the left side of the arrow, which is 210, must also equal the sum of the mass numbers on the right side of the arrow: $206 + 4 = 210$. Therefore, the mass number is conserved.

All alpha decays follow this pattern because the charge of all alpha particles is 2. We can write the general equation for alpha decay as:

$$ {}^{A}_{Z}N_{\text{parent}} \rightarrow {}^{A-4}_{Z-2}N_{\text{daughter}} + {}^{4}_{2}\mathrm{He} $$

where N_{parent} is the parent nucleus and N_{daughter} is the daughter nucleus. The letter Z represents the atomic number (number of protons) of the parent element, and A represents the mass number of the parent isotope (the number of protons plus neutrons).

Did You KNOW?

Polonium and the Spy

Former Russian spy Alexander Litvinenko was murdered using a radioactive isotope. He died three weeks after ingesting polonium-210, which had been dissolved most likely in a pot of tea. Polonium-210 is a strong emitter of alpha particles. Although alpha particles cannot travel very far, they can do tremendous damage to cells if they get inside the body through swallowing or inhaling. Doctors suspected that Mr. Litvinenko ingested less than a microgram of polonium-210.

SAMPLE PROBLEM 1

Determine the Nuclear Equation for Alpha Decay

Write the nuclear equation for the alpha decay of americium-241. What element has americium been transmuted into?

Solution

The atomic number of americium is 95 from the Periodic Table. Since the element undergoes alpha decay, the products will be a daughter nucleus and an alpha particle, ${}^{4}_{2}\mathrm{He}$.

$${}^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\mathrm{He}$$

Americium has been transmuted into neptunium.

Practice

Write the nuclear equation for the alpha decay of radium-226.

Beta Decay

In beta decay, the nucleus emits a **beta particle**, β, which is actually an electron, ${}^{0}_{-1}\mathrm{e}$. Since the nucleus contains only protons and neutrons, how is it possible for the nucleus to emit an electron? Protons and electrons are very stable, but a neutron is not stable. A neutron in an unstable nucleus can decay into a proton, an electron, and a neutrino. Therefore, the electron comes from the decay of a neutron. Note that a neutrino is a subatomic particle that has energy, but has no mass or electric charge.

An example of beta decay is when carbon-14 undergoes radioactive decay to transmute into nitrogen-14 (Figure 3). The nuclear equation is:

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

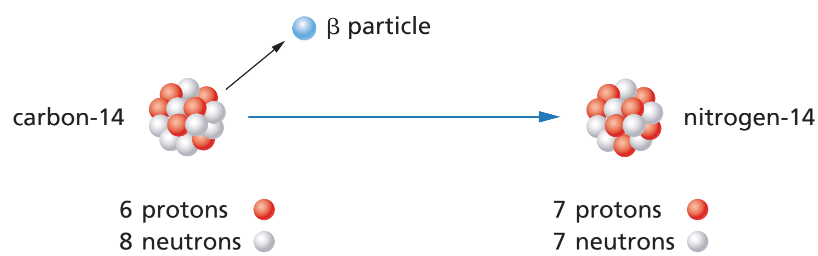


Figure 3 The beta decay of carbon-14

Note that in beta decay, the mass number of the daughter nucleus is the same as the parent nucleus. However, the atomic number of the daughter nucleus increases by one. For example, in the beta decay of carbon-14, when −1 is added to +7, the result is +6, which is the initial amount of electric charge. The neutrino often is omitted from beta decay equations.

Because the charge of all beta particles is −1 and the mass is close to 0, all beta decays follow this pattern. We can write the general equation as:

$${}^{A}_{Z}N_{\text{parent}} \rightarrow {}_{Z+1}^{A}N_{\text{daughter}} + {}^{0}_{-1}\mathrm{e}$$

where N_{parent} is the parent nucleus, N_{daughter} is the daughter nucleus, Z represents the atomic number, and A represents the mass number.

SAMPLE PROBLEM 2

Determine the Nuclear Equation for Beta Decay

Write the nuclear equation for the beta decay of the isotope cesium-137. What element has cesium been transmuted into?

Solution

The atomic number of cesium is 55 from the Periodic Table. Since the element undergoes beta decay, the products will be a daughter nucleus and a beta particle.

$$^{137}_{55}\text{Cs} \rightarrow\ ^{137}_{56}\text{Ba} +\ ^{0}_{-1}\text{e}$$

Cesium has been transmuted into barium.

Practice

Write the nuclear equation for the beta decay of xenon-133.

STUDY TIP

Summarizing (condensing main points in your own words) is a helpful study tool. After reading Section 10.3, write a brief summary for each type of radioactive decay. Compare your summaries with a friend. Is there anything important that should be added?

Gamma Decay

In gamma decay, the nucleus emits a **gamma ray**, γ, which is very high-energy electromagnetic radiation. When the nucleus of an atom is in an excited state following the emission of an alpha or beta particle, the nucleus has a surplus of energy. The nucleus lowers its amount of energy by emitting a gamma ray. Since a gamma ray has no electric charge or mass, gamma decay does not change the type of isotope—it only changes the isotope's energy.

The following example shows the production of an excited nucleus followed by gamma decay. When americium-241 undergoes alpha decay, the daughter nucleus produced is neptunium-237.

$$^{241}_{95}\text{Am} \rightarrow\ ^{237}_{93}\text{Np}^{*} +\ ^{4}_{2}\text{He}$$

The asterisk beside the symbol for neptunium indicates that the nucleus is in an excited state. The excited nucleus then undergoes gamma decay and changes to a normal, or ground, state.

$$^{237}_{93}\text{Np}^{*} \rightarrow\ ^{237}_{93}\text{Np} +\ ^{0}_{0}\gamma$$

Because the gamma ray has no charge and no mass, all gamma decays follow this pattern and we can write the general equation for gamma decay as:

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

Remember that gamma decay adjusts the energy levels in a nucleus, but does not otherwise change the nucleus.

Did You KNOW?

Harold Johns and Cobalt-60

Harold Johns (1915–1998) is regarded as the Father of Medical Physics. Johns was born in China, but moved to Canada in the mid-1920s. He developed the first cobalt-60 cancer treatment unit in Saskatchewan. Cobalt-60 units are still built in Canada and distributed around the world. In 1977, Johns was elected as an Officer of the Order of Canada. He was inducted into the Canadian Medical Hall of Fame in 1998.

SAMPLE PROBLEM 3

Determine the Nuclear Equation for Gamma Decay

Boron-12 undergoes beta decay to produce an excited daughter nucleus. Write the nuclear equation for this decay, and then write the nuclear equation for the gamma decay of the excited daughter nucleus. What element has boron been transmuted into?

Solution

$$^{12}_{5}\text{B} \rightarrow {}^{12}_{6}\text{C}^{*} + {}^{\ 0}_{-1}\text{e}$$

$$^{12}_{6}\text{C}^{*} \rightarrow {}^{12}_{6}\text{C} + {}^{0}_{0}\gamma$$

Boron has been transmuted into carbon.

Practice

The isotope cobalt-60 undergoes beta decay to produce a daughter nucleus in an excited state. Write the nuclear equation of the beta decay, and then write the nuclear equation that shows how the nucleus lowers its internal energy level.

Figure 4 In a cloud chamber, the alpha particles produce a thick, short track. Beta particles make a thin irregular track. Gamma rays have no charge and, thus, no track.

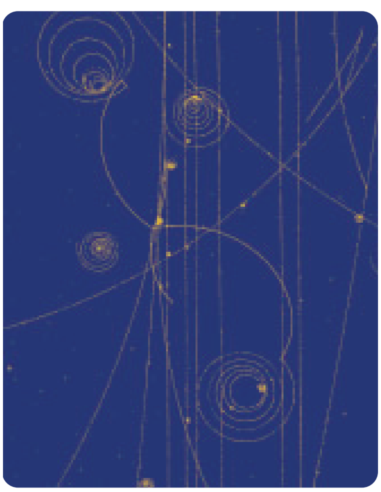


Figure 5 Tracks made by alpha and beta particles in a bubble chamber

To view an animation of a Geiger counter in action and to test your knowledge, go to **www.science.nelson.com**

Detection of Radioactive Emissions

How can scientists detect radioactive decay when alpha particles, beta particles, and gamma rays are invisible to the human eye? One device used to detect radioactivity is a cloud chamber. A diffusion cloud chamber is a small, clear plastic, sealed cylinder inside of which is a sponge saturated with alcohol. When the bottom of the cylinder is placed on dry ice, the air becomes supersaturated with alcohol. When a radioactive source is placed inside, it emits charged particles that remove some electrons from the atoms in the air as they travel, converting the atoms to positive ions. These ions cause the vapour to condense and create a visible track (Figure 4).

A bubble chamber is similar to a cloud chamber. The chamber contains a superheated liquid, such as propane or liquid hydrogen. When a charged particle passes through the liquid, bubbles form around the tracks of the particles. An electromagnet causes the charged particles to be deflected. Alpha and beta particles are deflected in opposite directions (Figure 5).

Another device that can detect radiation is a Geiger counter. Geiger counters also are based on the fact that some radiations produce trails of charged atoms (ions) as they pass through a gas. It consists of a cylinder containing a gas and a wire inside. There is a high voltage between the cylinder case and the wire. Charged particles enter through a window at one end of the cylinder and ionize the gases inside the cylinder. The positive ions are attracted to the negatively charged wire, which produces a current that can be detected and read as a count. Each burst of current represents the detection of one particle. The Geiger counter is connected to a counting device that keeps count of radiation entering the tube. Geiger counters can detect beta particles and gamma rays. Alpha particles are not able to penetrate the window of most counters.

10.3

CHECK YOUR Understanding

1. What happens when a radioactive atom undergoes radioactive decay?
2. How many beta particles would it take to have the same mass as a single alpha particle?
3. Why are alpha and beta radiation referred to as particles, while gamma radiation is referred to as rays?
4. Write a definition of transmutation in your own words.
5. What happens to the atomic number (Z) and mass number (A) of a parent nucleus during alpha decay?
6. List two differences between an alpha particle and a helium atom.
7. The following parent isotopes undergo alpha decay. Write the nuclear equation for these transmutations.
   (a) tungsten-180
   (b) samarium-147
   (c) sodium-20
8. Write a brief description of beta decay in your own words.
9. The mass number of an atom undergoing beta decay does not change. However, the daughter nucleus is a different element than the parent. Explain how this is possible.
10. The following parent isotopes undergo beta decay. Write the nuclear equation for this transmutation.
    (a) nickel-64
    (b) tritium
    (c) iron-59
11. How do the atomic number and the mass number of an atom change as a result of gamma decay? Why does an atom emit gamma radiation?
12. Iron-60 undergoes beta decay. The daughter produced is in an excited state and undergoes gamma decay. Write nuclear equations to show these two processes.
13. State whether the following descriptions apply to alpha, beta, or gamma radiation:
    (a) has a negative charge
    (b) is a helium nucleus
    (c) its path is deflected by a magnet
    (d) is similar to X-rays
    (e) is stopped by a few sheets of paper
    (f) an electric charge does not affect its path
    (g) has the most mass
    (h) easily penetrates skin and tissue
14. Complete the following nuclear equations:
    (a) ${}^{239}_{93}\text{Np} \rightarrow \textbf{?} + {}^{\ 0}_{-1}\text{e}$
    (b) ${}^{232}_{90}\text{Th} \rightarrow \textbf{?} + {}^{4}_{2}\text{He}$
    (c) ${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + \textbf{?}$
    (d) ${}^{152}_{66}\text{Dy}^{*} \rightarrow {}^{152}_{66}\text{Dy} + \textbf{?}$
    (e) ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + \textbf{?}$
    (f) $\textbf{?} \rightarrow {}^{209}_{81}\text{Tl} + {}^{4}_{2}\text{He}$
    (g) ${}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + \textbf{?}$
    (h) $\textbf{?} \rightarrow {}^{239}_{94}\text{Pu} + {}^{\ 0}_{-1}\text{e}$
    (i) $\textbf{?} \rightarrow {}^{99}_{43}\text{Tc} + {}^{0}_{0}\gamma$
15. Name and describe three devices that are used to detect radioactivity.
16. Alpha and beta radiation leave visible tracks in a cloud chamber. However, gamma rays do not. Why?
17. Why do alpha particles leave short thick tracks in a cloud chamber, while beta particles leave long thin tracks?
18. How is a Geiger counter similar to a cloud chamber?
19. Why are some Geiger counters unable to detect alpha radiation?

10.4 Half-Life

Figure 1 Pitchblende, the major uranium ore, is a heavy mineral that contains uranium oxides, lead, and trace amounts of other radioactive elements. Pierre and Marie Curie found radium and polonium in pitchblende residues.

10B *Investigation*

The Half-Life of Popcorn

To perform this investigation, turn to page 300.

In this investigation, you will simulate the radioactive decay using popcorn kernels.

A sample of radioactive material, such as uranium ore (Figure 1), contains an immense number of radioactive atoms, any of which can undergo radioactive decay. The decay of a nucleus is an individual random event. The rate of radioactive decay of a sample is not affected by physical or chemical changes, including temperature and pressure. In addition, the age of a nucleus does not affect the probability that it will decay. Although there is no way of determining when an individual nucleus will decay, we can predict the average rate of decay for a large number of nuclei. In the beginning, there are a large number of radioactive parent nuclei and, therefore, there will be a high rate of decay per second. As time passes and parent nuclei decay, there will be fewer and fewer parent nuclei, and more and more daughter nuclei. Over time, both the number of parent nuclei present and the rate of decay will decrease.

The number of decays per second of a sample is known as the activity of the sample and is measured in becquerels (Bq). A becquerel is equal to one decay per second. The average length of time for half of the parent nuclei in a sample to decay is called the **half-life**. The half-life is different for different isotopes, but is a constant number for a given isotope. 10B *Investigation*

The activity of a sample depends on the size of the sample (how many radioactive nuclei were present initially) and the age of the sample (how many radioactive nuclei are left). However, for any sample, the number of parent nuclei left in the sample and the activity level of the sample always follow the curves shown in Figures 2 and 3. These curves are for a fictitious (made up) radioactive source.

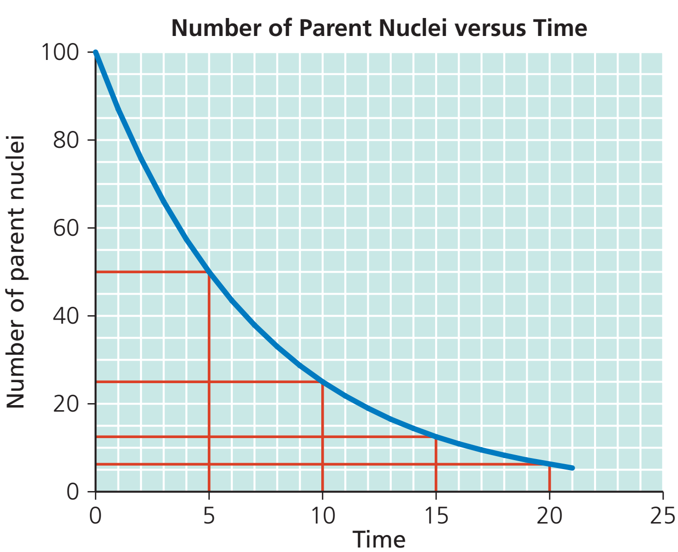


Figure 2 Parent nuclei decay curve

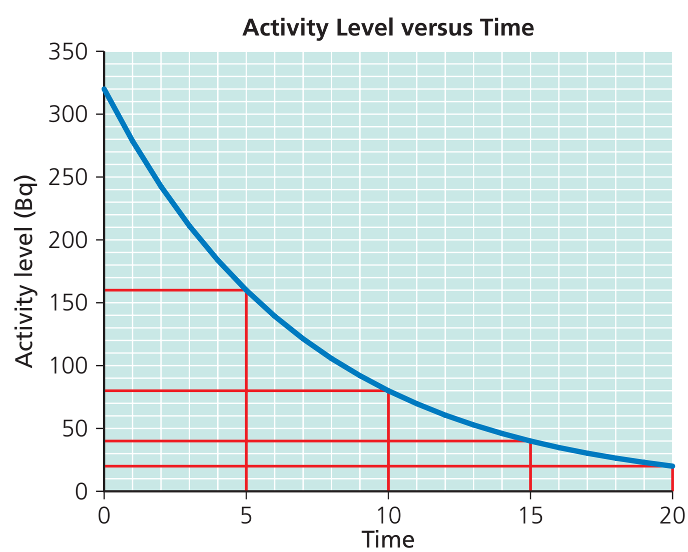


Figure 3 Activity curve

Both curves have an identical shape. You can see from the figures that the sample has a half-life of 5 units of time. The number of parent nuclei goes from 100 to 50 to 25 to 12.5 to 6.25 at times of 0, 5, 10, 15, and 20 time units. Similarly, the activity level of the sample goes from 320 to 160 to 80 to 40 to 20 at times of 0, 5, 10, 15, and 20 time units.

Some radioactive isotopes are used in medicine. For example, the radioactive isotope thallium-201 can be injected into a patient's bloodstream where it is carried to the patient's heart. A camera detects the radiation given off from the decay of thallium-201 and produces an image of the heart (Figure 4). Comparison of scans made during exercise and at rest may show areas of the heart not receiving adequate blood flow. Figure 5 shows how the activity level of an injection of thallium-201 decreases.

LEARNING TIP

A line graph can be used to show a trend over a period of time. Ask yourself, "What information is presented on the left side and along the bottom of Figure 5? What has happened to thallium-201 over a period of time?"

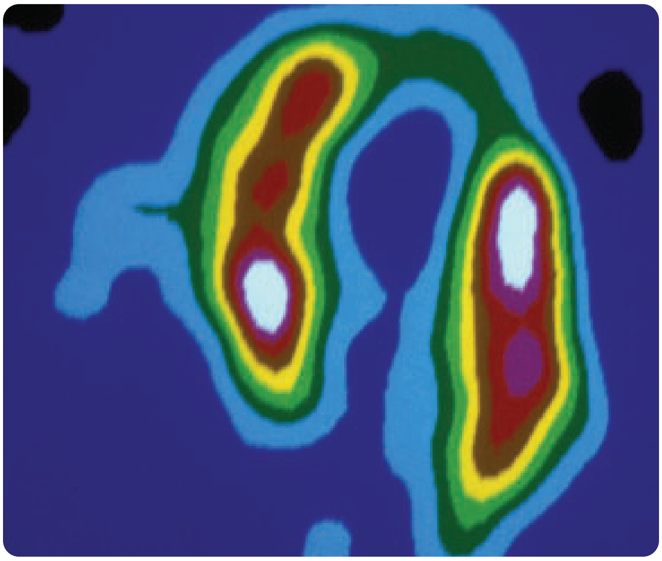


Figure 4 A thallium scan of a normal heart

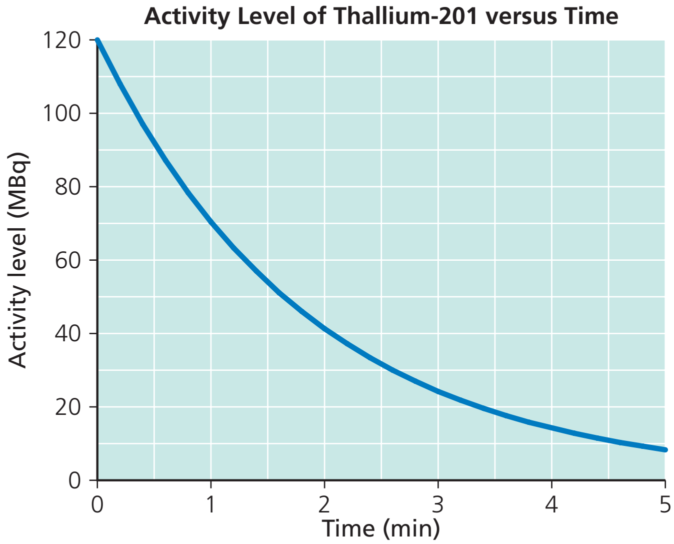


Figure 5 Activity of thallium-201

We can use the graph to determine the half-life of thallium-201. The initial activity of 120 MBq is reduced to 60 MBq after 1.3 min. This means that the half-life is 1.3 min. Note that the half-life is so short that most of the thallium will decay quickly and not stay in the blood for much time.

As every half-life passes, the number of parent nuclei present and the activity level decreases by half. To find out how many half-lives have passed, divide the time by the half-life of the isotope. Table 1 shows how these fractions can be expressed.

Table 1 Calculating Half-Lives Using Fractions

Number of half-lives	1	2	3	4	5	n
Fraction remaining	$\frac{1}{2}$	$\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$	$\frac{1}{4} \times \frac{1}{2} = \frac{1}{8}$	$\frac{1}{8} \times \frac{1}{2} = \frac{1}{16}$	$\frac{1}{16} \times \frac{1}{2} = \frac{1}{32}$	
Exponential notation	$\frac{1}{2^1} = \frac{1}{2}$	$\frac{1}{2^2} = \frac{1}{4}$	$\frac{1}{2^3} = \frac{1}{8}$	$\frac{1}{2^4} = \frac{1}{16}$	$\frac{1}{2^5} = \frac{1}{32}$	$\frac{1}{2^n}$

Another way to calculate the amount of the parent nuclei remaining is to use percentages. The original amount is 100 %. Therefore, we can calculate the amount left after every half-life by dividing the previous amount by two. Table 2 shows the percentage left after the first five half-lives. This table can be used for problems calculating the amount of parent nuclei left. Can you determine the percentage that would be left after six half-lives?

Table 2 Calculating Half-Lives Using Percentages

Number of half-lives	1	2	3	4	5
Percent remaining	50 %	25 %	12.5 %	6.25 %	3.25 %

SAMPLE PROBLEM 1

Use Half-life to Determine the Time Passed

Cesium-124 has a half-life of 31 s. A sample of cesium-124 in a laboratory has an initial mass of 20 mg.

(a) Calculate the amount of time it will take for the sample to decay to 5 mg.

(b) Calculate how much cesium-124 will remain after 93 s.

Solutions

(a) First determine how many half-lives have passed. This can be done using either the fraction or percentage method.

Fraction Method

The fraction left is

$$\frac{5}{20} = \frac{1}{4} = \frac{1}{2^2}$$

Percentage Method

The percent left is

$$\frac{5}{20} \times 100\ \% = 25\ \%$$

By using either method, we can see that two half-lives have passed.

Now calculate the total amount of time that has passed.

Since two half-lives have passed, the total time that has passed will be $2 \times 31\text{ s} = 62\text{ s}$.

Figure 6 shows a graph of the mass–time. From the graph, we can see that at about 62 s, the mass is reduced to 5 mg. This is in agreement with the calculated solution.

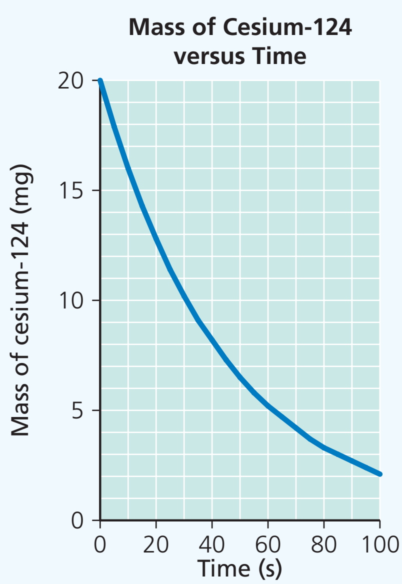


Figure 6 Decay curve for cesium-124

(b) Since the half-life of cesium-124 is 31 s, we can determine the number of half-lives:

$$\text{number of half-lives} = \frac{\text{total time}}{\text{half-life}} = \frac{93\text{ s}}{31\text{ s}} = 3\text{ half-lives}$$

Now calculate the mass (m) remaining. This can be done using either the fraction or percentage method.

Fraction Method

$$m = \frac{1}{2^3}(20\text{ mg})$$

$$m = 2.5\text{ mg}$$

Percentage Method

After three half-lives, there is 12.5 % remaining.

$$m = \left(\frac{12.5\ \%}{100\ \%}\right) 20\text{ mg}$$

$$m = 2.5\text{ mg}$$

The mass remaining is 2.5 mg. We can also see on the graph that the approximate mass remaining is about 2.5 mg.

Practice

A sample of fluorine-18 in a laboratory has an initial mass of 50 mg. Fluorine-18 has a half-life of 1.8 h. Figure 7 shows the decay curve for fluorine-18.

(a) Calculate the amount of time it will take for the initial mass of fluorine-18 to be reduced from 50 mg to 12.5 mg. You can use the graph to confirm your answer.

(b) Calculate what mass of fluorine-18 remains after 5.4 h. You can use the graph to confirm your answer.

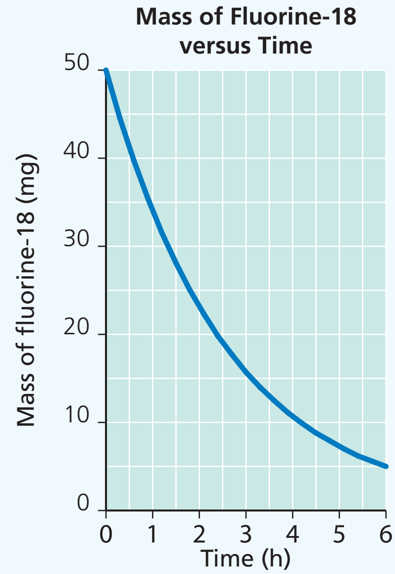


Figure 7 Decay curve for fluorine-18

SAMPLE PROBLEM 2

Determine the Activity Level Using Half-life

Radium-226 has a half-life of 1600 years. A material containing radium-226 has an activity of 500 MBq.

(a) Determine what the activity level will be in the material after 8000 years.

(b) How many years earlier was the activity level in the material 2000 MBq?

Solutions

(a) First, determine the number of half-lives.

$$\frac{8000 \text{ years}}{1600 \frac{\text{years}}{\text{half-life}}} = 5 \text{ half-lives}$$

Now determine the activity level.

$$\text{activity} = 500 \text{ MBq} \times \frac{1}{2^5} = 15.625 \text{ MBq}$$

After 8000 years, the activity level will be 16 MBq.

(b) The activity level of 500 MBq is one-quarter the activity level of 2000 MBq.

$\frac{1}{4} = \frac{1}{2^2}$ This represents a period of two half-lives.

We can calculate the amount of time as

$t = 2 \times 1600 \text{ years} = 3200 \text{ years}$

The activity level was 2000 MBq 3200 years earlier.

Practice

Silicon-32 has a half-life of 160 years. A material containing silicon-32 has an activity of 80 MBq.

(a) Determine what the activity level of the material will be after 320 years.

(b) How many years earlier was the activity level of the material 640 MBq?

Table 3 Decay Series of Uranium-238

Decay	Half-life
${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$	4.5×10^{9} years
${}^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$	24 d
${}^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{0}_{-1}\mathrm{e}$	6.7 h
${}^{234}_{92}\mathrm{U} \rightarrow {}^{230}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$	2.5×10^{5} years
${}^{230}_{90}\mathrm{Th} \rightarrow {}^{226}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}$	7.5×10^{4} years
${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$	1600 years
${}^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\mathrm{He}$	3.8 d
${}^{218}_{84}\mathrm{Po} \rightarrow {}^{214}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$	3.1 min
${}^{214}_{82}\mathrm{Pb} \rightarrow {}^{214}_{83}\mathrm{Bi} + {}^{0}_{-1}\mathrm{e}$	27 min
${}^{214}_{83}\mathrm{Bi} \rightarrow {}^{214}_{84}\mathrm{Po} + {}^{0}_{-1}\mathrm{e}$	20 min
${}^{214}_{84}\mathrm{Po} \rightarrow {}^{210}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$	1.6×10^{-4} s
${}^{210}_{82}\mathrm{Pb} \rightarrow {}^{210}_{83}\mathrm{Bi} + {}^{0}_{-1}\mathrm{e}$	22 years
${}^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + {}^{0}_{-1}\mathrm{e}$	5 d
${}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$	138 d

Decay Series

In biological families, a parent can have a daughter. After time passes, the daughter becomes a parent and produces another generation. In a similar way, a radioactive parent nucleus produces a daughter nucleus, which can also be radioactively unstable. In turn, the daughter nucleus becomes a parent nucleus, which continues the sequence of events. When radioactive nuclei form such a chain, it is called a **decay series**. The decay series always ends in the formation of a stable isotope.

For example, uranium-238 forms a decay series ending with the stable isotope lead-206 as shown in Table 3. Note that some of the isotopes have very short half-lives. However, uranium-238 has a half-life of about 4.5 billion years. The decay series of uranium-238 provides some isotopes that would not otherwise be present on Earth. The decay series of uranium-238 can be graphed as shown in Figure 8.

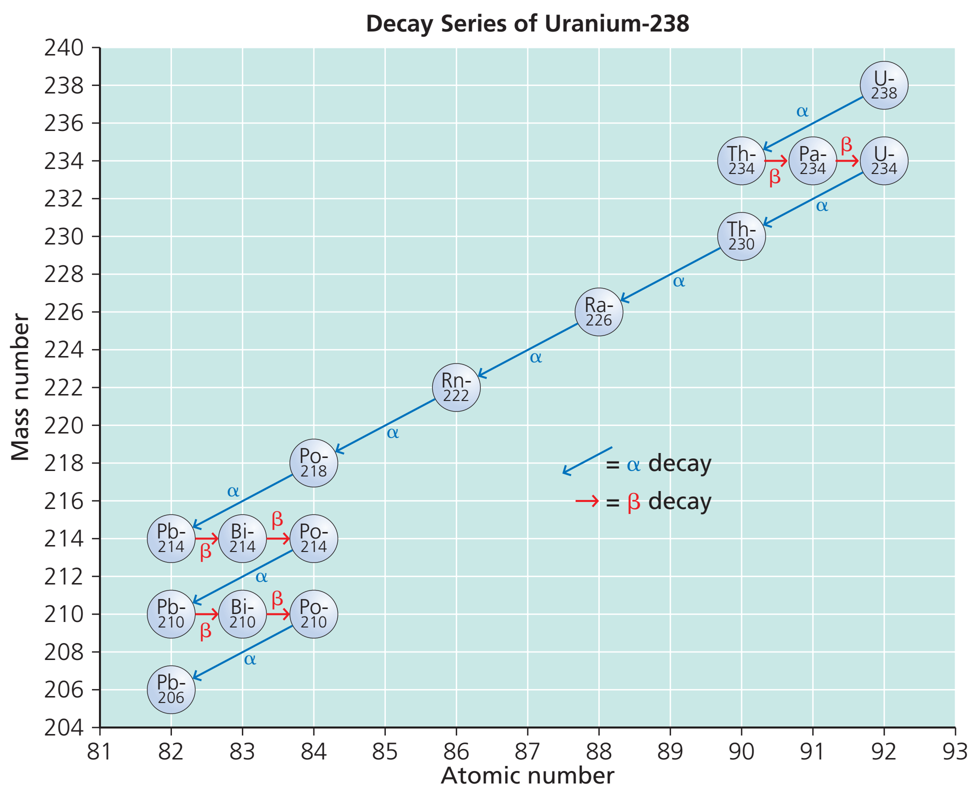


Figure 8 Uranium-238 is changed into lead-206 in a decay series of 14 steps.

Figure 9 The remains of a human were found in glacial ice in the Alps. Scientists used carbon-14 dating to determine that he lived about 5300 years ago.

Radioactive Dating

Since radioactive isotopes decay according to their half-lives, it is possible to date materials using appropriate isotopes. Carbon-14 is a radioactive isotope that can be used to date material that was once alive (Figure 9). Almost all naturally occurring carbon is carbon-12. However, an extremely small fraction of carbon (about one atom in a trillion) is carbon-14. The half-life of carbon-14 is 5730 years. With this half-life, there should be no carbon-14 left on Earth, which is about 4.5 billion years old. However, our Sun and all the stars in the universe produce cosmic radiation. Energetic neutrons are part of cosmic radiation, and the neutrons combine with nitrogen in the upper atmosphere to form carbon-14 and a proton according to the following nuclear equation:

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

This process keeps the level of carbon-14 constant on Earth and in living organisms.

When an organism dies, the amount of carbon-14 in the organism starts to decrease as it radioactively decays, and no new carbon-14 enters the organism through eating or respiration. Carbon-14 has a half-life of 5730 years, which means that the ratio of carbon-14 in an organism decreases by half every 5730 years. Figure 10 shows the decay curve for carbon-14. It is clear from the graph that carbon-14 can only be used to date objects less than 40 000 years old. With a more accurate graph (or by calculation), the useful time range can be extended to about 60 000 years. Note that carbon-14 dating will only date things that were once alive.

Other isotopes can be used to date things that are more than 60 000 years old or that were never alive. For example, uranium-235 decays to lead-207 with a half-life of 704 million years, and uranium-238 decays to lead-206 with a half-life of 4.46 billion years. Dating materials using two different isotopes make the age estimates very accurate. Uranium-238 has been used to determine that the oldest rocks that have been dated on Earth are about 4 billion years old.

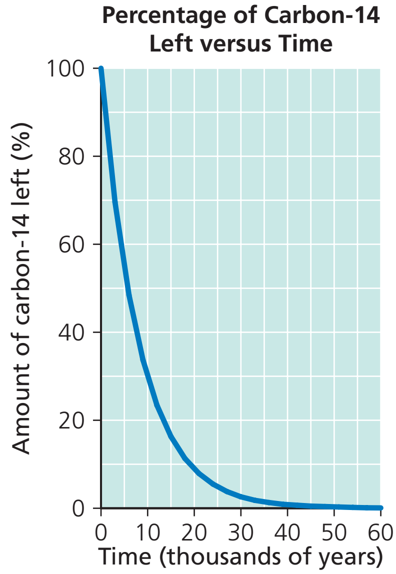


Figure 10 Decay curve for carbon-14

To find out more about carbon-14 dating go to **www.science.nelson.com**

To test your skills on half-life and radioactive dating, go to **www.science.nelson.com**

SAMPLE PROBLEM 3

Use Radioactive Dating to Determine the Age of a Sample

A piece of leather was found to have 12.5 % of its original carbon-14 present. Determine the age of the leather using Figure 10 and by calculation.

Solution

From the graph, we can see that the time is approximately 17 000 years.

The decrease from 100 % to 12.5 % is a ratio of $\frac{12.5\ \%}{100\ \%} = \frac{1}{8} = \frac{1}{2^3}$

Therefore, the time taken is 5730 $\frac{\text{years}}{\text{half-life}} \times 3$ half-lives $= 17\ 190$ years

The piece of leather is approximately 17 200 years old.

Practice

A bone fragment was found to have 25 % of its original carbon-14 present. Determine the age of the bone fragment using Figure 10 and by calculation.

10.4 CHECK YOUR Understanding

1. How are the terms "activity" and "becquerel" related?
2. What is the activity level of the following samples?
   (a) 3600 decays in 42 s
   (b) 35 decays in 35 min
   (c) 45 000 decays in 7.5 min
   (d) 1200 decays in 3 h
   (e) 250 000 decays in 55 min and 17 s
3. Nitrogen-13 decays to produce carbon-13. A laboratory sample contains 500 000 nitrogen-13 atoms. Use the decay curve for the sample over time shown in Figure 11 to answer the following questions.

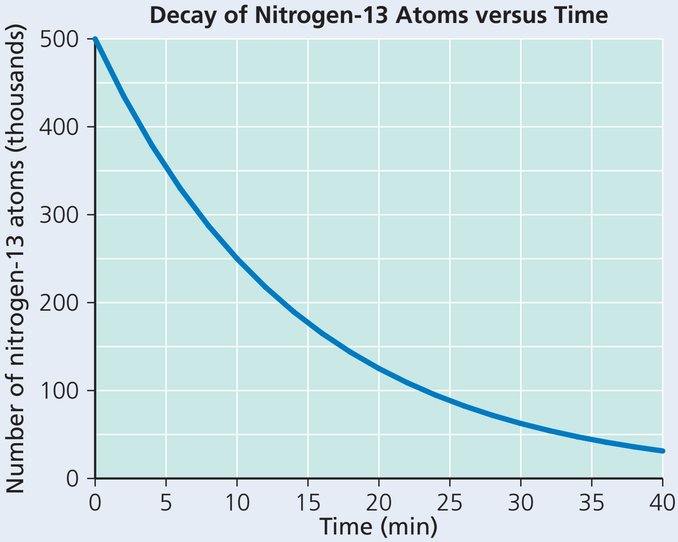


Figure 11 Decay curve for nitrogen-13

   (a) How many nitrogen-13 atoms will be left after 16 min?
   (b) How many carbon-13 atoms will be present after 25 min?
   (c) What is the half-life of nitrogen-13?
   (d) How many nitrogen-13 atoms will be present after 40 min?
4. A radioactive isotope source has a mass of 120 μg. If the isotope had a half-life of 20 s, what would be the mass of the isotope after 2 min?
5. Beryllium-7 has a half-life of 53 d. A sample was observed for 1 min and there were 26 880 decays.
   (a) What is the activity level of the sample?
   (b) What will the activity level of the sample be after 265 d?
   (c) After how many days will the activity level of the sample be 112 Bq?
   (d) What was the activity level 106 d before the sample was observed?
   (e) How many days earlier was the activity level eight times greater than the observed level?
6. A granite rock is thought to be about two billion years old. Why is it not possible to determine the age of the rock using carbon-14 dating?
7. A hair sample has 80 % of its original carbon-14 present. What is the age of the sample?
8. A bone fragment has lost 75 % of its original carbon-14. What is the age of the bone fragment?
9. An organic sample is 28 650 years old. What percentage of the original carbon-14 is still present in the sample?

BRACHYTHERAPY

Brachytherapy is a powerful tool used to kill cancer cells. A radioactive isotope is implanted directly within the tumour. By placing all of the radioactivity in the tumour, the damage to surrounding normal cells is minimized.

Did you know that almost 73 000 people will die from cancer this year in Canada? In fact, according to the Canadian Cancer Society, one out of every four Canadians will die from cancer. The good news is that mortality rates from certain types of cancer are declining, in part because the disease is being detected earlier and in part because of advances in treatments.

Soon after Marie and Pierre Curie discovered radium, it was used to treat skin cancer. Doctors who administered the radiation had little understanding about how radiation worked, although they did know that it killed cancer cells. We now know that not only does radiation kill cancer cells, but it also harms normal cells. To help minimize the damage done to normal cells, while maximizing damage to cancer cells, medical physicists and doctors use brachytherapy to treat cancer. Brachytherapy (which means treatment from a short distance) involves implanting radioactive isotopes directly into a cancerous tumour. Radioactive isotopes can be inserted directly into the body cavity to treat bronchial, gynecological, and esophageal tumours, or through needles that puncture the tumour for prostate, breast, lip, and tongue tumours.

When treating cancers with brachytherapy, it is important to choose the right radioisotope. Radioisotopes are chosen based on their half-life, activity (source strength), and the energy of the gamma rays that they produce. Sometimes the radioisotopes are implanted permanently in the tumour. In this case, it is important that the radioisotope have a relatively short half-life. For example, iodine (^{125}I), which has a half-life of 60 d, or palladium (^{103}Pd), which has a half-life of 17 d, is used to treat prostate cancer (Figure 1). An isotope of gold (^{198}Au), which has a half-life of 2.7 d, is used to treat lip cancer. These radioisotopes are referred to as seeds because they are sealed inside a metal capsule (usually titanium) that keeps the isotope and decay products inside.

Sometimes the radioisotopes are inserted temporarily into the body and then removed after a few minutes or even days. This is usually done using a robot called a remote afterloader (Figure 2). The robot can pull the radioisotope in or out of the tumour and can even move it within the tumour. The radioisotope is kept inside a tube so that it can be reused for many patients. Radioisotopes such as cesium (^{137}Cs), with a half-life of 30 years, and iridium (^{192}Ir), with a half-life of 74 d, are used for this type of therapy. These radioisotopes have a longer half-life so that they can be used many times.

Brachytherapy is a promising way of treating many types of cancer. Placing the radioactive seeds directly into a tumour is the best way to make sure that the radiation reaches the target cells and keeps away from healthy tissues.

Figure 1 Eighty-eight iodine seeds were implanted permanently in the prostate gland. It is important that the seeds not be too close to the urethra.

Figure 2 One or more fine tubes are inserted into or adjacent to the tumour. The radiation seeds travel from the machine, through the tube to the tumour, and deliver a high dosage of radiation in minutes.

10A • Investigation •

Penetrating Ability of Nuclear Radiation

The radiation that is emitted from the nucleus of radioactive atoms comes in different types. The types have different characteristics, such as electric charge, mass, and penetrating ability. By knowing the characteristics of different types of radiation, you can identify the types of radiation that different materials emit. If you know the penetrating ability of the radiation, you can design safety shields for the particular radiation.

In this investigation, you will observe the penetrating ability of three different types of radiation. You will look at alpha, beta, and gamma radiation.

INQUIRY SKILLS

○ Questioning	● Conducting	● Evaluating
○ Hypothesizing	● Recording	● Synthesizing
○ Predicting	● Analyzing	● Communicating
○ Planning		

Question

What type and amount of material is needed to stop alpha, beta, and gamma radiation?

Experimental Design

Your teacher will perform this experiment using a Geiger counter (Figure 1). A Geiger counter is able to detect these types of radiation and keeps count of the number of emissions that strike the Geiger counter.

Figure 1 Geiger counters are particle detectors that measure ionizing radiation. There are several different types of Geiger counters that you may see in your studies.

Materials

- set of radioactive samples (alpha, beta, and gamma sources)
- Geiger counter
- 10 sheets of paper
- 10 sheets of aluminum foil
- 10 lead sheets

The radioactive sources used are very weak. However, care needs to be taken around any radioactive sources. Do not come any closer to them than needed, and keep them in storage until needed.

Procedure

1. Your teacher will turn the Geiger counter on without any radioactive sources nearby. Make sure nobody is wearing a watch near the Geiger counter as it may invalidate the reading. Record the number of counts, if any, made in 1 min.
2. As material is placed between the radioactive source and the Geiger counter, the rate of radiation should decrease from 100 % to 0 %. However, because of background radiation, the rate may not decrease to 0 %. As a class, choose a percentage that you think is acceptable to consider the radiation to be effectively stopped.
3. Hold the Geiger counter above a source and observe the counting rate of the Geiger counter. Slowly move the Geiger counter away from the source. Note what happens to the rate as the distance increases.

4. Copy Table 1 into your notebook.

Table 1

	Alpha radiation	Beta radiation	Gamma radiation
paper			
aluminum			
lead			

5. Place the Geiger counter over the alpha source. Insert sheets of paper between the source and the Geiger counter (Figure 2). Keep adding sheets until the rate of counts is almost stopped. This is the penetrating ability of alpha radiation with paper. Repeat this with sheets of aluminum foil and lead.

Figure 2

6. Repeat step 5 using the beta sample and the gamma sample.

Conclusion

Complete the following items to answer the question posed at the beginning of the investigation.

Analysis

(a) What happened to the decay rate as the Geiger counter moved away from the source? Why do you think this happened?

(b) During this investigation, did you or your teacher receive more exposure to radiation?

(c) List the three types of radiation from least penetrating to most penetrating.

Evaluation

(d) In step 1, you observed the behaviour of the Geiger counter without any sources nearby. If it "counted" without any sources nearby, did this influence the investigation? If so, how did you make accommodation for this count?

(e) Some Geiger counters come equipped with a holder for the tube. Why should the tube be placed in the holder rather than held in the teacher's hand?

Synthesis

(f) Counts were detected by the Geiger counter when your teacher turned it on, even when there were no radioactive sample sources nearby. What could cause the Geiger counter to detect these counts?

(g) How would you compare the penetrating ability of X-rays with alpha, beta, and gamma radiation?

(h) If you worked in an area of a hospital that used radioactive sources, what would you do to protect yourself? Research to find out how hospital workers protect themselves from radiation.

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10B Investigation

The Half-Life of Popcorn

When a radioactive sample decays, there is one less parent nuclei and one more daughter nuclei. As this decay process continues, the number of parent nuclei decreases and the number of daughter nuclei increases. Eventually there are no parent nuclei left to decay into daughter nuclei and no further decays occur.

In this activity, you will use a model to see how the rate of radioactivity of a sample changes over time. In this investigation, you will use popcorn kernels to represent parent nuclei.

INQUIRY SKILLS

- ○ Questioning
- ○ Hypothesizing
- ● Predicting
- ○ Planning
- ● Conducting
- ● Recording
- ● Analyzing
- ● Evaluating
- ● Synthesizing
- ● Communicating

Question

What happens to the rate of radioactive decay in a sample as time passes?

Prediction

Write a prediction of how you think the rate of radioactive decay will change.

Materials

- 100 popcorn kernels
- container such as an empty film canister or a Petri dish

Procedure

1. Copy Table 1 into your notebook. You will begin with 100 popcorn kernels. Since these represent parent nuclei, they will be referred to as parent kernels. The first row in the table shows that there are 100 parent kernels and no daughter kernels.

Table 1

Time (shakes)	Number of parent kernels	Number of daughter kernels
0	100	—

2. Count the popcorn kernels to make sure that there are exactly 100. Put the kernels in a container, shake the container, and carefully drop the kernels on your desk. Imagine each kernel as the hour hand of a clock. If the point of the kernel is between 12 and 3 on the "clock," assume that the kernel has decayed. Figure 1 shows how to determine which kernels have decayed and which are still alive. Decayed kernels represent daughter nuclei. Count the number of daughter kernels and record the number in your table. Record in your table how many parent kernels are left. This is one unit of time as measured in shakes.

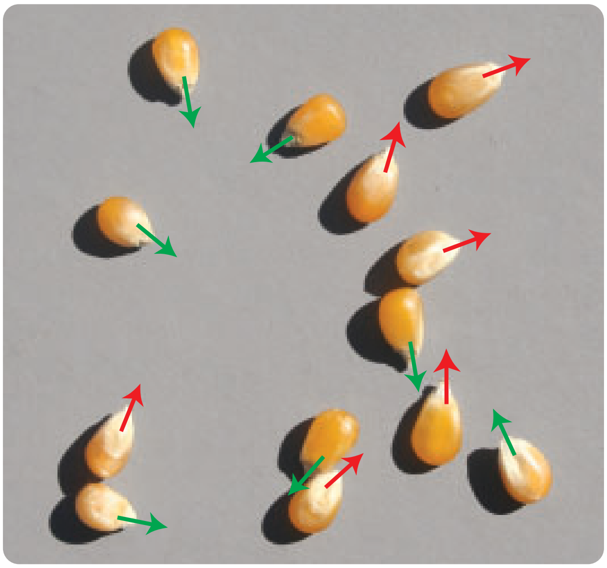


Figure 1 The popcorn kernels with the red arrows are pointing between 12 and 3 on your "clock." They are decayed.

3. Remove the daughter kernels. Put the parent kernels back in the container and repeat step 2. This is the second unit of shake time.
4. Repeat step 3 until all of the parent kernels have decayed and there are no parent kernels left. Always record the number of decayed popcorn—even if that number is zero!
5. Make two graphs. On the first graph, plot the number of daughter kernels produced versus time as measured in shakes. On the second graph, plot the number of parent kernels remaining versus time as measured in shakes. Draw a line of best fit for each graph. In this case, the line is not a straight line and will need to be drawn with a curve. (Refer to Appendix B5.)

Conclusion

Complete the following items to answer the question posed at the beginning of the investigation.

Analysis

(a) What happened to the number of parent kernels over time?

(b) What happened to the rate at which daughter kernels are produced over time?

(c) How many shakes did it take until all the parent kernels had decayed? How did your number compare with other students in the class?

(d) On the graph of parent kernels versus time, at what time (as measured in shakes) did the number of parent kernels become approximately 50? How much more time passed before the number of parent kernels was reduced to approximately 25? How do these two numbers compare?

(e) Using your response to (d), what is the half-life of popcorn as determined by your results?

Evaluation

(f) In this investigation, popcorn represented parent nuclei. In what ways did the popcorn behave similarly to parent nuclei, and in what ways was it different?

Synthesis

(g) Are your popcorn decay results identical to those of your classmates? Explain your answer.

(h) If you had performed this activity with 10 000 kernels of popcorn, do you think that the answers would be different? Give reasons for your answer.

(i) If the parent kernel decayed when the point was between the hours of 12 and 1 (instead of between 12 and 3), how would this affect the results?

(j) What other materials or devices could have been used to simulate radioactive decay? For example, how could you use a computer to generate random numbers and then use them?

CHAPTER 10

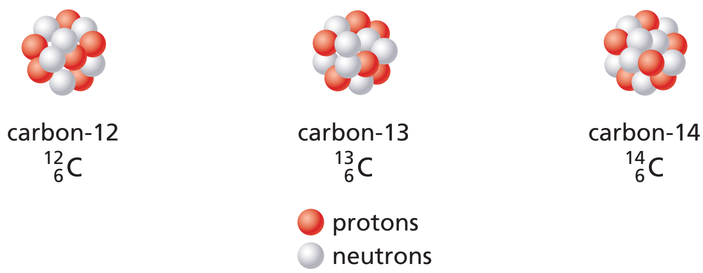
Review

Radioactivity and the Atom

Key Ideas

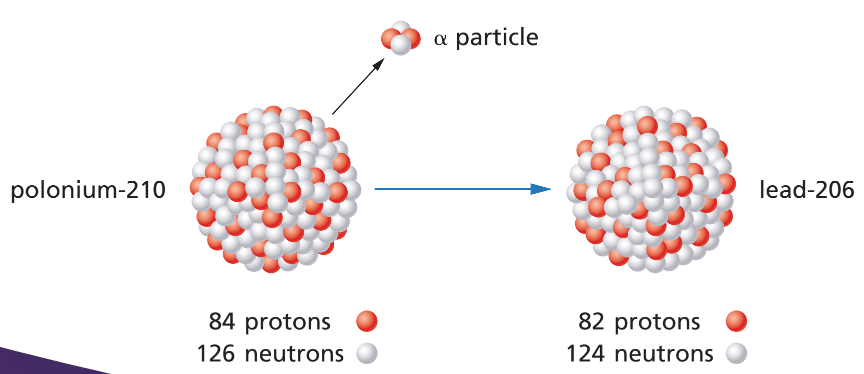
Atoms of a single element that differ in mass are called isotopes.

- All atoms are made of subatomic particles.
- All atoms of an element have the same chemical properties, although the atoms of an element can have different masses.
- An isotope of an element has the same atomic number, but a different mass number, as other isotopes of the same element.
- Isotopes can be written in standard atomic notation; for example, uranium-238 is $^{238}_{92}U$ and carbon-12 is $^{12}_{6}C$.



The atoms of some elements are radioactive, which means that they undergo radioactive decay.

- Radioactive atoms emit radiation of three different types: alpha, beta, and gamma radiation.
- Alpha, beta, and gamma radiation have different properties of mass, charge, penetrating ability, and reaction to electric and magnetic charges.
- The amount of radiation emitted by a radioactive source is not affected by chemical or physical factors.
- Cathode rays and X-rays are types of radiation that are not produced by radioactive sources.



Vocabulary

radioactivity, p. 278
nucleus, p. 280
proton, p. 281
neutron, p. 281
isotope, p. 281
radioactive decay, p. 284
parent nucleus, p. 284
daughter nucleus, p. 284
alpha particle (α), p. 285
beta particle (β), p. 286
gamma ray (γ), p. 287
half-life, p. 290
decay series, p. 294

There are three basic types of radioactive decay and these processes can be written as nuclear equations.

- During alpha decay, a radioactive isotope emits an alpha particle, which is a helium nucleus. The nuclear equation is

$$^{A}_{Z}N_{\text{parent}} \rightarrow {}^{A-4}_{Z-2}N_{\text{daughter}} + {}^{4}_{2}\text{He}$$

- During beta decay, a radioactive isotope emits a beta particle, which is an electron. The nuclear equation is

$$^{A}_{Z}N_{\text{parent}} \rightarrow {}_{Z+1}^{\;\;A}N_{\text{daughter}} + {}^{\;\;0}_{-1}\text{e}$$

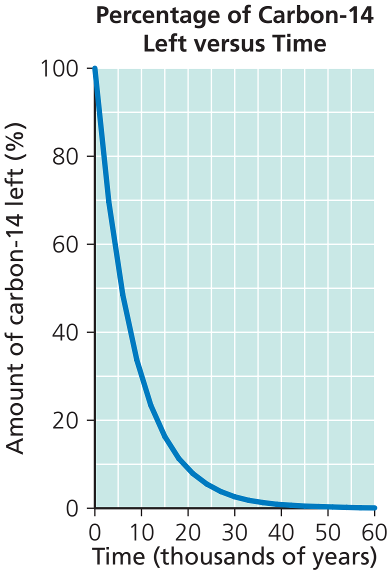
- During gamma decay, a radioactive isotope emits a gamma ray. The nuclear equation is

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

- Alpha and beta decay transmute atoms into different elements. Gamma decay simply releases energy from an atom's nucleus, but does not transmute the element.
- Radioactive decay can be detected by different devices, such as cloud chambers, bubble chambers, and Geiger counters.

The rate of decay of a radioactive sample is predictable and is described by the half-life of the radioactive isotope.

- The activity level of a radioactive isotope is the rate of decays and is measured in becquerels (Bq). A becquerel is one decay per second.
- An isotope of a radioactive element has a half-life, which is the amount of time it takes for the activity level to be reduced by one-half. This is equal to the time for half of the parent nuclei to decay.
- The half-life of a radioactive isotope can be determined from graphs of number of parent nuclei versus time and activity level versus time.
- Some radioactive isotopes decay in a characteristic series of events.
- Some radioactive isotopes are useful in medicine for diagnosis and treatment.
- Radioactive isotopes can be used to determine the age of some materials.
- Carbon-14 has a half-life of 5730 years and is useful for radioactive dating of material that was once living.



Many of these questions are in the style of the Science 10 Provincial Exam.
The following icons indicate an exam-style question and its cognitive level.
K Knowledge **U** Understanding and Application **HMP** Higher Mental Processes

Review Key Ideas and Vocabulary

1. Draw a model of carbon-14 in your notebook and include protons, neutrons and electrons. What is the relationship between the number of protons and neutrons? What is the relationship between the number of protons and electrons?
2. Explain the difference between an atom and an isotope.

K 3. Which of the following statements correctly compares protons and neutrons?
   A. Protons have positive charges and neutrons have no charge.
   B. The mass of a proton is very much greater than the mass of a neutron.
   C. The electric charge of a proton is equal but opposite to the electric charge of a neutron.
   D. Protons can be found in the nucleus of the atom; neutrons are never found in the nucleus.

4. Describe the difference between alpha decay and beta decay.

K 5. Which of the following correctly identifies a material that will stop each type of radiation?

	Alpha	Beta	Gamma
A.	aluminum	paper	lead
B.	lead	paper	aluminum
C.	paper	aluminum	lead
D.	paper	lead	aluminum

K 6. Which of the following describes gamma radiation?
   A. an electron
   B. a helium nucleus
   C. a hydrogen nucleus
   D. high-energy electromagnetic radiation

Use What You've Learned

7. Heavy water is composed of deuterium atoms instead of hydrogen atoms. How much heavier is one molecule of heavy water than one molecule of normal water?

8. Copy Table 1 into your notebook and fill in the missing data.

Table 1 Decay Series of Thorium-232

$^{232}_{90}\text{Th} \rightarrow {}^{228}_{?}\text{Ra} + \textbf{?}$	1.4×10^{10} year
$^{228}_{88}\textbf{?} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\text{e}$	5.8 year
$^{228}_{89}\text{Ac} \rightarrow {}^{228}_{?}\text{Th} + \textbf{?}$	6.1 h
$^{228}_{90}\text{Th} \rightarrow {}^{224}_{?}\textbf{?} + \textbf{?}$	1.9 year
$^{224}_{88}\text{Ra} \rightarrow \textbf{?} + {}^{4}_{2}\text{He}$	3.6 d
$^{?}_{88}\text{Rn} \rightarrow {}^{216}_{?}\textbf{?} + {}^{4}_{2}\text{He}$	54 s
$^{216}_{84}\text{Po} \rightarrow {}^{212}_{82}\text{Pb} + \textbf{?}$	0.16 s
$^{212}_{82}\text{Pb} \rightarrow \textbf{?} + {}^{0}_{-1}\text{e}$	10.6 h
$^{212}_{83}\text{Bi} \rightarrow \textbf{?} + {}^{0}_{-1}\text{e}$	60.5 min
$^{212}_{84}\text{Po} \rightarrow \textbf{?} + {}^{4}_{2}\text{He}$	0.3 µs

U 9. Gadolinium-164 decays by beta emission. If a 15 g sample of gadolinium-164 undergoes 3400 decays in 2 min, what is the activity rate of the sample?
   A. 0.125 Bq
   B. 7.5 Bq
   C. 28.3 Bq
   D. 75.6 Bq

10. Krypton-83 has a half-life of 4.5 h.
   (a) How many half-lives is 27 h?
   (b) If an original sample of krypton-83 had a mass of 600 g, how much would be left after 27 h?
   (c) If a sample had an activity of 200 Bq, what was its activity 13.5 h earlier?

U 11. Ten years ago, a hospital bought a radioactive source of cobalt-60, which produces gamma rays. Which of the following describes what has happened to the activity level of the source since it was bought?
   A. The activity level increased.
   B. The activity level decreased.
   C. The activity level remained constant.
   D. The activity level first decreased and then increased.

12. Calcium-47 undergoes beta decay. Figure 1 shows how the activity level of a sample of calcium-47 changes over time.

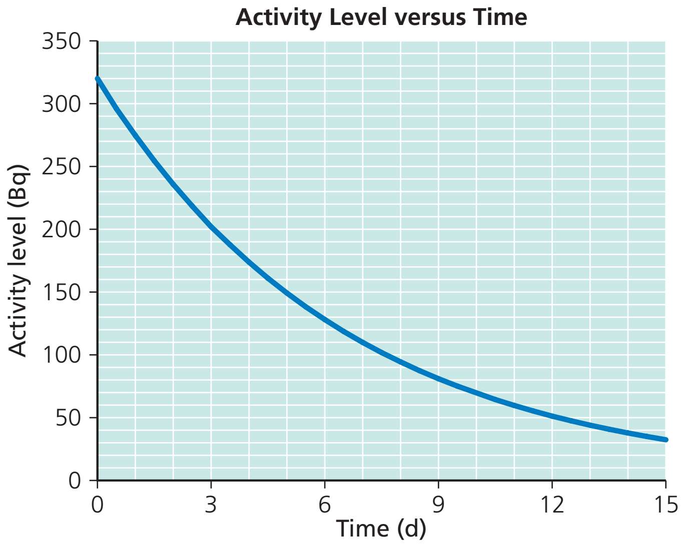


Figure 1

(a) Write the nuclear equation for the beta decay of calcium-47.
(b) After how many days has the activity level of the sample been reduced to 100 Bq?
(c) What is the half-life of calcium-47?
(d) After how much time will the activity level of the sample be reduced to $\frac{1}{8}$ of its initial value of 320 Bq?
(e) At what rate are scandium-47 atoms being produced after seven days?

U **13.** The following nuclear equation represents the decay of uranium-238:

$$^{238}_{92}U \rightarrow \, ^{234}_{90}Th + \textbf{?}$$

Which of the following is the missing decay product?

A. $^{0}_{0}\gamma$

B. $^{0}_{-1}e$

C. $^{4}_{2}He$

D. $^{0}_{+1}e$

14. A sample contained 6000 radioactive atoms. The number of radioactive atoms left was counted every 0.5 s. Figure 2 shows a graph of the number of atoms left. What is the half-life?

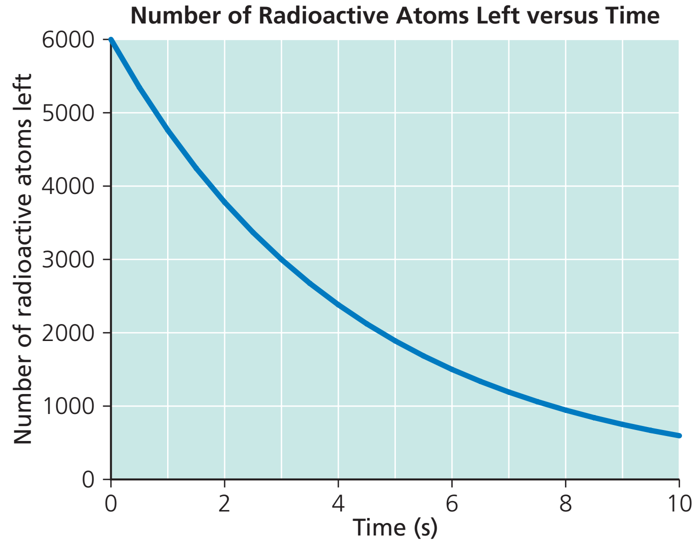


Figure 2

A. 1 s
B. 2 s
C. 3 s
D. 5 s

Think Critically

15. Is it possible to change the amount of radiation emitted by a material by chemical means? If so, provide an example.

16. Research some applications of natural radioactivity.

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17. Explain why radioisotope dating cannot be used directly on fossils of dinosaur bones. Research how scientists age fossils.

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Reflect on Your Learning

18. Describe how your understanding of radiation has changed as a result of studying this chapter.

Visit the Quiz Centre at

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