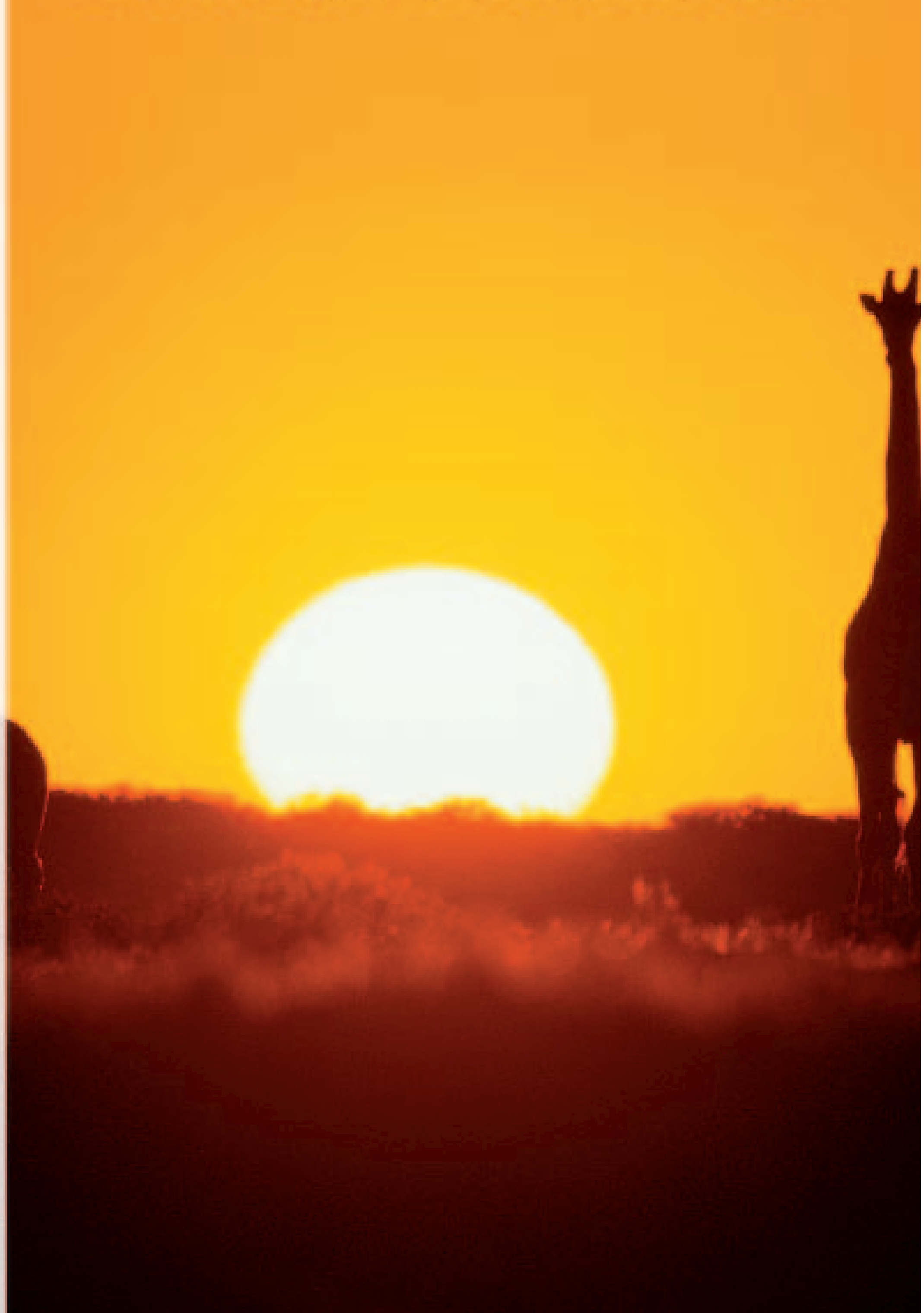
SPS3. Students will distinguish the characteristics and components of radioactivity. **Also covers:** SCSh1, 4, 7, 9

Español

chapter 18

Radioactivity and Nuclear Reactions



BIG Idea
Protons and neutrons are held together in a nucleus by the strong nuclear force.

18.1 Radioactivity
MAIN Idea The repulsive electrical force between protons causes some nuclei to be unstable.

18.2 Nuclear Decay
MAIN Idea Unstable nuclei can emit particles and energy when they decay.

18.3 Detecting Radioactivity
MAIN Idea Nuclear radiation produces charged particles in matter than can be detected.

18.4 Nuclear Reactions
MAIN Idea Nuclear fission splits nuclei apart and nuclear fusion joins nuclei together.

Planet Power
Although less than one-billionth of the energy emitted by the Sun falls on Earth, this energy powers the entire planet. Solar energy is produced inside the Sun by nuclear fusion-a nuclear reaction in which atomic nuclei are joined together..

Science Journal
In your Science Journal, write a paragraph describing your impressions of the sun.

(bkgd.)Paul Souders/Getty Images

Start-Up Activities

Launch LAB

The Size of a Nucleus

Do you realize you are made up mostly of empty space? Your body is made of atoms, and atoms are made of electrons whizzing around a small nucleus of protons and neutrons. The size of an atom is the size of the space in which the electrons move around the nucleus. In this lab, you'll find out how the size of an atom compares with the size of a nucleus.

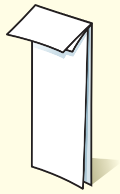
1. Go outside and pour several grains of sugar onto a sheet of paper.
2. Choose one of the grains of sugar to represent the nuculeus of an atom.
3. Brush the rest of the sugar off the paper and place the sugar grain in the center of the paper.
4. Use a meterstick to measure a distance of 10 m from the sugar grain. This distance represents the radius of the electron cloud around an atom.
5. **Think Critically** In your Science Journal, explain why an atom contains mostly empty space. Use the fact that an electron is much smaller than the nucleus.

FOLDABLES™ Study Organizer

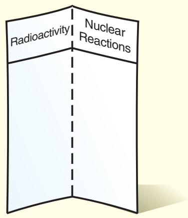
Radioactivity and Nuclear Reactions Make the following Foldable to help you understand radioactivity and nuclear reactions.

STEP 1 **Fold** a sheet of paper in half lengthwise.

STEP 2 **Fold** paper down 2.5 cm from the top. (Hint: From the tip of your index finger to your middle knuckle is about 2.5 cm.)



STEP 3 **Open and draw** lines along the 2.5-cm fold. **Label** as shown.



Summarize in a Table As you read the chapter, write what you learn about radioactivity in the left column, and what you learn about nuclear reactions in the right column.

Science Online — Preview this chapter's content and activities at gpscience.com

SCSh9c. Students will enhance reading in all curriculum areas by building vocabulary knowledge....
Also covers: SCSh1a–c, 3c, 3e–f, 4a

section 1

Radioactivity

(t)Mark Burnett, (b)David Frazier/The Image Works

Reading Guide

What You'll Learn

- **Describe** the structure of an atom and its nucleus.
- **Explain** what radioactivity is.
- **Contrast** properties of radioactive and stable nuclei.
- **Discuss** the discovery of radioactivity.

Why It's Important

Radioactivity is everywhere because every element on the periodic table has some atomic nuclei that are radioactive.

Review Vocabulary

long-range force: a force that becomes weaker with distance, but never vanishes

New Vocabulary

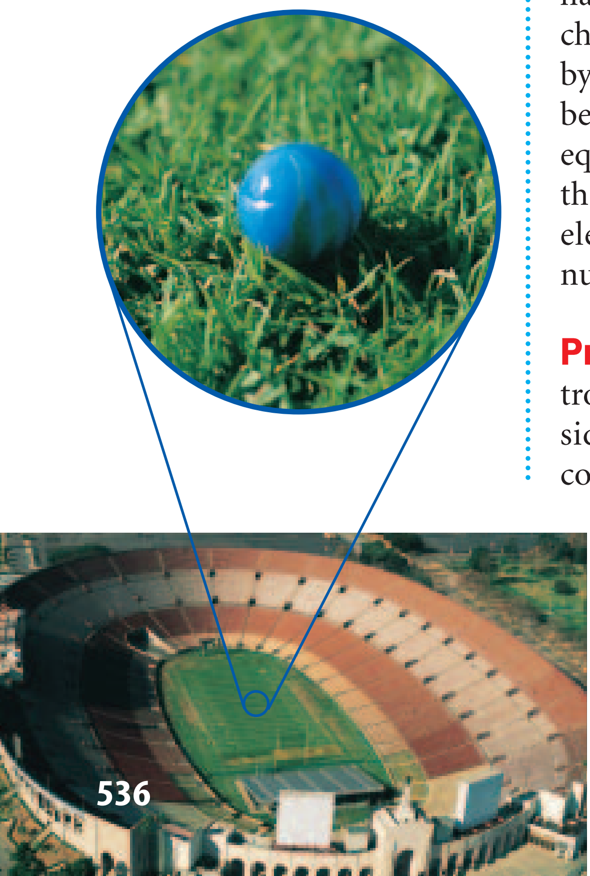
- strong force
- radioactivity

The Nucleus

Every second you are being bombarded by energetic particles. Some of these particles come from unstable atoms in soil, rocks, and the atmosphere. What types of atoms are unstable? What type of particles do unstable atoms emit? The answers to these questions begin with the nucleus of an atom.

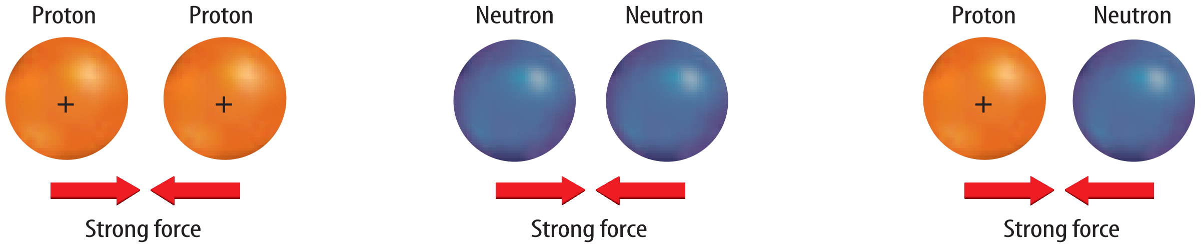
Recall that atoms are composed of protons, neutrons, and electrons. The nucleus of an atom contains the protons, which have a positive charge, and neutrons, which have no electric charge. The total amount of charge in a nucleus is determined by the number of protons, which also is called the atomic number. You might remember that an electron has a charge that is equal but opposite to a proton's charge. Atoms usually contain the same number of protons as electrons. Negatively charged electrons are electrically attracted to the positively charged nucleus and swarm around it.

Figure 1 The size of a nucleus in an atom can be compared to a marble sitting in the middle of an empty football stadium.



Protons and Neutrons in the Nucleus Protons and neutrons are packed together tightly in a nucleus. The region outside the nucleus in which the electrons are located is large compared to the size of the nucleus. As **Figure 1** shows, the nucleus occupies only a tiny fraction of the space in the atom. If an atom were enlarged so that it was 1 km in diameter, its nucleus would have a diameter of only a few centimeters. But the nucleus contains almost all the mass of the atom, because the mass of one proton or neutron is almost 2,000 times greater than the mass of an electron.

Figure 2 The particles in the nucleus are attracted to each other by the strong force.



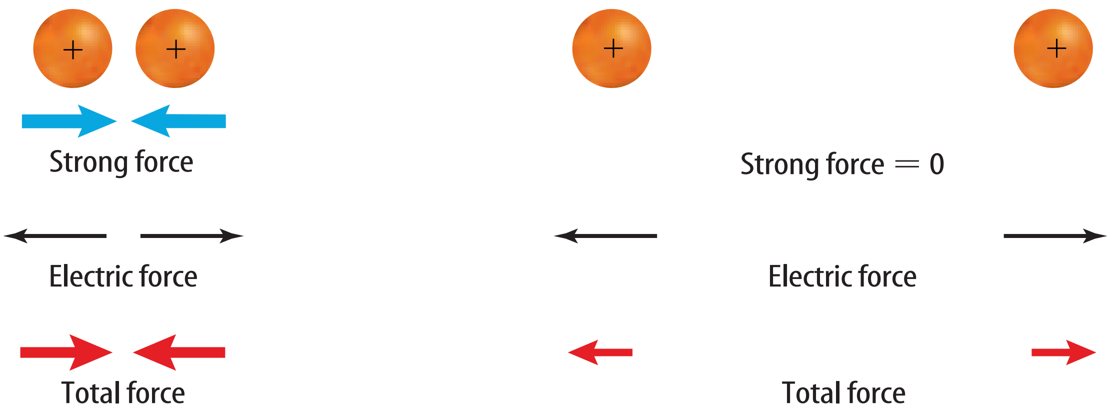
The Strong Force

How do you suppose protons and neutrons are held together so tightly in the nucleus? Positive electric charges repel each other, so why don't the protons in a nucleus push each other away? Another force, called the **strong force,** causes protons and neutrons to be attracted to each other, as shown in **Figure 2.**

The strong force is one of the four basic forces in nature and is about 100 times stronger than the electric force. The attractive forces between all the protons and neutrons in a nucleus keep the nucleus together. However, protons and neutrons have to be close together, like they are in the nucleus, to be attracted by the strong force. The strong force is a short-range force that quickly becomes extremely weak as protons and neutrons get farther apart. The electric force is a long-range force, so protons that are far apart still are repelled by the electric force, as shown in **Figure 3.**

Reading Check ***What causes the attraction between protons and neutrons?***

Figure 3 The total force between two protons depends on how far apart they are. **Infer** *whether the total force between two protons could become zero.*



When protons are close together, they are attracted to each other. The attraction due to the short-range strong force is much stronger than the repulsion due to the long-range electric force.

When protons are too far apart to be attracted by the strong force, they still are repelled by the electric force between them. Then the total force between them is repulsive.

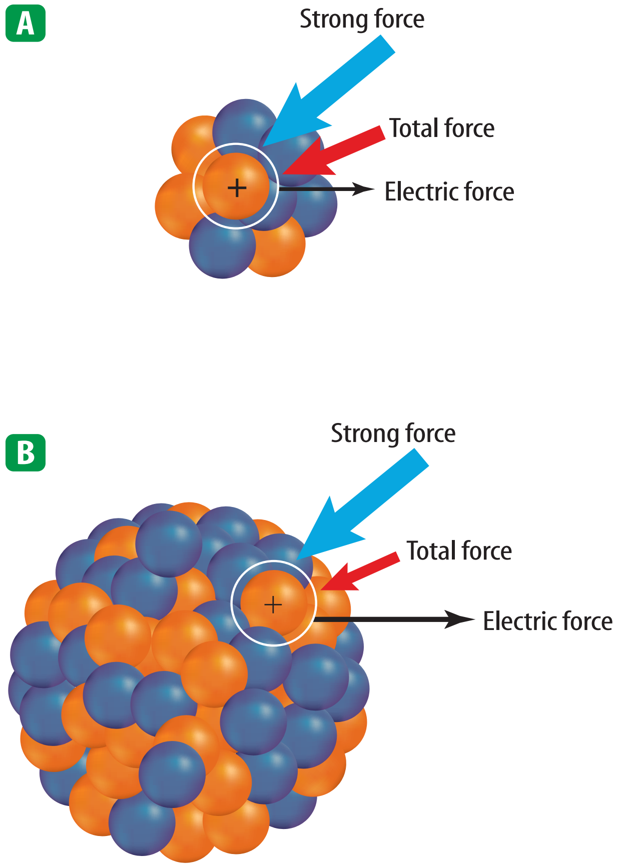


Figure 4 Protons and neutrons are held together less tightly in large nuclei. The circle shows the range of the attractive strong force. **A** Small nuclei have few protons, so the repulsive force on a proton due to the other protons is small. **B** In large nuclei, the attractive strong force is exerted only by the nearest neighbors, but all the protons exert repulsive forces. The total repulsive force is large.

Attraction and Repulsion Some atoms, such as uranium, have many protons and neutrons in their nuclei. These nuclei are held together less tightly than nuclei containing only a few protons and neutrons. To understand this, look at **Figure 4A.** If a nucleus has only a few protons and neutrons, they are all close enough together to be attracted to each other by the strong force. Because only a few protons are in the nucleus, the total electric force causing protons to repel each other is small. As a result, the overall force between the protons and the neutrons attracts the particles to each other.

Forces in a Large Nucleus However, if nuclei have many protons and neutrons, each proton or neutron is attracted to only a few neighbors by the strong force, as shown in **Figure 4B.** The other protons and neutrons are too far away. Because only the closest protons and neutrons attract each other in a large nucleus, the strong force holding them together is about the same as in a small nucleus. However, all the protons in a large nucleus exert a repulsive electric force on each other. Thus, the electric repulsive force on a proton in a large nucleus is larger than it would be in a small nucleus. Because the repulsive force increases in a large nucleus while the attractive force on each proton or neutron remains about the same, protons and neutrons are held together less tightly in a large nucleus.

Radioactivity

In many nuclei the strong force is able to keep the nucleus permanently together, and the nucleus is stable. When the strong force is not large enough to hold a nucleus together tightly, the nucleus can decay and give off matter and energy. This process of nuclear decay is called **radioactivity**.

Large nuclei tend to be unstable and can break apart or decay. In fact, all nuclei that contain more than 83 protons are radioactive. However, many other nuclei that contain fewer than 83 protons also are radioactive. Even some nuclei with only one or a few protons are radioactive.

Almost all elements with more than 92 protons don't exist naturally on Earth. They have been produced only in laboratories and are called synthetic elements. These synthetic elements are unstable, and decay soon after they are created.

Isotopes The atoms of an element all have the same number of protons in their nuclei. For example, the nuclei of all carbon atoms contains six protons. However, naturally occurring carbon nuclei can have six, seven, or eight neutrons. Nuclei that have the same number of protons but different numbers of neutrons are called isotopes. The element carbon has three isotopes that occur naturally. The atoms of all isotopes of an element have the same number of electrons, and have the same chemical properties. **Figure 5** shows two isotopes of helium.

Stable and Unstable Nuclei The ratio of neutrons to protons is related to the stability of the nucleus. In less massive elements, an isotope is stable if the ratio is about 1 to 1. Isotopes of the heavier elements are stable when the ratio of neutrons to protons is about 3 to 2. However, the nuclei of any isotopes that differ much from these ratios are unstable, whether the elements are light or heavy. In other words, nuclei with too many or too few neutrons compared to the number of protons are radioactive.

Nucleus Numbers A nucleus can be described by the number of protons and neutrons it contains. The number of protons in a nucleus is called the atomic number. Because the mass of all the protons and neutrons in a nucleus is nearly the same as the mass of the atom, the number of protons and neutrons is called the mass number.

Reading Check *What is the atomic number of a nucleus?*

A nucleus can be represented by a symbol that includes its atomic number, mass number, and the symbol of the element it belongs to. The symbol for the nucleus of the stable isotope of carbon is shown below as an example.

$$\begin{array}{r} \text{mass number} \rightarrow \\ \text{atomic number} \rightarrow \end{array} {}^{12}_{6}\mathrm{C} \leftarrow \text{element symbol}$$

This isotope is called carbon-12. The number of neutrons in the nucleus is the mass number minus the atomic number. So the number of neutrons in the carbon-12 nucleus is $12 - 6 = 6$. Carbon-12 has six protons and six neutrons. Now, compare the isotope carbon-12 to this radioactive isotope of carbon:

$$\begin{array}{r} \text{mass number} \rightarrow \\ \text{atomic number} \rightarrow \end{array} {}^{14}_{6}\mathrm{C} \leftarrow \text{element symbol}$$

The radioactive isotope is carbon-14. How many neutrons does carbon-14 have?

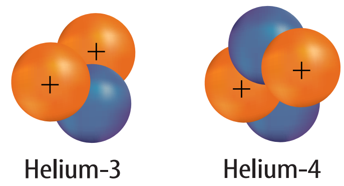


Figure 5 These two isotopes of helium each have the same number of protons, but different numbers of neutrons.
Identify *the ratio of protons to neutrons in each of these isotopes of helium.*

Mini LAB

Modeling the Strong Force

Procedure

1. Gather **15 yellow candies** to represent neutrons and **13 red** and **2 green candies** to represent protons.
2. Model a small nucleus by placing 2 red protons and 3 neutrons around a green proton so they touch.
3. Model a larger nucleus by arranging the remaining candies around the other green proton so they are touching.

Analysis

1. Compare the number of protons and neutrons touching a green proton in both models.
2. Suppose the strong force on a green proton is due to protons and neutrons that touch it. Compare the strong force on a green proton in both models.

Try at Home

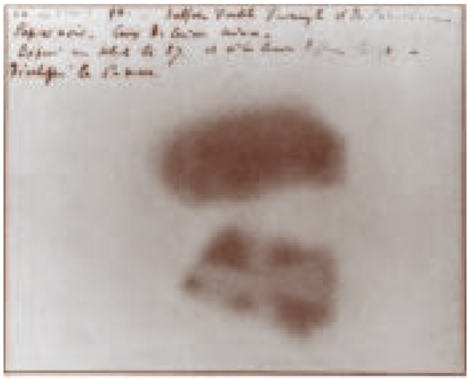


Figure 7 The dark spots on this photographic plate were made by the radiation emitted by radioactive uranium atoms. Uranium salt had been placed next to the plate by Henri Becquerel in 1896.

INTEGRATE History

The Discovery of Radioactivity In 1896, Henri Becquerel left uranium salt in a desk drawer with a photographic plate. Later, when he developed the plate, shown in **Figure 6,** he found an outline of the clumps of the uranium salt. He hypothesized that the uranium salt had emitted some unknown invisible rays, or radiation, that had darkened the film.

Two years after Becquerel's discovery, Marie and Pierre Curie discovered two new elements, polonium and radium, that also were radioactive. To obtain a sample of radium large enough to be studied, they developed a process to extract radium from the mineral pitchblende. After more than three years, they were able to obtain about 0.1 g of radium from several tons of pitchblende. Years of additional processing gradually produced more radium that was made available to other researchers all over the world.

Science Online

Topic: Marie Curie

Visit gpscience.com for Web links to information about the life of Marie Curie.

Activity Create a timeline showing important events in the life of Marie Curie.

section 1 review

Summary

The Strong Force

- The short-ranged strong force causes neutrons and protons to be attracted to each other.
- The long-ranged electric force causes protons to repel each other.
- The combination of the strong and electric forces causes protons and neutrons in a large nucleus to be held together less tightly than in a small nucleus.

Radioactivity and Isotopes

- Radioactivity is the process of nuclear decay.
- Isotopes of an element have the same number of protons, but different numbers of neutrons.
- The atomic number is the number of protons in a nucleus. The mass number is the number of protons and neutrons in a nucleus.

Self Check

1. **Describe** the properties of the strong force.
2. **Compare** the strong force between protons and neutrons in a small nucleus and a large nucleus.
3. **Explain** why large nuclei are unstable.
4. **Identify** the contributions of the three scientists who discovered the first radioactive elements.
5. **Think Critically** What is the ratio of protons to neutrons in lead-214? Explain whether you would expect this isotope to be radioactive or stable.

Applying Math

6. **Calculate a Ratio** What is the ratio of neutrons to protons in a nucleus of radon-222?
7. **Use Percentages** A silicon rod contains 30.21 g of silicon-28, 1.53 g of silicon-29, and 1.02 g of silicon-30. Calculate the percentage of each isotope in the rod.

Science Online gpscience.com/self_check_quiz

SPS3a. Differentiate among alpha and beta particles and gamma radiation. **SPS3c.** Explain the process half-life as related to radioactive decay. **Also covers: SCSh9c**

section 2

Nuclear Decay

Reading Guide

What You'll Learn

- **Compare and contrast** alpha, beta, and gamma radiation.
- **Define** the half-life of a radioactive material.
- **Describe** the process of radioactive dating.

Why It's Important

Nuclear decay produces nuclear radiation that can both harm people and be useful.

Review Vocabulary

electromagnetic wave: a transverse wave consisting of vibrating electric and magnetic fields

New Vocabulary

- alpha particle
- transmutation
- beta particle
- gamma ray
- half-life

Nuclear Radiation

When an unstable nucleus decays, particles and energy called nuclear radiation are emitted from it. The three types of nuclear radiation are alpha, beta (BAY tuh), and gamma radiation. Alpha and beta radiation are particles. Gamma radiation is an electromagnetic wave.

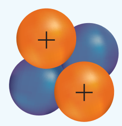
Alpha Particles

When alpha radiation occurs, an **alpha particle**—made of two protons and two neutrons, as shown in **Table 1**—is emitted from the decaying nucleus. An alpha particle is the same as the nucleus of a helium atom and has a charge of +2 and an atomic mass of 4. Its symbol is the same as the symbol of a helium nucleus, $^{4}_{2}He$.

Reading Check *What does an alpha particle consist of?*

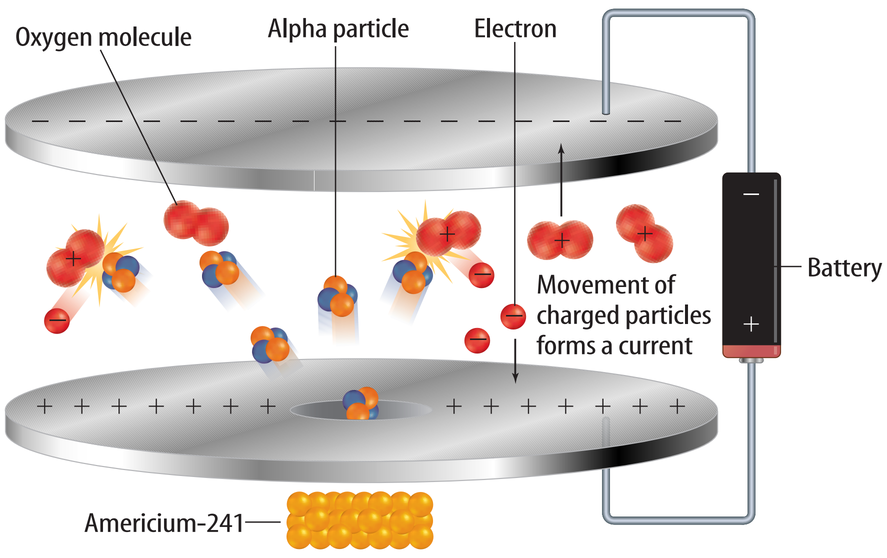
Compared to beta and gamma radiation, alpha particles are much more massive. They also have the most electric charge. As a result, alpha particles lose energy more quickly when they interact with matter than the other types of nuclear radiation do. When alpha particles pass through matter, they exert an electric force on the electrons in atoms in their path. This force pulls electrons away from atoms and leaves behind charged ions. Alpha particles lose energy quickly during this process. As a result, alpha particles are the least penetrating form of nuclear radiation. Alpha particles can be stopped by a sheet of paper.

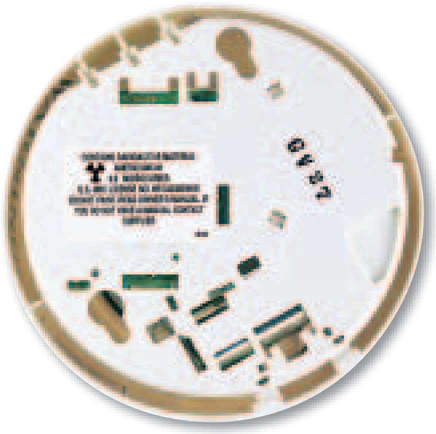
Table 1 Alpha Particles



Symbol	$^{4}_{2}He$
Mass	4
Charge	+2

Figure 7 When alpha particles collide with molecules in the air, positively-charged ions and electrons result. The ions and electrons move toward charged plates, creating a current in the smoke detector.



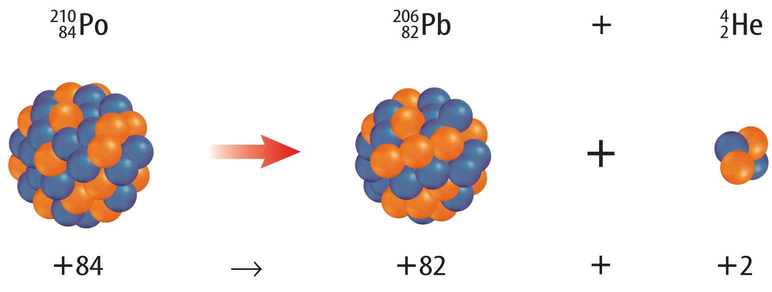


Damage from Alpha Particles Alpha particles can be dangerous if they are released by radioactive atoms inside the human body. Biological molecules inside your body are large and easily damaged. A single alpha particle can damage many fragile biological molecules. Damage from alpha particles can cause cells not to function properly, leading to illness and disease.

Smoke Detectors Some smoke detectors give off alpha particles that ionize the surrounding air. Normally, an electric current flows through this ionized air to form a circuit, as in **Figure 7.** But if smoke particles enter the ionized air, they will absorb the ions and electrons. The circuit is broken and the alarm goes off.

Transmutation When an atom emits an alpha particle, it has two fewer protons, so it is a different element. **Transmutation** is the process of changing one element to another through nuclear decay. In alpha decay, two protons and two neutrons are lost from the nucleus. The new element has an atomic number two less than that of the original element. The mass number of the new element is four less than the original element. **Figure 8** shows a nuclear transmutation caused by alpha decay. The charge of the original nucleus equals the sum of the charges of the nucleus and the alpha particle that are formed.

Figure 8 In this transmutation, polonium emits an alpha particle and changes into lead.
Determine *whether the charges and mass numbers of the products equal the charge and mass number of the polonium nucleus.*



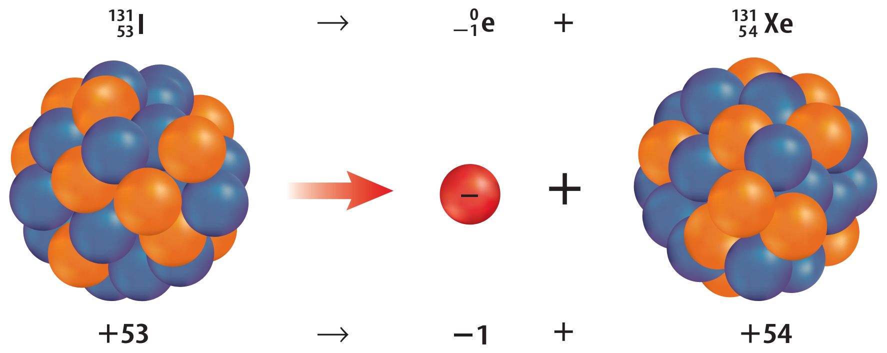


Figure 9 Nuclei that emit beta particles undergo transmutation. In beta decay shown here, iodine changes to xenon.
Compare *the total atomic number and mass number of the products with the atomic number and mass number of the iodine nucleus.*

Beta Particles

A second type of radioactive decay is called beta decay, which is summarized in **Table 2.** Sometimes in an unstable nucleus a neutron decays into a proton and emits an electron. The electron is emitted from the nucleus and is called a **beta particle.** Beta decay is caused by another basic force called the weak force.

Because the atom now has one more proton, it becomes the element with an atomic number one greater than that of the original element. Atoms that lose beta particles undergo transmutation. However, because the total number of protons and neutrons does not change during beta decay, the mass number of the new element is the same as that of the original element. **Figure 9** shows a transmutation caused by beta decay.

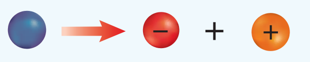
Damage from Beta Particles Beta particles are much faster and more penetrating than alpha particles. They can pass through paper but are stopped by a sheet of aluminum foil. Just like alpha particles, beta particles can damage cells when they are emitted by radioactive nuclei inside the human body.

Gamma Rays

The most penetrating form of nuclear radiation is gamma radiation. **Gamma rays** are electromagnetic waves with the highest frequencies and the shortest wavelengths in the electromagnetic spectrum. They have no mass and no charge and travel at the speed of light. They usually are emitted from a nucleus when alpha decay or beta decay occurs. The properties of gamma rays are summarized in **Table 3.**

Thick blocks of dense materials, such as lead and concrete, are required to stop gamma rays. However, gamma rays cause less damage to biological molecules as they pass through living tissue. Suppose an alpha particle and a gamma ray travel the same distance through matter. The gamma ray produces fewer ions because it has no electric charge.

Table 2 Beta Particles



Symbol	$^{0}_{-1}e$
Mass	0.0005
Charge	−1

Table 3 Gamma Rays

Symbol	γ
Mass	0
Charge	0

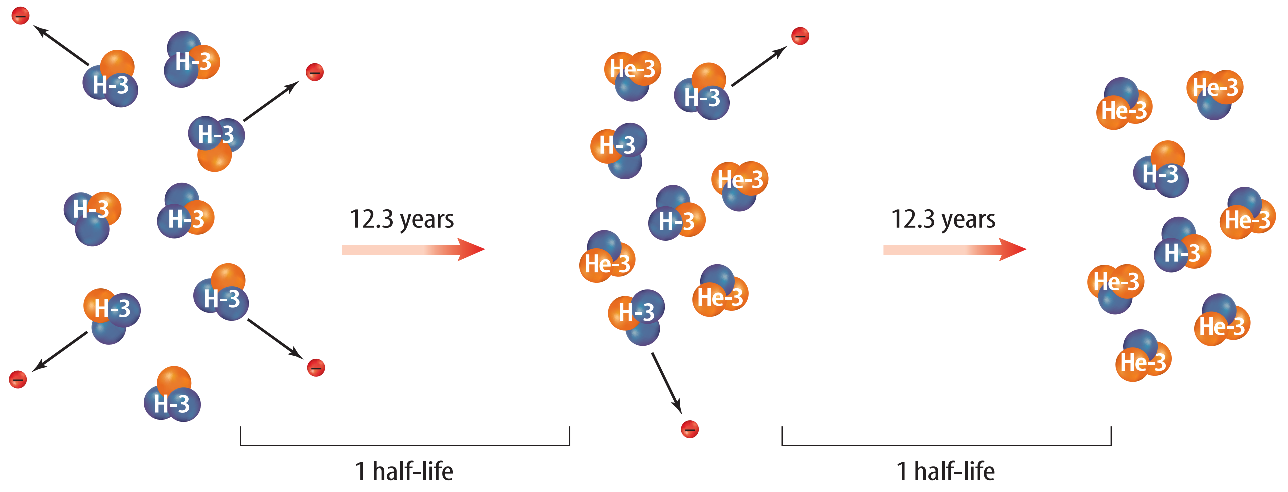


Figure 10 The half-life of $^{3}_{1}H$ is 12.3 years. During each half-life, half of the atoms in the sample decay into helium.
Infer *how many hydrogen atoms will be left in the sample after the next half-life.*

Radioactive Half-Life

If an element is radioactive, how can you tell when its atoms are going to decay? Some radioisotopes decay to stable atoms in less than a second. However, the nuclei of certain radioactive isotopes require millions of years to decay. A measure of the time required by the nuclei of an isotope to decay is called the half-life. The **half-life** of a radioactive isotope is the amount of time it takes for half the nuclei in a sample of the isotope to decay. The nucleus left after the isotope decays is called the daughter nucleus. **Figure 10** shows how the number of decaying nuclei decreases after each half-life.

Half-lives vary widely among the radioactive isotopes. For example, polonium-214 has a half-life of less than a thousandth of a second, but uranium-238 has a half-life of 4.5 billion years. The half-lives of some other radioactive elements are listed in **Table 4.**

Reading Check *What is a daughter nucleus?*

Table 4 Sample Half-Lives

Isotope	Half-Life
$^{3}_{1}H$	12.3 years
$^{212}_{82}Pb$	10.6 hr
$^{14}_{6}C$	5,730 years
$^{211}_{84}Po$	0.5 s
$^{235}_{92}U$	7.04×10^{8} years
$^{131}_{53}I$	8.04 days

Radioactive Dating

Some geologists, biologists, and archaeologists, among others, are interested in the ages of rocks and fossils found on Earth. The ages of these materials can be determined using radioactive isotopes and their half-lives. First, the amounts of the radioactive isotope and its daughter nucleus in a sample of material are measured. Then, the number of half-lives that need to pass to give the measured amounts of the isotope and its daughter nucleus is calculated. The number of half-lives is the amount of time that has passed since the isotope began to decay. It is also usually the amount of time that has passed since the object was formed, or the age of the object. Different isotopes are useful in dating different types of materials.

Carbon Dating The radioactive isotope carbon-14 often is used to estimate the ages of plant and animal remains. Carbon-14 has a half-life of 5,730 years and is found in molecules such as carbon dioxide. Plants use carbon dioxide when they make food, so all plants contain carbon-14. When animals eat plants, carbon-14 is added to their bodies.

The decaying carbon-14 in a plant or animal is replaced when an animal eats or when a plant makes food. As a result, the ratio of the number of carbon-14 atoms to the number of carbon-12 atoms in the organism remains nearly constant. But when an organism dies, its carbon-14 atoms decay without being replaced. The ratio of carbon-14 to carbon 12 then decreases with time. By measuring this ratio, the age of an organism's remains can be estimated. However, only material from plants and animals that lived within the past 50,000 years contains enough carbon-14 to be measured.

Uranium Dating Radioactive dating also can be used to estimate the ages of rocks. Some rocks contain uranium, which has two radioactive isotopes with long half-lives. Each of these uranium isotopes decays into a different isotope of lead. The amount of these uranium isotopes and their daughter nuclei are measured. From the ratios of these amounts, the number of half-lives since the rock was formed can be calculated.

section 2 review

Summary

Nuclear Radiation

- When an unstable nucleus decays it emits nuclear radiation that can be alpha particles, beta particles, or gamma rays.
- An alpha particle consists of two protons and two neutrons.
- A beta particle is an electron and is emitted when a neutron decays into a proton.
- Gamma rays are electromagnetic waves of very high frequency that usually are emitted when alpha decay or beta decay occurs.

Half-Life and Radioactive Dating

- The half-life of a radioactive isotope is the amount of time for half the nuclei in a sample of the isotope to decay.
- The amounts of a radioactive isotope and its daughter nucleus are needed to date materials.

Self Check

1. **Infer** how the mass number and the atomic number of a nucleus change when it emits a beta particle.
2. **Determine** the daughter nucleus formed when a radon-222 nucleus emits an alpha particle.
3. **Describe** how each of the three types of radiation can be stopped.
4. **Think Critically** Sample 1 contains nuclei with a half-life of 10.6 hr and sample 2 contains an equal number of nuclei with a half-life of 0.5 s. After 3 half-lives pass for each sample, which sample contains more of the original nuclei?

Applying Math

5. **Use Percentages** What is the percentage of radioactive nuclei left after 3 half-lives pass?
6. **Use Fractions** If the half-life of iodine 131 is 8 days, how much of a 5-g sample is left after 32 days?

Science Online gpscience.com/self_check_quiz

SCSh9c. Students will enhance reading in all curriculum areas by building vocabulary knowledge.

section 3

Detecting Radioactivity

Reading Guide

What You'll Learn

- **Describe** how radioactivity can be detected in cloud and bubble chambers.
- **Explain** how an electroscope can be used to detect radiation.
- **Explain** how a Geiger counter can measure nuclear radiation.

Why It's Important

Devices that detect and measure radioactivity are used to monitor exposure to humans.

Review Vocabulary

ion: an atom that has gained or lost electrons

New Vocabulary

- cloud chamber
- bubble chamber
- Geiger counter

Radiation Detectors

Because you can't see or feel alpha particles, beta particles, or gamma rays, you must use instruments to detect their presence. Some tools that are used to detect radioactivity rely on the fact that radiation forms ions in the matter it passes through. The tools detect these newly formed ions in several ways.

Cloud Chambers A **cloud chamber,** shown in **Figure 11,** can be used to detect alpha or beta particle radiation. A cloud chamber is filled with water or ethanol vapor. When a radioactive sample is placed in the cloud chamber, it gives off charged alpha or beta particles that travel through the water or ethanol vapor. As each charged particle travels through the chamber, it knocks electrons off the atoms in the air, creating ions. It leaves a trail of ions in the chamber. The water or ethanol vapor condenses around these ions, creating a visible path of droplets along the track of the particle. Beta particles leave long, thin trails, and alpha particles leave shorter, thicker trails.

Reading Check *Why are trails produced by alpha and beta particles seen in cloud chambers?*

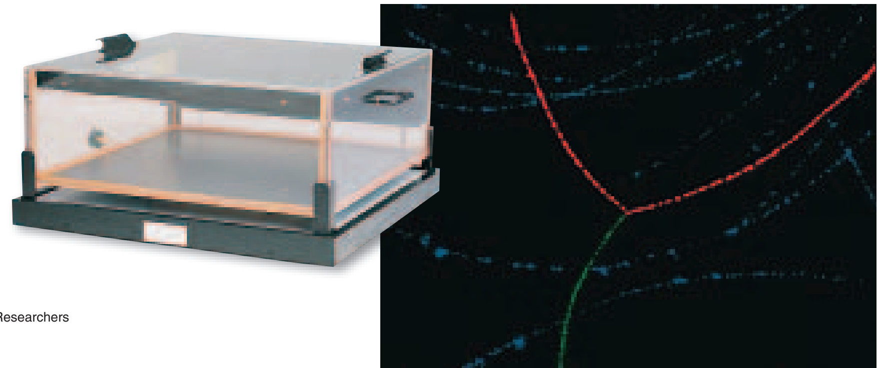


Figure 11 If a sample of radioactive material is placed in a cloud chamber, a trail of condensed vapor will form along the paths of the emitted particles.

Bubble Chambers Another way to detect and monitor the paths of nuclear particles is by using a bubble chamber. A **bubble chamber** holds a superheated liquid, which doesn't boil because the pressure in the chamber is high. When a moving particle leaves ions behind, the liquid boils along the trail. The path shows up as tracks of bubbles, like the ones in **Figure 12.**

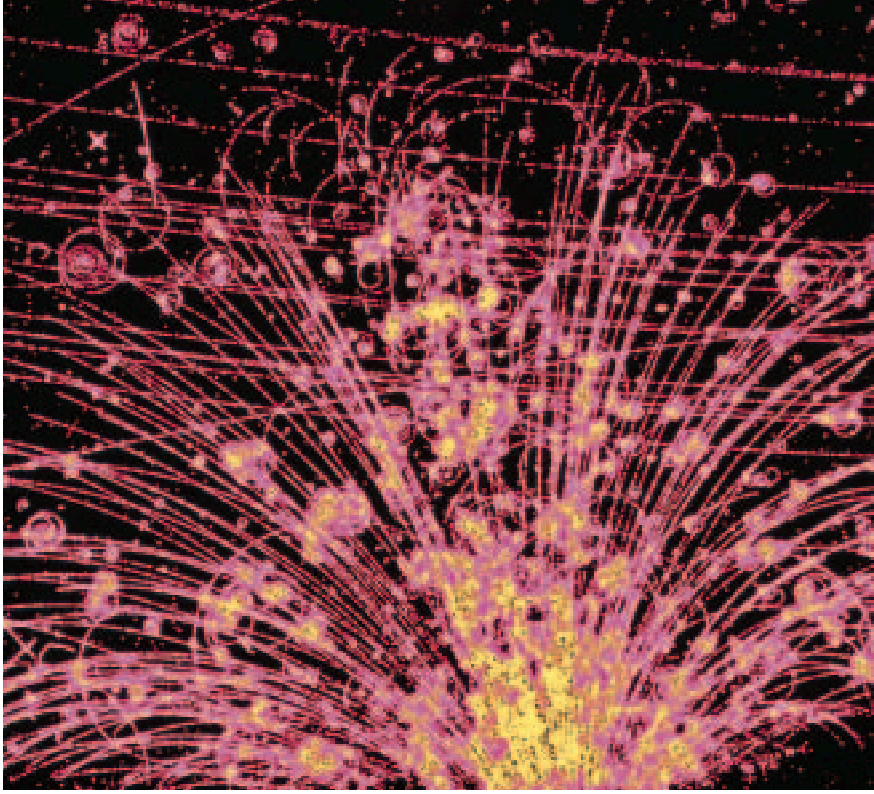
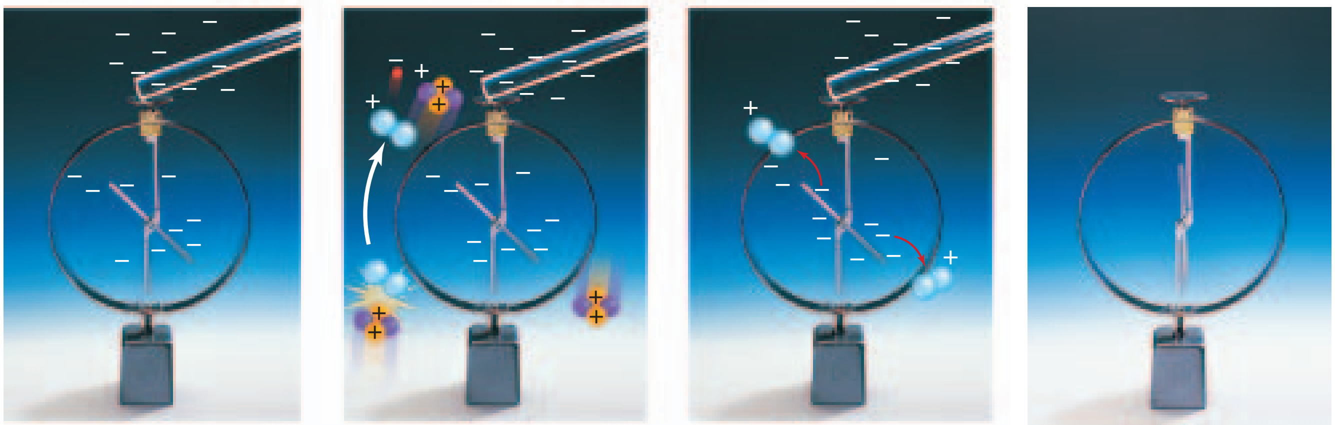


Figure 12 Particles of nuclear radiation can be detected as they leave trails of bubbles in a bubble chamber.

Electroscopes Do you remember how an electroscope can be used to detect electric charges? When an electroscope is given a negative charge, its leaves repel each other and spread apart, as in **Figure 13A.** They will remain apart until their extra electrons have somewhere to go and discharge the electroscope. The excess charge can be neutralized if it combines with positive charges. Nuclear radiation moving through the air can remove electrons from some molecules in air, as shown in **Figure 13B,** and cause other molecules in air to gain electrons. When this occurs near the leaves of the electroscope, some positively charged molecules in the air can come in contact with the electroscope and attract the electrons from the leaves, as **Figure 13C** shows. As these negatively charged leaves lose their charges, they move together. **Figure 13D** shows this last step in the process. The same process also will occur if the electroscope leaves are positively charged. Then the electrons move from negative ions in the air to the electroscope leaves.

Figure 13 Nuclear radiation can cause an electroscope to lose its charge.



A The electroscope leaves are charged with negative charge.

B Nuclear radiation, such as alpha particles, can create positive ions.

C Negative charges move from the leaves to positively charged ions.

D The electroscope leaves lose their negative charge and come together.

Measuring Radiation

It is important to monitor the amount of radiation a person is being exposed to because large doses of radiation can be harmful to living tissue. A **Geiger counter** is a device that measures the amount of radiation by producing an electric current when it detects a charged particle.

CALCULATING ROCK AGE

Measuring the Age of Rocks The nucleus uranium-238 has a half-life of 4.5 billion years and decays to produce the daughter nucleus lead-206. This decay can be used to date rocks. The age of a rock sample can be calculated from this equation:

$$age = (1.44 \times H) \ln[1 + \frac{N_L}{N_U}]$$

where H is the half-life of uranium 238, N_L is the number of lead-206 atoms in the sample, and N_U is the number of uranium-238 atoms. In the above equation, "ln" means the natural logarithm of the number $1 + N_L/N_U$ inside the brackets. Find the age of a sample in which the ratio N_L/N_U is measured to be 0.55.

1. **This is what you know:** half-life of uranium-238: H = 4.5 billion years

   lead-206 to uranium-238 ratio: $\frac{N_L}{N_U} = 0.55$

2. **This is what you need to find:** age of mineral sample: *age*

3. **Use this formula:** $age = (1.44 \times H) \ln[1 + \frac{N_L}{N_U}]$

4. **Substitute:** the values of H and N_L/N_U into the formula.

   $age = (1.44 \times 4.5) \ln[1 + 0.55]$

   $= (6.48) \ln(1.55)$

   To calculate ln(1.55), enter 1.55 on your calculator and press the "ln" button. The result is 0.438. Substitute this value in the above equation:

   $age = (6.48)(0.438) = 2.84$

5. **Determine the units:** The logarithm of a number does not have any units.

   units of *age* = units of H = billion years

Answer: The age of the mineral sample is 2.84 billion years.

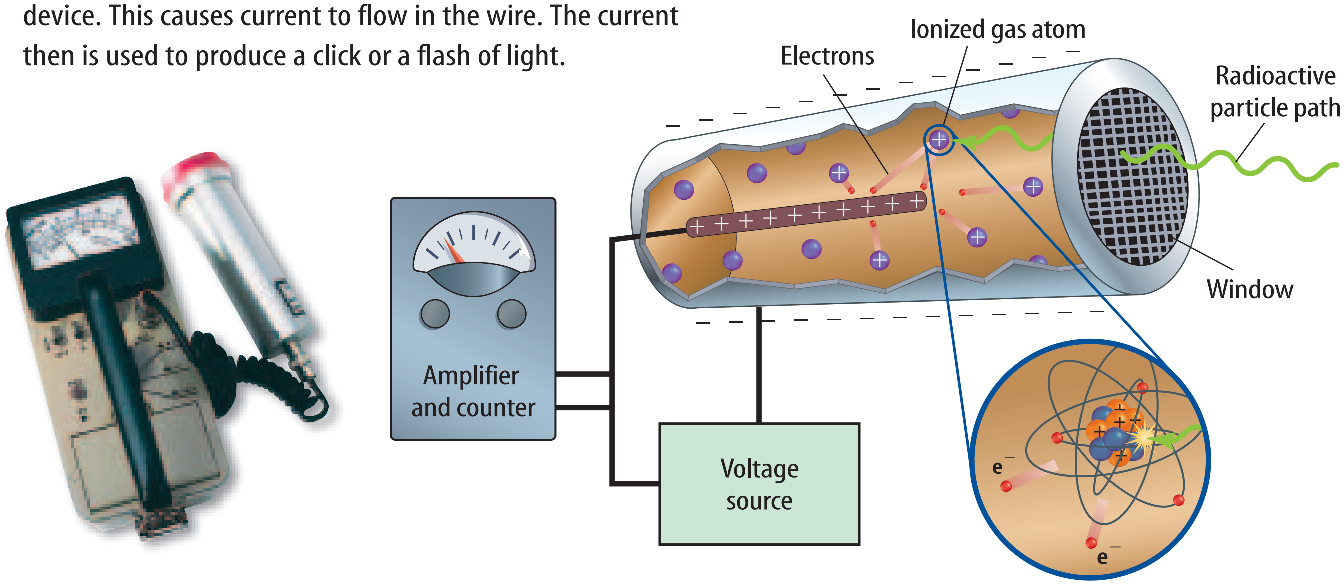
Practice Problems

1. In a mineral sample, the ratio of the number of lead-206 atoms to uranium-238 atoms is 0.91. What is the age of the sample?
2. In a certain mineral sample there are 750,000 uranium-238 atoms and 50,000 lead-206 atoms. What is the age of the sample?
3. **Challenge** What is the ratio of lead-206 atoms to uranium-238 atoms after one half-life?

Science Online

For more practice problems, go to page 834, and visit gpscience.com/extra_problems.

Figure 14 Electrons that are stripped off gas molecules in a Geiger counter move to a positively charged wire in the device. This causes current to flow in the wire. The current then is used to produce a click or a flash of light.



Geiger Counters A Geiger counter, shown in **Figure 14,** has a tube with a positively charged wire running through the center of a negatively charged copper cylinder. This tube is filled with gas at a low pressure. When radiation enters the tube at one end, it knocks electrons from the atoms of the gas. These electrons then knock more electrons off other atoms in the gas, and an "electron avalanche" is produced. The free electrons are attracted to the positive wire in the tube. When a large number of electrons reaches the wire, a short, intense current is produced in the wire. This current is amplified to produce a clicking sound or flashing light. The intensity of radiation present is determined by the number of clicks or flashes of light each second.

Reading Check *How does a Geiger counter indicate that radiation is present?*

Background Radiation

It might surprise you to know that you are bathed in radiation that comes from your environment. This radiation, called background radiation, is not produced by humans. Instead it is low-level radiation emitted mainly by naturally occurring radioactive isotopes found in Earth's rocks, soils, and atmosphere. Building materials such as bricks, wood, and stones contain traces of these radioactive materials. Traces of naturally occurring radioactive isotopes are found in the food, water, and air consumed by all animals and plants. As a result, animals and plants also contain small amounts of these isotopes.

INTEGRATE Social Studies

Artificial Rainmaking It may be possible to ease the health and economic hardships caused by severe droughts by artificially making rain. The formation of raindrops in a cloud is similar to the formation of droplets in a cloud chamber. Rain forms when cold droplets freeze around microscopic particles of dust, and then melt as they fall through warmer air. Research artificial rainmaking and report you findings to your class.

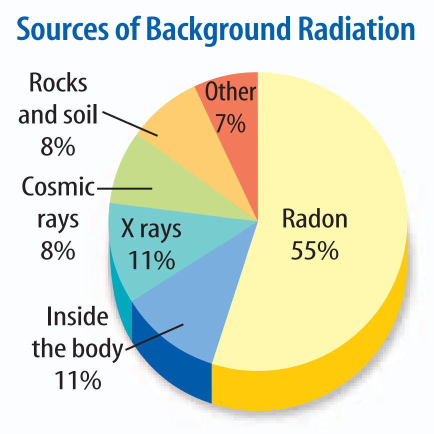


Figure 15 This circle graph shows the sources of background radiation received on average by a person living in the United States.

Sources of Background Radiation Background radiation comes from several sources, as shown in **Figure 15.** The largest source comes from the decay of radon gas. Radon is produced in Earth's crust by the decay of uranium-238 and emits an alpha particle when it decays. Radon gas can seep into houses and basements from the surrounding soil and rocks.

Some background radiation comes from high-speed nuclei, called cosmic rays, that strike Earth's atmosphere. They produce showers of particles, including alpha, beta, and gamma radiation. Most of this radiation is absorbed by the atmosphere. Higher up, there is less atmosphere to absorb this radiation, so the background radiation from cosmic rays increases with altitude.

Radiation in Your Body Some of the elements that are essential for life have naturally occurring radioactive isotopes. For example, about one out of every trillion carbon atoms is carbon-14, which emits a beta particle when it decays. With each breath, you inhale about 3 million carbon-14 atoms.

The amount of background radiation a person receives can vary greatly. The amount depends on the type of rocks underground, the type of materials used to construct the person's home, and the elevation at which the person lives, among other things. However, because it comes from naturally occurring processes, background radiation never can be eliminated.

section 3 review

Summary

Radiation Detectors

- Alpha and beta particles can be detected by the trail of ions they form when they pass through a cloud chamber or a bubble chamber.
- The presence of alpha or beta particles can cause an electroscope to become discharged.
- A Geiger counter produces a clicking sound or a flash of light when alpha or beta particles enter the Geiger counter tube, and is used to measure radiation levels.

Background Radiation

- Background radiation is low-level radiations emitted mainly by radioactive isotopes in Earth's rocks, soils, and atmosphere.
- The largest source of background radiation is from the alpha decay of radon gas.

Self Check

1. **Describe** why a charged electroscope will discharge when placed near a radioactive material.
2. **Compare and contrast** cloud and bubble chambers.
3. **Describe** that process that occurs in a Geiger counter when a click is produced.
4. **Explain** why background radiation never can be completely eliminated.
5. **Think Critically** If the radioactive isotope radon-222 has a half-life of only four days, how can radon gas be continually present inside houses?

Applying Math

6. **Use Percentages** The amount of radiation can be measured in units called millirems. If 25 millirems from cosmic rays is 8.0 percent of the average background radiation, what is the amount of the average background radiation in millirems?

SPS3b. Differentiate between fission and fusion. **Also covers: SCSh1a–c, 3c, 3e–f, 4a, 7c, 9c**

Nuclear Reactions

Reading Guide

What You'll Learn

- **Explain** nuclear fission and how it can begin a chain reaction.
- **Discuss** how nuclear fusion occurs in the Sun.
- **Describe** how radioactive tracers can be used to diagnose medical problems.
- **Discuss** how nuclear reactions can help treat cancer.

Why It's Important

Almost all of the different atoms that you are made of were formed by the nuclear reactions inside ancient, distant stars.

Review Vocabulary

kinetic energy: energy of motion; increases as the mass or speed of an object increases

New Vocabulary

- nuclear fission
- chain reaction
- critical mass
- nuclear fusion
- tracer

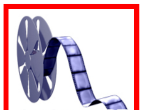
Nuclear Fission

In the 1930s the physicist Enrico Fermi thought that by bombarding nuclei with neutrons, nuclei would absorb neutrons and heavier nuclei would be produced. However, in 1938, Otto Hahn and Fritz Strassmann found that when a neutron strikes a uranium-235 nucleus, the nucleus splits apart into smaller nuclei.

In 1939 Lise Meitner was the first to offer a theory to explain these results. She proposed that the uranium-235 nucleus is so distorted when the neutron strikes it that it divides into two smaller nuclei, as shown in **Figure 16.** The process of splitting a nucleus into several smaller nuclei is **nuclear fission.** The word *fission* means "to divide."

Reading Check *What initiates nuclear fission of a uranium-235 nucleus?*

Only large nuclei, such as the nuclei of uranium and plutonium atoms, can undergo nuclear fission. The products of a fission reaction usually include several individual neutrons in addition to the smaller nuclei. The total mass of the products is slightly less than the mass of the original nucleus and the neutron. This small amount of missing mass is converted to a tremendous amount of energy during the fission reaction.



CLICK HERE

Figure 16 When a neutron hits a uranium-235 nucleus, the uranium nucleus splits into two smaller nuclei and two or three free neutrons. Energy also is released.

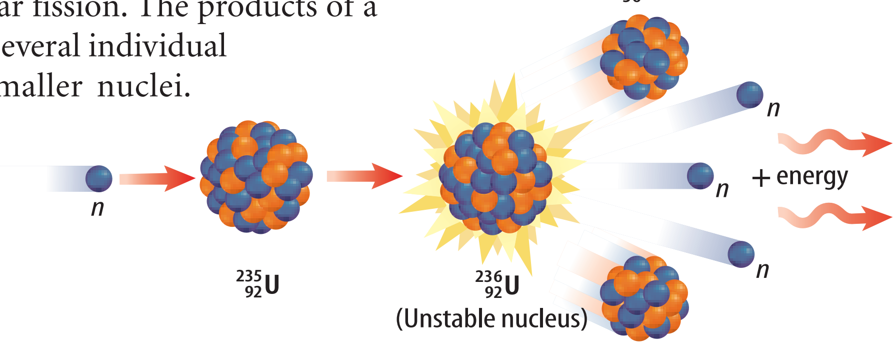
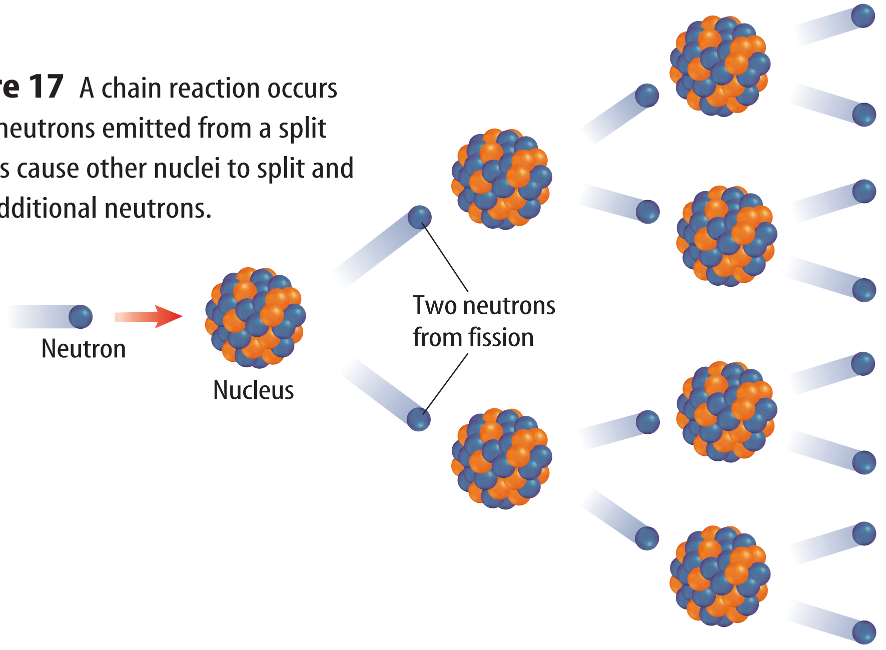


Figure 17 A chain reaction occurs when neutrons emitted from a split nucleus cause other nuclei to split and emit additional neutrons.



Mini LAB

Modeling a Nuclear Reaction

Procedure

1. Put **32 marbles,** each with an attached lump of **clay,** into a large **beaker.** These marbles with clay represent unstable atoms.
2. During a 1-min period, remove half of the marbles and pull off the clay. Place the removed marbles into another beaker and place the lumps of clay into a pile. Marbles without clay represent stable atoms. The clay represents waste from the reaction—smaller atoms that still might decay and give off energy.
3. Repeat this procedure four more times.

Analysis

1. What is the half-life of this reaction?
2. Explain whether the waste products could undergo nuclear fission.

Mass and Energy Albert Einstein proposed that mass and energy were related in his special theory of relativity. According to this theory, mass can be converted to energy and energy can be converted to mass. The relation between mass and energy is given by this equation:

Mass-Energy Equation

Energy (joules) = mass (kg) × [speed of light (m/s)]^2

$$E = mc^2$$

A small amount of mass can be converted into an enormous amount of energy. For example, if one gram of mass is converted to energy, about 100 trillion joules of energy are released.

Chain Reactions When a nuclear fission reaction occurs, the neutrons emitted can strike other nuclei in the sample, and cause them to split. These reactions then release more neutrons, causing additional nuclei to split, as shown in **Figure 17.** The series of repeated fission reactions caused by the release of neutrons in each reaction is a **chain reaction.**

If the chain reaction is uncontrolled, an enormous amount of energy is released in an instant. However, a chain reaction can be controlled by adding materials that absorb neutrons. If enough neutrons are absorbed, the reaction will continue at a constant rate.

For a chain reaction to occur, a critical mass of material that can undergo fission must be present. The **critical mass** is the amount of material required so that each fission reaction produces approximately one more fission reaction. If less than the critical mass of material is present, a chain reaction will not occur.

Nuclear Fusion

Tremendous amounts of energy can be released in nuclear fission. In fact, splitting one uranium-235 nucleus produces about 30 million times more energy than chemically reacting one molecule of dynamite. Even more energy can be released in another type of nuclear reaction, called nuclear fusion. In **nuclear fusion**, two nuclei with low masses are combined to form one nucleus of larger mass. Fusion fuses atomic nuclei together, and fission splits nuclei apart.

Temperature and Fusion For nuclear fusion to occur, positively charged nuclei must get close to each other. However, all nuclei repel each other because they have the same positive electric charge. If nuclei are moving fast, they can have enough kinetic energy to overcome the repulsive electrical force between them and get close to each other.

Remember that the kinetic energy of atoms or molecules increases as their temperature increases. Only at temperatures of millions of degrees Celsius are nuclei moving so fast that they can get close enough for fusion to occur. These extremely high temperatures are found in the center of stars, including the Sun.

Nuclear Fusion and the Sun The Sun is composed mainly of hydrogen. Most of the energy given off by the Sun is produced by a process involving the fusion of hydrogen nuclei. This process occurs in several stages, and one of the stages is shown in **Figure 18.** The net result of this process is that four hydrogen nuclei are converted into one helium nucleus. As this occurs, a small amount of mass is changed into an enormous amount of energy. Earth receives a small amount of this energy as heat and light.

As the Sun ages, the hydrogen nuclei are used up as they are converted into helium. So far, only about one percent of the Sun's mass has been converted into energy. Eventually, no hydrogen nuclei will be left, and the fusion reaction that changes hydrogen into helium will stop. However, it is estimated that the Sun has enough hydrogen to keep this reaction going for another 5 billion years.

Science Online

Topic: Fusion Reactors
Visit gpscience.com for Web links to information about the use of nuclear fusion as a future energy source.

Activity Write a paragraph describing the different types of fusion reactors that have been developed.

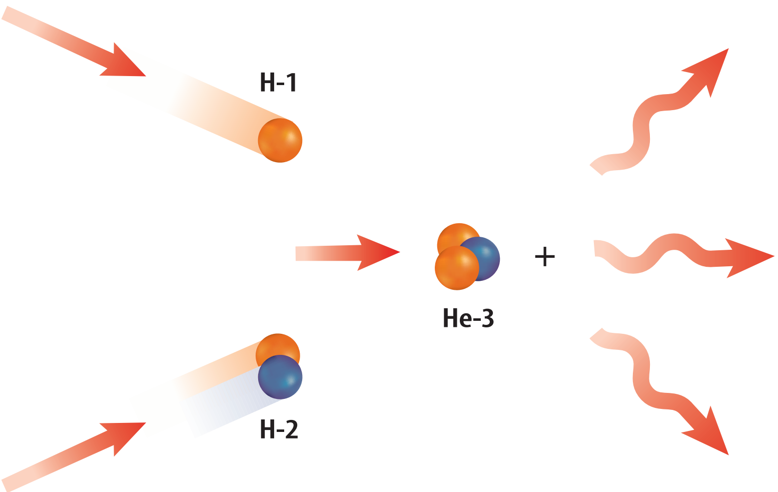


Figure 18 The fusion of hydrogen to form helium takes place in several stages in the Sun. One of these stages is shown here. An isotope of helium is produced when a proton and the hydrogen isotope H-2 undergo fusion.

INTEGRATE Chemistry

Radioactive Decay Equations A uranium-235 atom can fission, or break apart, to form barium and krypton. Use a periodic table to find the atomic numbers of barium and krypton. What do they add up to? A uranium-235 atom can fission in several other ways such as producing neodymium and another element. What is the other element?

Using Nuclear Reactions in Medicine

If you were going to meet a friend in a crowded area, it would be easier to find her if your friend told you that she would be wearing a red hat. In a similar way, scientists can find one molecule in a large group of molecules if they know that it is "wearing" something unique. Although a molecule can't wear a red hat, if it has a radioactive atom in it, it can be found easily in a large group of molecules, or even in a living organism. Radioactive isotopes can be located by detecting the radiation they emit.

When a radioisotope is used to find or keep track of molecules in an organism, it is called a **tracer.** Scientists can use tracers to follow where a particular molecule goes in your body or to study how a particular organ functions. Tracers also are used in agriculture to monitor the uptake of nutrients and fertilizers. Examples of tracers include carbon-11, iodine-131, and sodium-24. These three radioisotopes are useful tracers because they are important in certain body processes. As a result, they accumulate inside the organism being studied.

Reading Check *How are tracers located inside the human body?*

INTEGRATE Health

Iodine Tracers in the Thyroid The thyroid gland is located in your neck and produces chemical compounds called hormones. These hormones help regulate several body processes, including growth. Because the element iodine accumulates in the thyroid, the radioisotope iodine-131 can be used to diagnose thyroid problems. As iodine-131 atoms are absorbed by the thyroid, their nuclei decay, emitting beta particles and gamma rays. The beta particles are absorbed by the surrounding tissues, but the gamma rays penetrate the skin. The emitted gamma rays can be detected and used to determine whether the thyroid is healthy, as shown in **Figure 19.** If the detected radiation is not intense, then the thyroid has not properly absorbed the iodine-131 and is not functioning properly. This could be due to the presence of a tumor. **Figure 20** shows how radioactive tracers are used to study the brain.

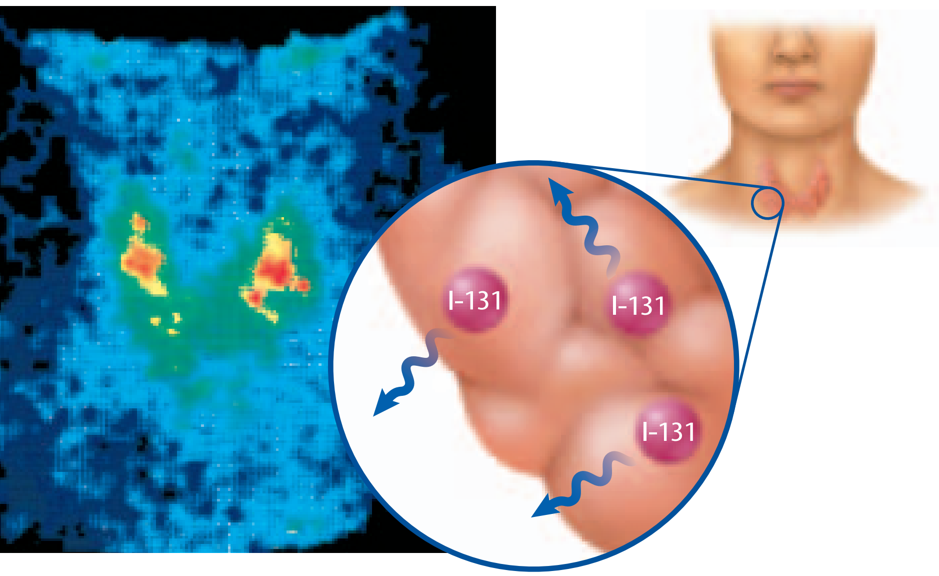


Figure 19 Radioactive iodine-131 accumulates in the thyroid gland and emits gamma rays, which can be detected to form an image of a patient's thyroid.
List *some advantages of being able to use iodine-131 to form an image of a thyroid.*

Oliver Meckes//Nicole Ottawa/Photo Researchers

NATIONAL GEOGRAPHIC VISUALIZING PET SCANS

Figure 20

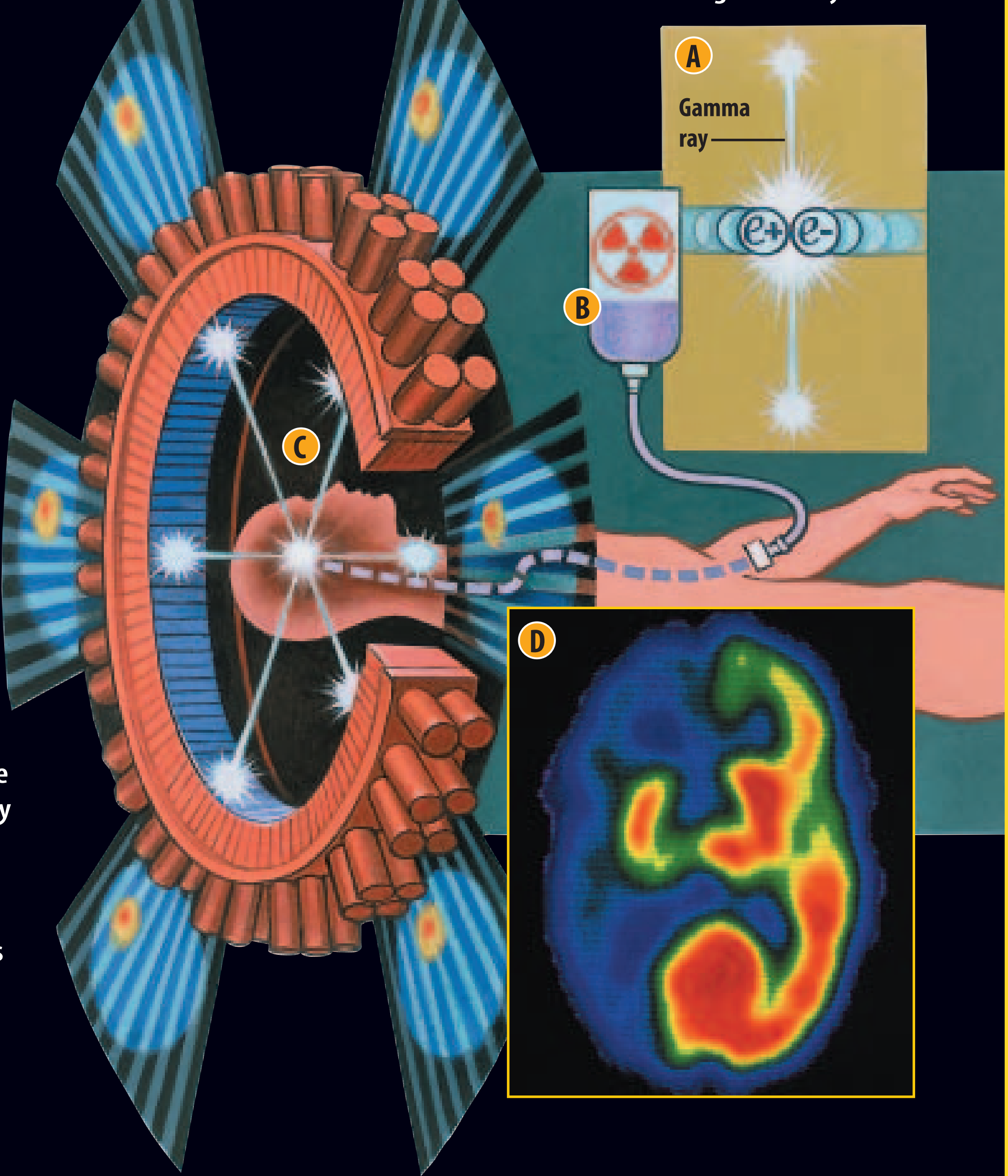
The diagram below shows an imaging technique known as Positron Emission Tomography, or PET. Positrons are emitted from the nuclei of certain radioactive isotopes when a proton changes to a neutron. PET can form images that show the level of activity in different areas of the brain. These images can reveal tumors and regions of abnormal brain activity.

A When positrons are emitted from the nucleus of an atom, they can hit electrons from other atoms and become transformed into gamma rays.

B The radioactive isotope fluorine-18 emits positrons when it decays. Fluorine-18 atoms are chemically attached to molecules that are absorbed by brain tissue. These compounds are injected into the patient and carried by blood to the brain.

C Inside the patient's brain, the decay of the radioactive fluorine-18 nuclei emits positrons that collide with electrons. The gamma rays that are released are sensed by the detectors.

D A computer uses the information collected by the detectors to generate an image of the activity level in the brain. This image shows normal activity in the right side of the brain (red, yellow, green) but below-normal activity in the left (purple).



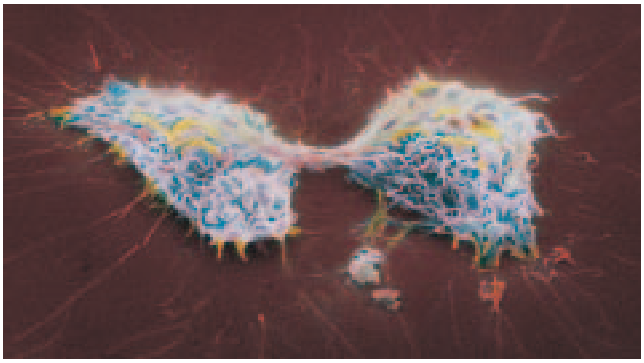


Figure 21 Cancer cells, such as the ones shown here, can be killed with carefully measured doses of radiation.

Treating Cancer with Radioactivity

When a person has cancer, a group of cells in that person's body grows out of control and can form a tumor. Radiation can be used to stop some types of cancerous cells from growing. Remember that the radiation that is given off during nuclear decay is strong enough to ionize nearby atoms. If a source of radiation is placed near cancer cells, such as those shown in **Figure 21,** atoms in the cells can be ionized. If the ionized atoms are in a critical molecule, such as the DNA or RNA of a cancer cell, then the molecule might no longer function properly. The cell then could die or stop growing.

When possible, a radioactive isotope such as gold-198 or iridium-192 is implanted within or near the tumor. Other times, tumors are treated from outside the body. Typically, an intense beam of gamma rays from the decay of cobalt-60 is focused on the tumor for a short period of time. The gamma rays pass through the body and into the tumor. How can physicians be sure that only the cancer cells will absorb radiation? Because cancer cells grow quickly, they are more susceptible to absorbing radiation and being damaged than healthy cells are. However, other cells in the body that grow quickly also are damaged, which is why cancer patients who have radiation therapy sometimes experience severe side effects.

section 4 review

Summary

Nuclear Fission

- Nuclear fission occurs when a neutron strikes a nucleus, causing it to split into smaller nuclei.
- A chain reaction requires a critical mass of fissionable material.

Nuclear Fusion

- Nuclear fusion occurs when two nuclei combine to form another nucleus.
- Nuclear fusion occurs at temperatures of millions of degrees, which occur inside the Sun.

Medical Uses of Radiation

- Radioactive isotopes are used as tracers to locate various atoms or molecules in organisms.
- Radiation emitted by radioactive isotopes is used to kill cancer cells.

Self Check

1. **Infer** whether mass is conserved in a nuclear reaction.
2. **Explain** why fusion reactions can occur inside stars.
3. **Explain** how a chain reaction can be controlled.
4. **Describe** two properties of a tracer isotope used for monitoring the functioning of an organ in the body.
5. **Think Critically** Explain why high temperatures are needed for fusion reactions to occur, but not for fission reactions to occur.

Applying Math

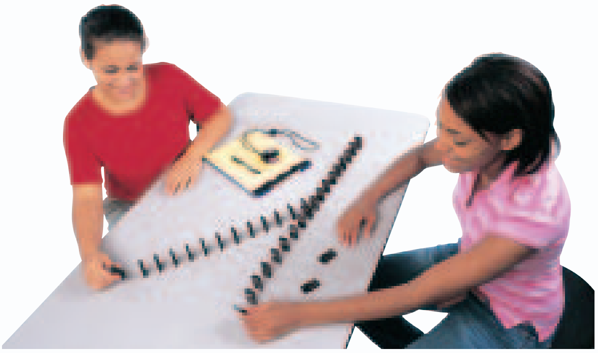
6. **Calculate Number of Nuclei** In a chain reaction, two neutrons are emitted by each nucleus that is split. If one nucleus is split in the first step of the reaction, how many nuclei will have been split after the fifth step?

Science Online gpscience.com/self_check_quiz

LAB

Chain Reactions

In an uncontrolled nuclear chain reaction, the number of reactions increases as additional neutrons split more nuclei. In a controlled nuclear reaction, neutrons are absorbed, so the reaction continues at a constant rate. How could you model a controlled and an uncontrolled nuclear reaction in the classroom?



Real-World Question

How can you use dominoes to model chain reactions?

Goals

- **Model** a controlled and uncontrolled chain reaction.
- **Compare** the two types of chain reactions.

Materials

dominoes
stopwatch

Procedure

1. Set up a single line of dominoes standing on end so that when the first domino is pushed over, it will knock over the second and each domino will knock over the one following it.
2. Using the stopwatch, time how long it takes from the moment the first domino is pushed over until the last domino falls over. Record the time.
3. Using the same number of dominoes as in step 1, set up a series of dominoes in which at least one of the dominoes will knock down two others, so that two lines of dominoes will continue falling. In other words, the series should have at least one point that looks like the letter Y.
4. Repeat step 2.

Conclude and Apply

1. **Compare** the amount of time it took for all of the dominoes to fall in each of your two arrangements.
2. **Determine** the average number of dominoes that fell per second in both domino arrangements.
3. **Identify** which of your domino arrangements represented a controlled chain reaction and which represented an uncontrolled chain reaction.
4. **Describe** how the concept of critical mass was represented in your model of a controlled chain reaction.
5. Assuming that they had equal amounts of material, which would finish faster—a controlled or an uncontrolled nuclear chain reaction? Explain.

Communicating Your Data

Explain to friends or members of your family how a controlled nuclear chain reaction can be used in nuclear power plants to generate electricity.

Tim Courlas/Horizons Companies

LAB **Model and Invent**

(l)Fermilab/Visuals Unlimited, (r)Matt Meadows

Modeling Transmutations

Possible Materials
brown rice
white rice
colored candies
dried beans
dried seeds
glue
poster board

Safety Precautions

WARNING: *Never eat foods used in the lab.*

Data Source
Refer to your textbook for general information about transmutation.

Real-World Question

Imagine what would happen if the oxygen atoms around you began changing into nitrogen atoms. Without oxygen, most living organisms, including people, could not live. Fortunately, more than 99.9 percent of all oxygen atoms are stable and do not decay. Usually, when an unstable nucleus decays, an alpha or beta particle is thrown out of its nucleus, and the atom becomes a new element. A uranium-238 atom, for example, will undergo eight alpha decays and six beta decays to become lead. This process of one element changing into another element is called transmutation. How could you create a model of a uranium-238 atom and the decay process it undergoes during transmutation? What types of materials could you use to represent the protons and neutrons in a U-238 nucleus? How could you use these materials to model transmutation?

Make a Model

1. **Choose** two materials of different colors or shapes for the protons and neutrons of your nucleus model. Choose a material for the negatively charged beta particle.

2. **Decide** how to model the transmutation process. Will you create a new nucleus model for each new element? How will you model an alpha or beta particle leaving the nucleus?

3. **Create** a transmutation chart to show the results of each transmutation step of a uranium-238 atom with the identity, atomic number, and mass number of each new element formed and the type of radiation particle emitted at each step. A uranium-238 atom will undergo the following decay steps before transmuting into a lead-206 atom: alpha decay, beta decay, beta decay, alpha decay, alpha decay, alpha decay, alpha decay, alpha decay, alpha decay, beta decay, beta decay, alpha decay, beta decay, beta decay, alpha decay.
4. **Describe** your model plan and transmutation chart to your teacher and ask how they can be improved.
5. **Present** your plan and chart to your class. Ask classmates to suggest improvements in both.
6. Construct your model of a uranium-238 nucleus showing the correct number of protons and neutrons.

Test Your Model

1. Using your nucleus model, demonstrate the transmutation of a uranium-238 nucleus into a lead-206 nucleus by following the decay sequence outlined in the previous section.
2. Show the emission of an alpha particle or beta particle between each transmutation step.

Analyze Your Data

1. **Compare** how alpha and beta decay change an atom's atomic number.
2. **Compare** how alpha and beta decay change the mass number of an atom.

Conclude and Apply

1. **Calculate** the ratio of neutrons to protons in lead-206 and uranium-238. In which nucleus is the ratio closer to 1.5?
2. **Identify** Alchemists living during the Middle Ages spent much time trying to turn lead into gold. Identify the decay processes needed to accomplish this task.

Communicating Your Data

Show your model to the class and explain how your model represents the transmutation of U-238 into Pb-206.

Matt Meadows

TIME

SCIENCE AND HISTORY

SCIENCE CAN CHANGE THE COURSE OF HISTORY!

The Nuclear Alchemists

The colored tracks are alpha particles emitted from a speck of radium salt placed on a special photographic plate.

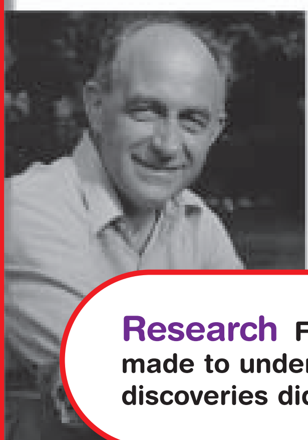
For centuries, ancient alchemists tried in vain to convert common metals into gold. However, in the early 20th century, some scientists realized there was a way to convert atoms of some elements into other elements—nuclear fission.

A Startling Discovery

As the twentieth century dawned, most scientists thought atoms could not be broken apart. In 1902, a New Zealand physicist Ernest Rutherford and his colleague Frederick Soddy showed that heavy elements uranium and thorium decayed into slightly lighter elements, with the production of helium gas. “Don't call it transmutation. They'll have our heads off as alchemists!” Rutherford warned Soddy. In 1908, Rutherford showed that the alpha particles emitted in radioactive decay were the same as a helium nucleus.

Something’s Missing

In 1938 in Germany, Otto Hahn and Fritz Strassmann found the uranium-235 nucleus would split if struck by a neutron. The process was called nuclear fission.



Enrico Fermi lead the development of the first nuclear reactor.

A year later, Austrian physicist Lise Meitner pointed out that the total mass of the particles produced when the uranium nucleus split was less than that of the original uranium nucleus. According to the special theory of relativity, this small amount of missing mass results in the release of a tremendous amount of energy when fission occurs. But is there any way this energy could be controlled?

Lise Meitner was the first to explain how nuclear fission occurs.

Controlling a Chain Reaction

Only a few years later, Italian physicist Enrico Fermi, working with colleagues in the United States, found the answer. Fermi realized that the neutrons released when fission occurs could lead to a chain reaction. However, materials that absorb neutrons could be used to control the chain reaction. In late 1942, Fermi and his colleagues built the first nuclear reactor by using cadmium rods to absorb neutrons and control the chain reaction. The tremendous energy released by nuclear fission could be controlled.

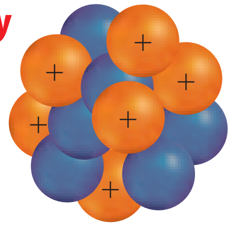
Research Find out more about the contributions these scientists made to understanding radioactivity and the nucleus. What other discoveries did Rutherford and Fermi make?

Science Online

For more information, visit gpscience.com/time

Reviewing Main Ideas

Section 1 Radioactivity



Nucleus

1. The protons and neutrons in an atomic nucleus, like the one to the right, are held together by the strong force.
2. The ratio of protons to neutrons indicates whether a nucleus will be stable or unstable. Large nuclei tend to be unstable.
3. Radioactivity is the emission of energy or particles from an unstable nucleus.
4. Radioactivity was discovered accidentally by Henri Becquerel about 100 years ago.

Section 2 Nuclear Decay

1. Unstable nuclei can decay by emitting alpha particles, beta particles, and gamma rays.
2. Alpha particles consist of two protons and two neutrons. A beta particle is an electron.
3. Gamma rays are the highest frequency electromagnetic waves.
4. Half-life is the amount of time in which half of the nuclei of a radioactive isotope will decay.
5. Because all living things contain carbon, the radioactive isotope carbon-14 can be used to date the remains of organisms that lived during the past 50,000 years, such as this skeleton.

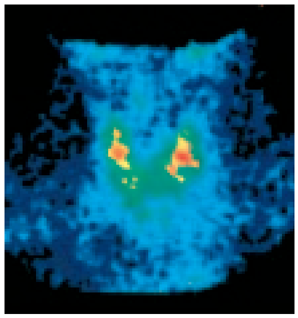
6. Radioactive isotopes of uranium are used to date rocks.

Section 3 Detecting Radioactivity

1. Radioactivity can be detected with a cloud chamber, a bubble chamber, an electroscope, or a Geiger counter.
2. A Geiger counter measures the amount of radiation by producing electric current when it is struck by a charged particle.
3. Background radiation is low-level radiation emitted by naturally occurring isotopes found in Earth's rocks and soils, the atmosphere, and inside your body.

Section 4 Nuclear Reactions

1. When nuclear fission occurs, a nucleus splits into smaller nuclei. Neutrons and a large amount of energy are emitted.
2. Neutrons emitted when a nuclear fission reaction occurs can cause a chain reaction. A chain reaction can occur only if a critical mass of material is present.
3. Nuclear fusion occurs at high temperatures when light nuclei collide and form heavier nuclei, releasing a large amount of energy.
4. Radioactive tracers that are absorbed by specific organs can help diagnose health problems. Nuclear radiation is used to kill cancer cells.



FOLDABLES™ Use the Foldable that you made at the beginning of this chapter to help you review advantages and disadvantages of using radioactive materials and nuclear reactions.

Using Vocabulary

alpha particle p. 541	half-life p. 544
beta particle p. 543	nuclear fission p. 551
bubble chamber p. 547	nuclear fusion p. 553
chain reaction p. 552	radioactivity p. 538
cloud chamber p. 546	strong force p. 537
critical mass p. 552	tracer p. 554
gamma ray p. 543	transmutation p. 542
Geiger counter p. 548	

Use what you know about the vocabulary words to explain the differences in the following sets of words. Then explain how the words are related.

1. cloud chamber—bubble chamber
2. chain reaction—critical mass
3. nuclear fission—nuclear fusion
4. radioactivity—half-life
5. alpha particle—beta particle—gamma ray
6. Geiger counter—tracer
7. nuclear fission—transmutation
8. electroscope—Geiger counter
9. strong force—radioactivity

Checking Concepts

Choose the word or phrase that best answers the question.

10. What keeps particles in a nucleus together?
    A) strong force
    B) repulsion
    C) electrical force
    D) atomic glue

11. Which device would be most useful for measuring the amount of radiation in a nuclear laboratory?
    A) a cloud chamber
    B) a Geiger counter
    C) an electroscope
    D) a bubble chamber

12. What is an electron that is produced when a neutron decays called?
    A) an alpha particle
    B) a beta particle
    C) gamma radiation
    D) a negatron

13. Which of the following describes an isotope's half-life?
    A) a constant time interval
    B) a varied time interval
    C) an increasing time interval
    D) a decreasing time interval

14. For which of the following could carbon-14 dating be used?
    A) a bone fragment
    B) a marble column
    C) dinosaur fossils
    D) rocks

15. Which term describes an ongoing series of fission reactions?
    A) chain reaction
    B) decay reaction
    C) positron emission
    D) fusion reaction

16. Which process is responsible for the tremendous energy released by the Sun?
    A) nuclear decay
    B) nuclear fission
    C) nuclear fusion
    D) combustion

17. Which radioisotope acts as an external source of ionizing radiation in the treatment of cancer?
    A) cobalt-60
    B) carbon-14
    C) gold-198
    D) technetium-99

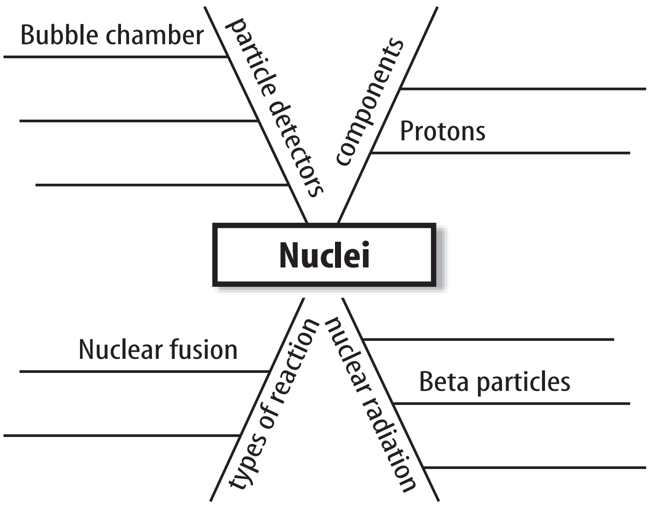
18. Which of the following describes all nuclei with more than 83 protons?
    A) radioactive
    B) repulsive
    C) synthetic
    D) stable

19. Which of the following describes atoms with the same number of protons and a different number of neutrons?
    A) unstable
    B) synthetic
    C) radioactive
    D) isotopes

Science Online gpscience.com/vocabulary_puzzlemaker

Interpreting Graphics

20. Copy and complete the following concept map on radioactivity.



21. **Make a table** summarizing the use of radioactive isotopes or nuclear radiation in the following applications: radioactive dating, monitoring the thyroid gland, and treating cancer. Include a description of the radioactive isotope or radiation involved.

Use the data in the table below to answer question 22.

Isotope Half-Lives

Isotope	Mass Number	Half-Life
Radon-222	222	4 days
Thorium-234	234	24 days
Iodine-131	131	8 days
Bismuth-210	210	5 days
Polonium-210	210	138 days

22. Graph the data in the table above with the *x*-axis the mass number and the *y*-axis the half-life. Infer from your graph whether there is a relation between the half-life and the mass number. If so, how does half-life depend on mass number?

Thinking Critically

23. **Explain** why the amount of background radiation a person receives can vary greatly from place to place.

24. **Infer** how the atomic number of a nucleus changes when the nucleus emits only gamma radiation.

25. **Identify** the properties of alpha particles that make them harmful to living cells.

26. **Determine** the type of nuclear radiation that is emitted by each of the following nuclear reactions:

a. uranium-238 to thorium-234
b. boron-12 to carbon-12
c. cesium-130 to cesium 130
d. radium-226 to radon-222

27. **Determine** how the motion of an alpha particle is affected when it passes between a positively-charged electrode and a negatively charged electrode. How is the motion of a gamma ray affected?

28. **Infer** how the background radiation a person receives changes when they fly in a jet airliner.

Applying Math

29. **Use a Ratio** The mass of an alpha particle is 4.0026 mass units, and the mass of a beta particle is 0.000548 mass units. How many times larger is the mass of an alpha particle than the mass of a beta particle?

30. **Calculate Number of Half-Lives** How many half-lives have elapsed when the amount of a radioactive isotope in a sample is reduced to 3.125 percent of the original amount in the sample.

chapter 18 Standardized Test Practice

Physical Science EOCT Practice

Part 1 Multiple Choice

Record your answers on the answer sheet provided by your teacher or on a sheet of paper.

1. If a radioactive material has a half-life of 10 y, what fraction of the material will remain after 30 y? SPS3c

A. one half **C.** one fourth
B. one third **D.** one eighth

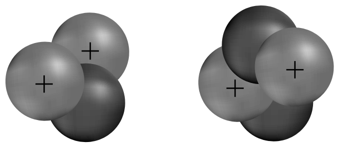
2. Which of the follow statements is true about all the isotopes of an element? SPS1a

A. They have the same mass number.
B. They have different numbers of protons.
C. They have different numbers of neutrons.
D. They have the same number of neutrons.

3. How does the beta decay of a nucleus cause the nucleus to change? SPS3a

A. The number of protons increases.
B. The number of neutrons increases.
C. The number of protons decreases.
D. The number of protons plus the number of neutrons decreases.

Use the illustration below to answer questions 4 and 5.



Helium-3 Helium-4

4. What does the illustration show? SPS1a

A. nuclear fusion **C.** isotopes
B. nuclear decay **D.** half-lives

5. Which is a TRUE statement about the two nuclei? SPS1a

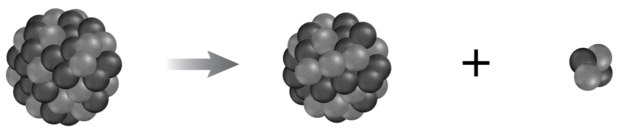
A. They have the same atomic number.
B. They have the same mass number.
C. They have different numbers of electrons.
D. They have different numbers of protons.

6. What is the atomic number of a nucleus equal to? SPS1a

A. the number of neutrons
B. the number of protons
C. the number of neutrons and protons
D. the number of neutrons minus the number of protons

Use the illustration below to answer questions 7 and 8.

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



7. What process is shown by this illustration?

A. nuclear fusion **C.** transmutation
B. chain reaction **D.** beta decay SPS3a

8. How do the total charge and total mass number of the products compare to the charge and mass number of the polonium nucleus? SPS3a

A. The charges are equal but the mass numbers are not equal.
B. The mass numbers are equal but the charges are not equal.
C. Neither the mass numbers or the charges are equal
D. The mass numbers and charges are equal.

9. Radioactive isotopes of which element are used to study the brain? SCSh9c

A. uranium **C.** carbon
B. fluorine **D.** lead

Test-Taking Tip

Understand the Question Be sure you understand the question before you read the answer choices. Make special note of words like NOT or EXCEPT. Read and consider all the answer choices before you mark your answer sheet.

Part 2 Short Response/Grid In

Record your answers on the answer sheet provided by your teacher or on a sheet of paper.

10. What process contributes the most to the background radiation received by a person in the United States?

11. Explain why alpha particles tend to produce more ions than beta particles or gamma rays when they pass through matter.

Use the table below to answer questions 12–14.

Half-Lives of Isotopes	
Isotope	**Half-life**
Carbon-14	5,730 years
Potassium-40	1.28 billion years
Iodine-131	8.04 days
Radon-222	4 days

12. Calculate how much of an 80 g sample of carbon-14 will be left after 17,190 years.

13. Potassium-40 decays to argon-40. What is the age of a rock in which 87.5 percent of the atoms are argon-40?

14. A sample containing which radioactive isotope will have one-eighth of the isotope left after 24 days?

15. Explain how control rods are able to control a chain reaction.

16. Describe the sequence of events that must occur for a nuclear chain reaction to occur.

17. A radioactive tracer with a half-life of 2 h is used to study the accumulation of a compound in the kidneys. Explain whether this study could be done over a 24-h period.

18. When the boron isotope boron-10 is bombarded with neutrons, it absorbs a neutron, and then emits an alpha particle. Identify the isotope that is formed in this process.

Part 3 Open Ended

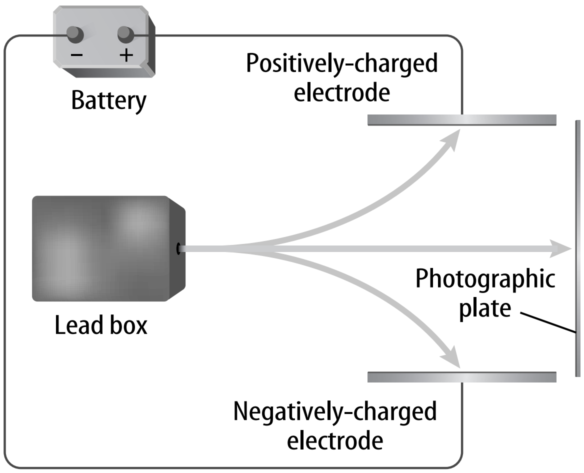
Record your answers on a sheet of paper.

19. Compare the strength of the strong force on a proton and the strength of the electric force on a proton in a small nucleus and a large nucleus.

20. Explain how the alpha particles emitted by the decay of the radioactive isotope americium-241 in a smoke detector produce an electric current between the charged plates of the smoke detector.

21. The geothermal heat that flows from inside Earth is produced by the decay of radioactive isotopes. Form a hypothesis about how the rate of geothermal heat production will change with time.

Use the illustration below to answer questions 22 and 23.



22. In the figure above, nuclear radiation is escaping from a small hole in the lead box. Which type of nuclear radiation is deflected toward the positively-charged electrode, and why is this radiation deflected toward this electrode?

23. Explain why the radiation that struck the photographic plate was not deflected by the electrodes.