CHAPTER

8

Nuclear reactions are among the most powerful energy sources in nature.

Learning Expectations

By the end of this chapter, you will:

Relating Science to Technology, Society, and the Environment

- research and assess how the production of radio-pharmaceuticals and food irradiation affect society and the environment

Developing Skills of Investigation and Communication

- use appropriate terminology related to energy transformations, including *fission* and *fusion*
- compare and contrast the input energy, useful output energy, and efficiency of energy generation methods, including nuclear fission and nuclear fusion
- investigate the relationship between conservation of mass and conservation of energy, and solve problems using mass–energy equivalence

Understanding Basic Concepts

- describe and compare nuclear fission and nuclear fusion
- identify and describe the structure of nuclear isotopes
- compare the characteristics of alpha particles, beta particles, and gamma rays
- explain the half-life of a radioisotope
- describe applications and consequences of radioactive decay
- explain the energy transformations that occur within a nuclear power plant

In a nuclear reaction, the nucleus of one atom collides with the nucleus of another atom, releasing energy and producing atoms of a different type. Nuclear reactions generate the light and heat of the stars. Almost all of the chemical elements were made in nuclear reactions in stars or supernovas.

Nuclear reactions are so powerful that they have revolutionized our technologies for generating electricity, diagnosing illness, and making war. Nuclear reactions power nuclear reactors, create medical images, and are the basic reactions in atomic and hydrogen bombs.

Some substances undergo nuclear reactions spontaneously, giving off radiation in the process. Cobalt-60 emits radiation energetic enough to kill cancer cells, sterilize medical equipment, and find microscopic flaws in solid steel. Figure 8.1 shows samples of cobalt-60 submersed in deep water, which cools the radioactive material and acts as a radiation shield.

Our awe (and fear) of all things nuclear has become a part of popular culture — Peter Parker becomes Spider-Man after being bitten by a radioactive spider, and Godzilla's size and heat-ray breath are mutations caused by radiation. Nuclear reactions are indeed dangerous, but with care they can be controlled and used to provide great benefits.

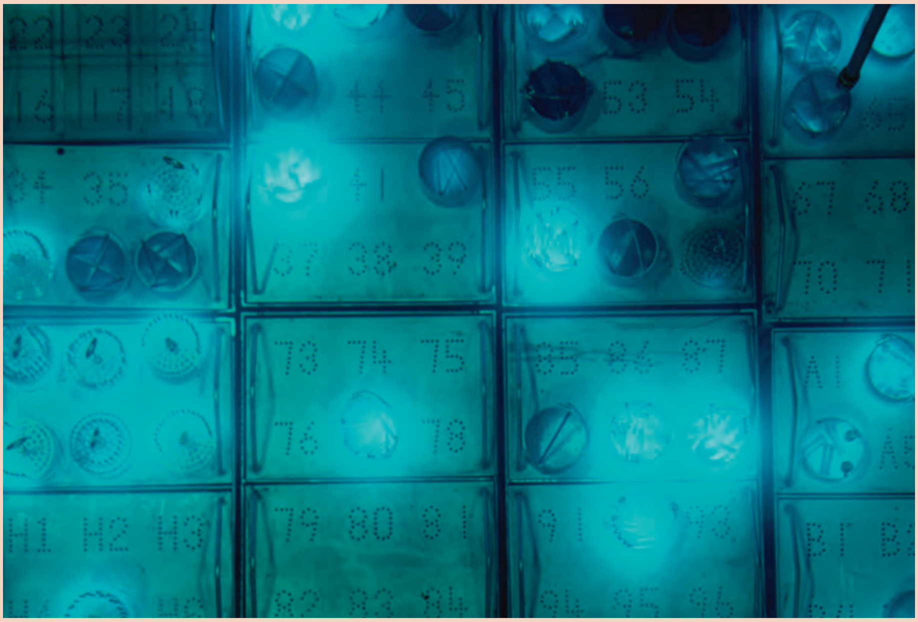


Figure 8.1 Cobalt-60 is a radioactive material used as a gamma-ray source for cancer therapy and food irradiation. The blue glow in the photograph is called Cerenkov radiation; it shows there is energy coming from the cobalt-60 sample. When a cobalt-60 nucleus decays, nuclear energy is transformed into kinetic energy of charged particles. When these particles enter the water of the storage tank, they quickly slow down. Their energy is transformed predominantly into ultraviolet and blue light. The gamma rays produced in the decay are invisible, but their energy can destroy living cells.

8.1 The Nucleus and Radioactive Decay

Section Summary

- The nucleus of an atom is made of protons and neutrons.
- Isotopes of a given element have different numbers of neutrons.
- Radiation is the transfer of energy as waves or fast-moving particles.
- Unstable nuclei decay by emitting nuclear radiation.
- Alpha, beta, and gamma decays are three common types of radioactive decay.
- The half-life of a radioactive isotope characterizes its rate of decay.
- Archaeological and geological objects can be dated using radioactive isotopes.

Inside the Atom

An **atom** is the smallest part of an element, such as hydrogen or helium, that has all of the element's properties. As shown in Figure 8.2, at the centre of the atom is a tiny **nucleus** made up of even tinier particles called **protons** and **neutrons** bound tightly together. Protons are positively charged and neutrons have no charge. Since both protons and neutrons exist in the nucleus, they are both referred to as **nucleons**. The nucleus is surrounded by even tinier **electrons** that occupy cloud-like energy levels. Electrons are negatively charged.

Most of the atom is empty space. The average diameter of an atom is about 1×10^{-10} m. The nucleus is 10 000 times smaller than the atom, and nucleons are about one-tenth the size of the nucleus. Electrons are at least 100 times smaller than a nucleon.

Table 8.1 on the next page shows the sizes of an atom and its parts. The diagrams in the table are not to scale. If you drew a scale model and made the atom 1 km in diameter, the protons and neutrons would be 1 cm wide, and the electrons would be the diameter of a hair.

About 99.9 percent of the mass of an atom is found in its extremely dense nucleus. A proton and a neutron have almost the same mass; a neutron's mass is slightly larger. An electron's mass is almost 2000 times less than the mass of a proton or neutron.

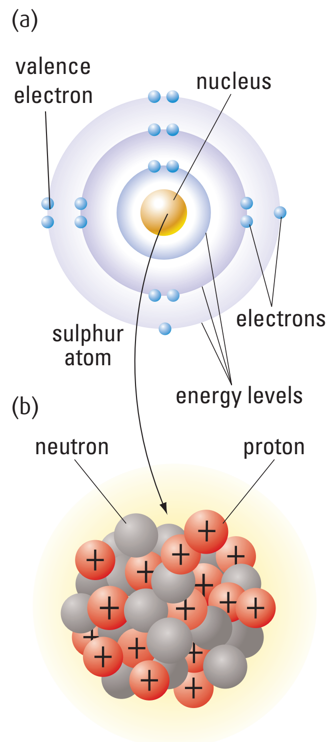


Figure 8.2 (a) A Bohr diagram of ordinary sulphur, which contains 16 protons, 16 neutrons, and 16 electrons (b) A diagram of the nucleus of a sulphur atom

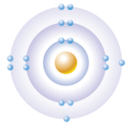
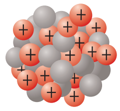
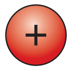
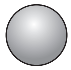
Charges on Particles

Protons and electrons carry an electric charge. In atomic physics, the amount of charge carried by a proton (1.602×10^{-19} coulombs) is used as the unit of charge, so a proton has a charge of $+1$. A neutron has no charge. An electron carries a charge of -1.

An electron's charge is equal in magnitude but opposite in sign to a proton's charge. Particles whose charges have opposite signs attract one another. Particles whose charges have the same sign repel one another.

When the number of protons in the nucleus of an atom is the same as the number of electrons outside the nucleus, the atom is electrically neutral, and it is called a **neutral atom**.

Table 8.1 The Sizes of an Atom and Its Parts

Part of Atom	Model	Diameter in Atoms	Diameter (m)	Mass (kg)
Atom		1	1×10^{-10} to 5×10^{-10}	1.67×10^{-27} to 4.52×10^{-25}
Nucleus		$\frac{1}{10\,000}$	10^{-14}	varies; similar to mass range of atom
Proton or neutron	 	$\frac{1}{100\,000}$	10^{-15}	proton: $1.672\,622 \times 10^{-27}$ neutron: $1.674\,927 \times 10^{-27}$
Electron		$\frac{1}{100\,000\,000}$	10^{-18}	$9.109\,383 \times 10^{-31}$

PHYSICS INSIGHT

Antihydrogen was first made in 1995 at LEAR at CERN. Presently the Large Hadron Collider at CERN collides beams of protons and antiprotons to create a host of subatomic particles.

Antiparticles

Every particle has a corresponding antiparticle; for example, the antiparticles of a proton, neutron, and electron are an antiproton, antineutron, and **positron**, respectively. Except for having the opposite electric charge, a particle and its antiparticle are identical; for example, an electron and a positron have the same mass, but a positron has a positive electric charge (+1). When a particle and its antiparticle meet, they annihilate each other into pure energy.

An antiparticle is denoted by adding a bar over the particle's symbol; for example, p for a proton and $\overline{\mathrm{p}}$ for an antiproton.

Antimatter is a form of matter composed only of antiparticles.

Energy Levels and Excited States

A Bohr diagram such as the one shown on the previous page in Figure 8.2(a) shows the possible **energy levels** for the electrons in a given atom. Energy levels exist around the nucleus and contain electrons. A higher level means a higher energy state. Each energy level has a maximum number of electrons it can hold.

The Bohr model is useful for visualizing energy levels. However, electrons do not actually circle the nucleus in spherical orbits. Instead, an electron has a set of probabilities for its position in a given energy state. This set of probabilities is called an **electron cloud**. Different electrons in the same energy state in an atom have different probability clouds. Figure 8.3 shows a few of these different cloud shapes.

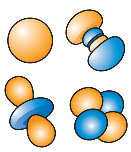


Figure 8.3 Depictions of electron clouds within an atom

Electrons can gain or lose energy by absorbing or emitting **photons**, which are particles of electromagnetic radiation. When an electron gains energy, it moves to a higher energy state. It may even break free of the atom. When an electron loses energy, it drops to a lower energy state.

The arrangement of electrons in an atom that gives the lowest total electron energy is called the atom's **ground state**. Atoms are normally found in their ground state.

An atom that has more energy than its ground state energy is in an **excited state**. An atom does not stay in an excited state indefinitely. Eventually, it emits radiation and makes a transition to either a lower-energy excited state, or directly to its ground state.

Ions

The electrons in an atom's highest energy level are called **valence electrons**. For example, the sulphur atom in Figure 8.2(a) has six valence electrons. Valence electrons are less tightly bound to the atom than electrons at lower energy levels and are easily removed.

Each energy level can hold only a certain number of electrons. Atoms whose highest energy level is full are the least chemically reactive. Atoms with just one or two valence electrons, or atoms whose highest energy level needs only one or two electrons to be full, are highly reactive.

When an atom loses one or more electrons, the number of positively charged protons in the nucleus exceeds the number of negatively charged electrons surrounding the nucleus. The atom becomes positively charged; it has become a positive **ion** of the same element (Figure 8.4).

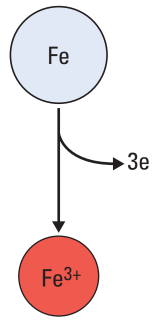


Figure 8.4 When an iron atom loses three electrons, it becomes an ion with a charge of +3.

Similarly, a negative ion is an atom that has gained electrons and become negatively charged. The process of removing electrons from an atom or adding electrons to an atom is called **ionization**.

Concept Check

1. What is a neutral atom?
2. Explain the difference between an atom in its ground state and in an excited state.
3. What is the difference between an atom and an ion?

Interactions Between Particles

Four fundamental interactions can occur between the particles in an atom: gravitation, electromagnetism, the strong interaction, and the weak interaction (also known as the strong and weak nuclear forces).

Gravitation is the means by which objects with mass attract one another. Gravitation is by far the weakest of the four fundamental interactions. Its effects are significant only when it acts between massive objects, and it plays almost no role at the atomic level.

Electromagnetism acts between electrically charged particles, either attracting or repelling the particles on which it acts. The magnetic and electrostatic forces produce the electromagnetic interaction. It is electromagnetism that binds negatively charged electrons to the positively charged protons in the nucleus to form atoms.

Protons are all positively charged, so when they are close together, they repel one another. The **strong interaction** is a powerful attractive force that is much stronger than the electrostatic force. The strong interaction is strong enough to overwhelm the repulsive electromagnetic force and bind nucleons together to form the nucleus.

The strong interaction acts between pairs of neutrons, pairs of protons, or a neutron and a proton. It has a very short range, about a femtometre (1 fm $= 1.0 \times 10^{-15}$ m). This is less than the diameter of the nucleus. At greater distances, the strong force is practically unobservable. Electrons do not feel the strong force.

The **weak interaction** is responsible for processes in which one particle changes into another type of particle.

Atomic Number and Atomic Mass

PHYSICS•SOURCE

Suggested Activity

- C13 Quick Lab Activity Overview on page 258

A hydrogen nucleus is a single proton. The nuclei of the atoms of all the other elements contain both protons and neutrons.

Although neutrons have no charge, they help to hold the nucleus together. Neutrons add to the strong interaction without adding to the repulsive electrostatic force of the positively charged protons. Most atoms have at least as many neutrons as protons. In general, the more protons there are in the nucleus, the higher the proportion of neutrons that are needed to hold the nucleus together.

The number of protons in a nucleus tells you which element the atom is. For example, if an atom has six protons, it is a carbon atom, no matter how many neutrons it has. Atoms of a given element always have the same number of protons, and atoms with the same number of protons are always the same element.

Three numbers describe the composition of a nucleus:

Atomic number, *Z*: the number of protons in a nucleus
Neutron number, *N*: the number of neutrons in the nucleus
Atomic mass number, *A*: the number of nucleons in the nucleus, $Z + N$

A specific atom is often indicated using the notation ${}^{A}_{Z}\mathrm{X}$, where X is the symbol for the element. This notation shows the composition of the atom's nucleus. For example, for a carbon atom with 6 protons and 6 neutrons, $Z = 6$, $N = 6$, and $A = 6 + 6 = 12$. The notation for this carbon atom is ${}^{12}_{6}\mathrm{C}$.

Example 8.1

How many neutrons are contained in the nucleus of this gold atom: ${}^{197}_{79}\mathrm{Au}$?

Given
$Z = 79$
$A = 197$

Required
neutron number (N)

Analysis and Solution
Since $A = Z + N$

$$N = A - Z = 197 - 79 = 118$$

Paraphrase
There are 118 neutrons in a nucleus of ${}^{197}_{79}\mathrm{Au}$.

Practice Problems

1. How many neutrons are in a nucleus of ${}^{24}_{12}\mathrm{Mg}$?
2. Find the atomic mass number for a uranium atom that contains 92 protons and 146 neutrons.
3. Write the nuclear notation for the atom with $Z = 26$ and $N = 30$.

Answers

1. 12 neutrons
2. 238
3. ${}^{56}_{26}\mathrm{Fe}$

Atomic Mass Units

The **atomic mass unit (u)** is often used for calculations involving nuclei and subatomic particles (1 u = 1.660 539 $\times$ 10^{-27} kg, exactly one-twelfth of the mass of the carbon-12 atom). Table 8.2 lists the masses of the electron and nucleons in atomic mass units.

Table 8.2 Masses of Subatomic Particles

Particle	Mass (u)
Electron	5.485 799 $\times$ 10^{-4}
Proton	1.007 276
Neutron	1.008 665

Isotopes

Isotopes are forms of an element that have the same number of protons (*Z*) but different numbers of neutrons (*N*). Many elements have two or more isotopes. For example, isotopes of the element hydrogen include hydrogen ($^{1}_{1}H$), deuterium ($^{2}_{1}H$), and tritium ($^{3}_{1}H$) (Figure 8.5).

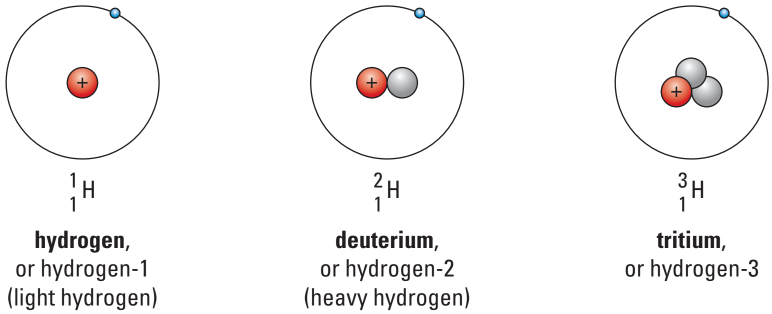


Figure 8.5 There are three naturally occurring isotopes for $Z = 1$. They are commonly known as hydrogen, deuterium, and tritium.

Specific isotopes are usually indicated by the element name and the atomic mass number. For example, carbon-12 is another way of writing $^{12}_{6}C$. For a particular element, one or two of the isotopes are usually more abundant; for example, hydrogen-1, carbon-12, and oxygen-16 are the most abundant isotopes of hydrogen, carbon, and oxygen.

Since the isotopes of an element all have the same number of protons and electrons, they have almost identical chemical properties. However, the physical properties of isotopes of an element can differ dramatically. Because the isotopes of an element each have a different number of neutrons, their masses are different. Varying the mass of an atom changes the mass of the compounds it forms and changes properties such as density, specific heat capacity, and the temperatures of phase transitions.

Figure 8.6 shows the information given for an element on the periodic table. Note that the atomic mass is not the atomic mass number. It is the average atomic mass (in u) of the common isotopes of the element.

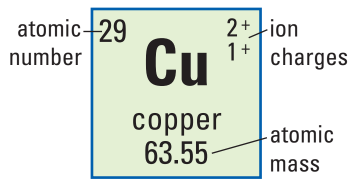


Figure 8.6 Information on the periodic table shows that an atom of the element copper (Cu) has 29 protons and an atomic mass of 63.55 u, and forms ions with charges of +1 and +2.

You can see on a periodic table that as the atomic mass of the elements increases, the ratio of neutrons to protons increases. Uranium has the largest naturally occurring nucleus, with 92 protons and over 140 neutrons.

Also note that when an ion forms, one or more electrons are gained (or lost), but neither *Z* nor *N* changes. So all the ions of an element have the same atomic number *Z* and the same atomic mass number *A*. In contrast, isotopes of an element all have the same *Z*, but their *N* differs.

The various isotopes of an element have very different stability. Certain combinations of neutrons and protons seem to work best to balance the interactions in a nucleus. The nuclei of some isotopes are very **stable**, remaining in the same form (with the same *Z* and *N*) forever.

A nucleus is **unstable** if it has too few or too many neutrons; the atom can exist for a while, but sooner or later it will begin to break up. If a nucleus has more than 83 protons, no number of neutrons can hold it together forever.

Concept Check

1. What interaction holds the nucleons together in the nucleus?
2. Explain why $A = Z + N$.
3. How do the nuclei $^{12}_{6}C$, $^{13}_{6}C$, and $^{14}_{6}C$ differ? How are they the same?

Radiation

Radiation is the emission of energy in the form of waves or fast-moving particles. The energy carried by radiation can be transferred to matter.

A common type of radiation is electromagnetic waves. As shown in Figure 8.7, the type of electromagnetic radiation is determined by its wavelength or frequency. Radio waves and microwaves increase the temperature of atoms or molecules, while radiation in or near the visible spectrum excites electrons up to higher energy levels. The higher the frequency of a wave, the more energy it carries. The very high-frequency X-rays and gamma rays have so much energy that they are often described as particles of electromagnetic energy, or photons.

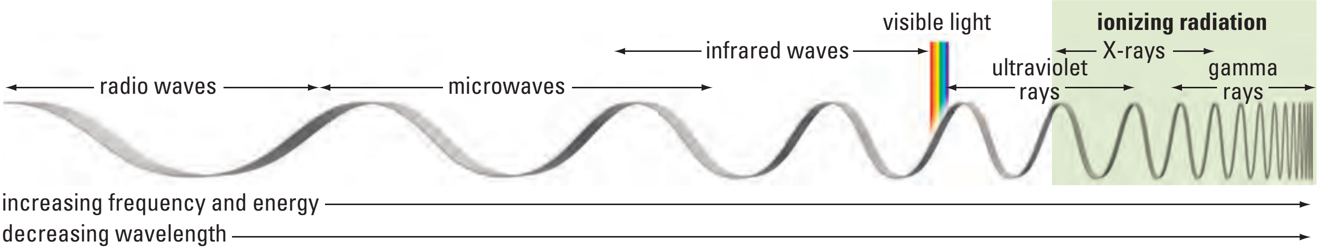


Figure 8.7 Electromagnetic radiation ranges from low-frequency radio waves to high-energy X-rays and gamma rays that can ionize the material through which they pass.

Ionizing Radiation

Ionizing radiation consists of waves or particles that carry enough energy to remove an electron from an atom or molecule, turning it into a positive ion. The negatively charged electrons and positively charged ions created by ionizing radiation can cause cell damage, or alter the bonds in a strand of DNA (Figure 8.8), causing problems if the cell reproduces. The same process allows us to use, ionizing radiation to kill cancer cells.

Visible light, microwaves, and radio waves are not ionizing. At low intensity they do not cause cell damage, but there is energy transferred — that is why radios and microwave ovens work. X-rays and gamma rays are ionizing radiation — they can harm tissue and must be used with care.

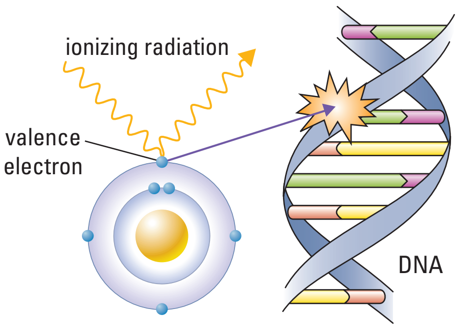


Figure 8.8 Ionizing radiation is very dangerous: it can penetrate human tissue and damage DNA.

Nuclear Radiation

Nuclear radiation is ionizing radiation emitted from the nucleus of an atom. An unstable nucleus spontaneously emits (sends out) particles and electromagnetic radiation, transforming an atom of one type into an atom of a different type. This phenomenon is called **radioactivity**, and the process is called **radioactive decay**, or nuclear decay. A substance is **radioactive** if it emits nuclear radiation. Radioactivity can change some isotopes into other isotopes, some elements into different elements, and even a single particle into two particles.

The common isotopes of lighter elements (elements with relatively low atomic mass) are not radioactive. The nuclei of these atoms have been the same since before Earth formed. In contrast, many of the heavier elements (for example, uranium, thorium, radium, and polonium) have isotopes that are radioactive. For example, if radium atoms decay, they become atoms of the lighter element radon.

There are three common forms of nuclear radiation. **Alpha** radiation is a stream of fast-moving helium nuclei. **Beta** radiation is a stream of fast-moving electrons. **Gamma** radiation is electromagnetic radiation of extremely high frequency — its energy is so high that it is better described as a photon, or particle of radiant energy. Gamma radiation is often emitted together with alpha and beta radiation.

Background Radiation

Everyone on Earth is exposed to ionizing radiation from natural sources at all times. This is called **natural background radiation**.

All animals have small amounts of radioactive isotopes such as potassium-40 and carbon-14 inside their bodies from interacting with the environment. Some rocks and minerals, such as uranium, emit radiation, which is absorbed by the soil and then by the plants we eat. Buildings made of brick and stone emit some radiation. Radon gas can diffuse out of the ground to mix with the air we breathe.

Some radiation also comes from cosmic rays. Cosmic rays are charged particles and gamma rays that reach Earth's surface from nuclear processes in stars and galaxies.

Human activity has added to **background radiation**. Tobacco smoke emits radiation (Figure 8.9). Medical and dental X-rays and gamma rays used in diagnostic imaging are a source. Some television and computer screens emit ionizing radiation. The strontium-90 from nuclear bombs and reactors has been absorbed into teeth, bones, and bone marrow. Tritium, a by-product in nuclear power plants, finds its way into water and milk.

Our bodies are equipped to repair damage from radiation, but all radiation, no matter how small the dose, increases the risk of damage and mutations to DNA in living things. The risks rise with cumulative exposure. Doctors, nurses, and technicians who work with radioactive materials are at greater risk because of their more frequent exposure, as are flight crews, who are exposed to higher levels of solar and cosmic radiation.

Figure 8.9 The tobacco leaves used in making cigarettes contain radioactive material, particularly lead-210 and polonium-210. These radioactive isotopes can accumulate into very high concentrations in the lungs of smokers. Burning tobacco releases hundreds of chemicals, many of which may play a role in lung cancer, but radiation is believed to be responsible for up to 90 percent of tobacco-related cancer.

Concept Check

1. Is all radiation dangerous? Explain.
2. Why is ionizing radiation dangerous?
3. Which type or types of electromagnetic radiation are ionizing? Which type or types of nuclear radiation are electromagnetic?

Types of Radioactive Decay

In radioactive decay, a **parent nucleus** (the initial nucleus) spontaneously decays into a **daughter nucleus**. Radioactive decay was the first observed example of transmutation. **Transmutation** is the process in which the atomic number of a nucleus changes, which converts it to a different chemical element.

Alpha Decay

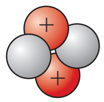


Figure 8.10 An alpha particle is a helium nucleus.

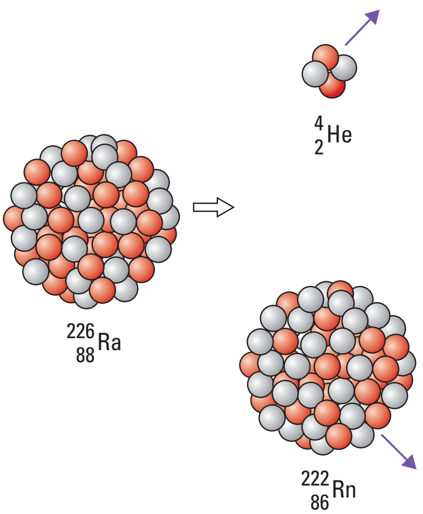


Figure 8.11 During alpha decay, a nucleus emits an alpha particle and becomes a nucleus with two fewer protons and two fewer neutrons.

An **alpha particle (α)** is a helium nucleus, a cluster of two protons and two neutrons (Figure 8.10). A helium nucleus is bound together much more tightly than other light nuclei and is highly stable.

Unstable nuclei may decay by spontaneously emitting alpha particles, as shown in Figure 8.11. The strong interaction that holds the protons and neutrons together in the nucleus is much stronger than the electromagnetic interaction that pushes the protons apart, but it has a much shorter range, less than the diameters of larger nuclei. Protons and neutrons move around inside a nucleus. If two protons and two neutrons (an alpha particle) move outside the influence of the strong interaction, they will break free of the nucleus, carrying kinetic energy away with them. This process, in which an alpha particle is emitted from a larger parent nucleus, is called **alpha decay**, or α decay.

There is a greater chance of alpha decay in a large nucleus than in a small one. With a few exceptions, alpha decay is only observed in nuclei with more than 82 protons.

A decay process can be analyzed in a fashion similar to writing out a chemical reaction. An alpha particle is written as α, $^{4}_{2}\alpha$, or $^{4}_{2}He$. The emission of an alpha particle removes 2 protons and 2 neutrons from the parent nucleus, so the atomic number of the atom decreases by 2 and the atomic mass number decreases by 4. The alpha decay process can be written:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

where X is the chemical symbol for the parent nucleus and Y is the symbol for the daughter nucleus. Here, A is the atomic mass number of the parent nucleus and Z is its atomic number. For example, alpha decay of uranium-238 produces thorium-234:

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

In this example, uranium-238 is the parent nucleus and thorium-234 is the daughter nucleus. The uranium atom transmutes into an atom of thorium, a different element. Thorium is also radioactive. It will decay and become another element, and so on, until eventually a stable element, in this case lead, results.

An alpha particle has a mass of about 4 u, which is relatively large for a subatomic particle. Because of its large mass, an alpha particle doesn't travel very fast. An alpha particle carries a charge of +2 from its two protons, and because of this large charge, an alpha particle ionizes other atoms strongly. Alpha particles lose energy quickly, and they can travel only a few centimetres in air, but an alpha particle can ionize thousands of air particles before it slows down. Alpha particles are easily stopped by anything solid — they can be absorbed by tissue paper or human skin. They can penetrate a few cells deep into softer tissues inside the body.

Concept Check

1. What is radioactive decay?
2. Explain the following terms: parent nucleus, daughter nucleus.
3. In alpha decay, both atomic mass number and charge are conserved. Explain.

Example 8.2

Predict the daughter nucleus that results from alpha decay of radium-226.

Analysis and Solution

From a periodic table, you can see that the atomic number of radium is 88. So, the parent nucleus is ${}^{226}_{88}\text{Ra}$. Since the alpha particle carries away four nucleons, including two protons, A decreases by 4 and Z decreases by 2:

$$ {}^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\alpha $$

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

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

The periodic table shows that the element with $Z = 86$ is radon (Rn).

Paraphrase

The daughter nucleus from the alpha decay of radium-226 is radon-222.

Practice Problems

Write the alpha decay process for these elements, and name the parent and daughter nuclei.

1. ${}^{230}_{90}\text{Th}$
2. ${}^{238}_{92}\text{U}$
3. ${}^{214}_{84}\text{Po}$

Answers

1. ${}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$, thorium-230, radium-226
2. ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$, uranium-238, thorium-234
3. ${}^{214}_{84}\text{Po} \rightarrow {}^{210}_{82}\text{Pb} + {}^{4}_{2}\alpha$, polonium-214, lead-210

Beta Decay

Sometimes when a nucleus has too many neutrons to be stable, the nucleus decays by emitting an electron. A neutron in the nucleus transforms into a proton, an electron, and an antineutrino. This process is called **beta decay** (or β decay) (Figure 8.12).

Neutrinos (ν) are produced in a variety of interactions, especially in particle decays. They have no charge and about one ten-millionth the mass of an electron. They rarely interact with matter. The symbol for a neutrino, ν, is the lowercase Greek letter "nu." An **antineutrino ($\bar{\nu}$)** is the antiparticle of a neutrino.

Since a neutron becomes a proton in beta decay, the atomic number of the parent nucleus increases by 1, and it transmutes into a new element, with different properties. But the atomic mass number does not change.

In all types of radioactive decay, charge is conserved: the total electric charge before and after the decay is the same. In beta decay, charge is conserved because the charge on the new proton balances the charge on the electron emitted from the nucleus. This electron is often called a **beta particle (β)**, shown in Figure 8.13. A beta particle is written as ${}^{0}_{-1}\beta$ in equations.

In general, beta decay can be written as:

$$ {}^{A}_{Z}\text{X} \rightarrow {}_{Z+1}^{A}\text{Y} + {}^{0}_{-1}\beta + \bar{\nu} $$

where X is the chemical symbol for the parent nucleus and Y is the symbol for the daughter nucleus. Here, A is the atomic mass number of the parent nucleus and Z is its atomic number.

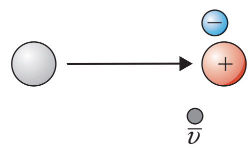


Figure 8.12 During beta decay, a neutron changes into a proton, an electron, and an antineutrino. The weak interaction is responsible for beta decay.

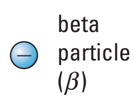


Figure 8.13 A beta particle is an electron.

PHYSICS•SOURCE

Explore More

How do astrophysicists use beta decay to model the universe during its first few minutes?

For example, beta decay of thallium-208 produces lead, and the equation is:

$$^{208}_{81}\text{Tl} \rightarrow {}^{208}_{82}\text{Pb} + {}^{0}_{-1}\beta + \bar{\upsilon}$$

After beta decay, a nucleus may still be unstable, and it may undergo alpha decay.

High-energy beta particles travel extremely fast, close to the speed of light. Compared to alpha particles, beta particles have very little mass. Because they carry a charge, beta particles can ionize atoms, but they are not as strongly ionizing as alpha particles. Beta particles given off by different radioactive materials vary in energy, but most can be easily stopped by a thin sheet of metal or plastic. Table 8.3 compares the properties of alpha and beta particles.

Table 8.3 Properties of Alpha and Beta Particles

Particle	Mass (u)	Charge	Speed ($c = 3 \times 10^8$ m/s)	Penetration of Tissue	Ionizing Ability
Alpha (α or ${}^{4}_{2}\text{He}$)	4.003	+2	slow $\sim(0.01-0.1)c$	about 5 cm in air, cannot penetrate skin	high
Beta (${}^{0}_{-1}\beta$ or ${}^{0}_{+1}\beta$)	0.0005	−1	fast $\sim(0.6-0.99)c$	about 30–50 cm in air, penetrates about 1 cm into body	moderate

Concept Check

1. What is a beta particle? Where does it come from?
2. Why does atomic number increase by one in beta decay?
3. Compare the ability of alpha and beta particles to penetrate tissue.

Example 8.3

Find the daughter nucleus for the beta decay of thorium-234.

Analysis and Solution

A periodic table shows that the atomic number for thorium is 90: the parent nucleus is ${}^{234}_{90}\text{Th}$.

In beta decay, one neutron becomes a proton. So, the value of Z increases by 1 and A remains the same. The other products are a beta particle and an antineutrino:

$$^{A}_{Z}\text{X} \rightarrow {}_{Z+1}^{A}\text{Y} + {}^{0}_{-1}\beta + \bar{\upsilon}$$

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Y} + {}^{0}_{-1}\beta + \bar{\upsilon}$$

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta + \bar{\upsilon}$$

The element with atomic number 91 is protactinium.

Paraphrase

The daughter nucleus from the beta decay of thorium-234 is protactinium-234.

Practice Problems

Write the beta decay process for these elements, and name the parent and daughter nuclei.

1. ${}^{228}_{88}\text{Ra}$
2. ${}^{212}_{82}\text{Pb}$
3. ${}^{61}_{26}\text{Fe}$

Answers

1. ${}^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta + \bar{\upsilon}$, radium-228, actinium-228
2. ${}^{212}_{82}\text{Pb} \rightarrow {}^{212}_{83}\text{Bi} + {}^{0}_{-1}\beta + \bar{\upsilon}$, lead-212, bismuth-212
3. ${}^{61}_{26}\text{Fe} \rightarrow {}^{61}_{27}\text{Co} + {}^{0}_{-1}\beta + \bar{\upsilon}$, iron-61, cobalt-61

Gamma Decay

When an electron moves to a lower atomic energy level, a photon of light is emitted. A similar phenomenon occurs in the nucleus. Nucleons usually exist at their lowest possible energy level. Sometimes, often following alpha or beta decay, the nucleons are in a disturbed arrangement, or an excited state. They rearrange into a lower energy state by emitting electromagnetic radiation. The difference between energy levels in the nucleus is much greater than between energy levels of electrons in the atom, so the nucleus emits a high-energy gamma photon instead of a photon of light. This nuclear process, in which the nucleons settle into a lower energy state and a photon is emitted, is called **gamma decay** (γ decay).

Gamma decay does not change the atomic number or the atomic mass number of the parent nucleus, so the nucleus does not change into another element or isotope as in alpha and beta decay. Gamma decay can be written as:

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

where * indicates an excited state of the nucleus and $^{0}_{0}\gamma$ represents a gamma ray.

Often, alpha or beta decay leaves the daughter nucleus in a highly excited state. The excited nucleus then makes a transition to its ground state, emitting a gamma ray as it does so. For example, when the beta decay of boron-12 produces carbon-12, the carbon nucleus is highly excited and quickly emits a gamma ray:

$$^{12}_{5}B \rightarrow {}^{12}_{6}C^* + {}^{0}_{-1}\beta + \bar{v}$$

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

A gamma ray is a high-energy photon. Photons have no mass and no charge. A gamma ray is also a high-frequency electromagnetic wave. Like all electromagnetic radiation, gamma rays travel at the speed of light. Since matter is mostly empty space, gamma rays pass through atoms with little chance of being deflected or absorbed. When a photon does encounter an atomic particle, it transfers energy to the particle.

Gamma rays do not ionize atoms directly, but they can cause atoms to emit other particles that will cause ionization. Their high energies, ranging from 10^{-16} J to 10^{-13} J, give them high penetrating power. Gamma rays can travel about 2 km in air, and can penetrate all the way through the human body. A large amount of dense mass, such as lead or other metal, concrete, or soil, is required to reduce their intensity significantly. Figure 8.14 compares the penetrating power of alpha, beta, and gamma radiation.

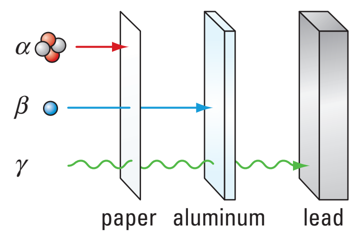


Figure 8.14 Penetrating power of alpha, beta, and gamma radiation

Half-Life

It is impossible to predict when an individual atom of a radioactive isotope, or **radioisotope**, will decay. Depending on the isotope, the atom could decay in a fraction of a second or not for billions of years. However, we can accurately predict the way a large amount of a given isotope will decay.

Half-life is the time required for one-half of the radioactive nuclei in a sample to decay. The half-life for a given isotope is always the same; it doesn't depend on the size of the sample or on how long the sample has been in existence.

PHYSICS•SOURCE

Explore More

What sort of visual organization can display all of the elements and their isotopes and give you a sense of their stability?

PHYSICS•SOURCE

Suggested Activity

- C14 Quick Lab Activity Overview on page 258

Thinking about half-life can help you appreciate just how many atoms there are in a visible chunk of material. Uranium-238 decays extremely slowly: it has a half-life of about 4.5 billion years. About 1 kg of uranium will emit about 3 million alpha particles per second. Yet only half of that 1 kg of uranium will be gone in 4.5 billion years.

Iodine-131 has a half-life of about 8 days. The graph below shows how much of a 2.0-μg sample of iodine-131 remains after various times (Figure 8.15). During the first 8 days, 1.0 μg of the iodine will decay so after 8 days 1.0 μg will remain. During the next 8 days, half of the remaining 1.0 μg will decay so there will be 0.5 μg left after 16 days. However much iodine there is at any moment, half of it will decay in the next 8 days. Notice that the graph gradually levels off — there is always a bit of iodine remaining, though there may be too little to measure accurately.

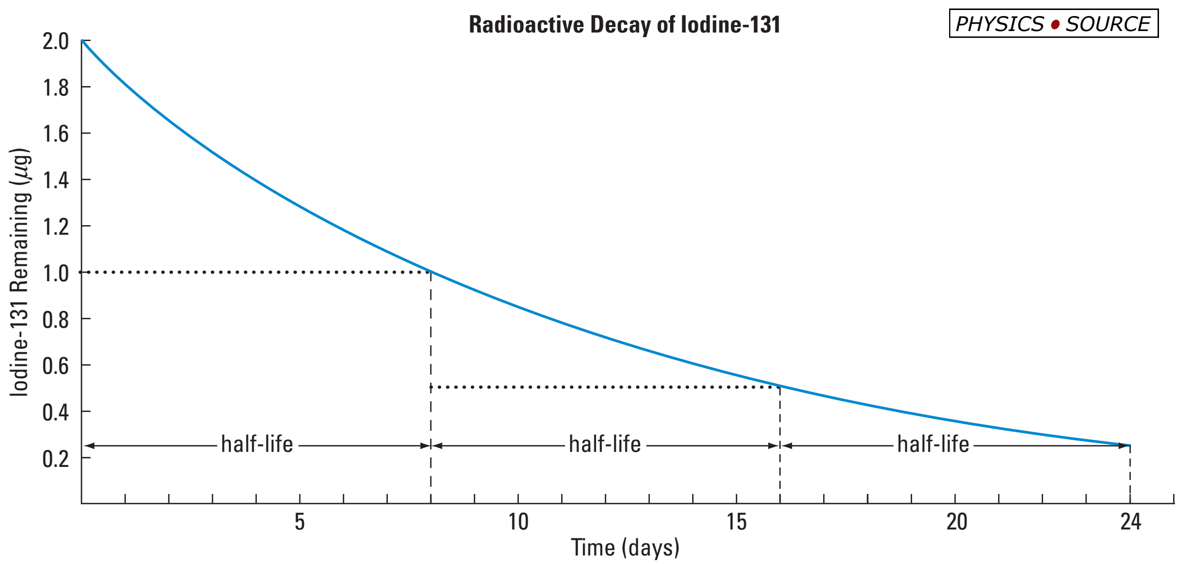


Figure 8.15 A graph showing the radioactive decay of a 2.0-μg sample of iodine-131

Concept Check

Use Figure 8.15 to answer the following questions about a 2.0-μg sample of iodine.

1. Estimate the times at which 1.6 μg and 0.8 μg of the sample of iodine remain. Explain why these times differ by 8 days.
2. How much of the iodine-131 sample will decay between 16 days and 24 days?
3. Estimate when there will be less than 0.1 μg of iodine-131 left.

PHYSICS INSIGHT

Only one part in a thousand of a radioactive sample remains after 10 half-lives, and one part in a million remains after 20 half-lives. A sample with 10^{21} atoms would need about 70 half-lives to decay to a single atom.

The main characteristic of radioactive decay is the large number of decays (per unit time) initially when there is plenty of radioactive material; at first the sample is quite radioactive. After a few half-lives, there are fewer decays (per unit time) because there is less material to decay; now the sample is much less radioactive. For example, molybdenum-99 is an unstable isotope with medical uses. It has a half-life of 66 hours. A freshly created sample of moly-99 is highly radioactive and useful for about a week. After that, its radioactivity falls too low to be effective.

Radioactive Dating

Nearly 6000 years ago, First Nations people of southwestern Alberta devised an ingenious method for hunting bison. By setting up barriers along a carefully chosen route, they funnelled herds of bison toward a hidden cliff and then drove them over the edge. There were about 150 buffalo jumps in Alberta. The most famous, Head-Smashed-In Buffalo Jump, is now a United Nations World Heritage Site. By carefully measuring the ratio of carbon-12 to carbon-14 in bones found at this site, archaeologists have shown that the site was used continuously for over 5500 years.

High-energy neutrons in cosmic rays produce the radioisotope carbon-14 by colliding with nitrogen atoms high in Earth's atmosphere:

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

This carbon-14 diffuses throughout the atmosphere. Some of it is absorbed by plants and enters the food chain. Carbon molecules are the basis of life on Earth, and a small proportion of the carbon content of all plants and animals is carbon-14.

Carbon-14 undergoes beta decay to form nitrogen-14, whereas carbon-12 is completely stable. When living matter dies, it stops absorbing carbon, and the proportion of carbon-14 gradually decreases as it decays (Figure 8.16). The half-life of carbon-14 is 5730 years.

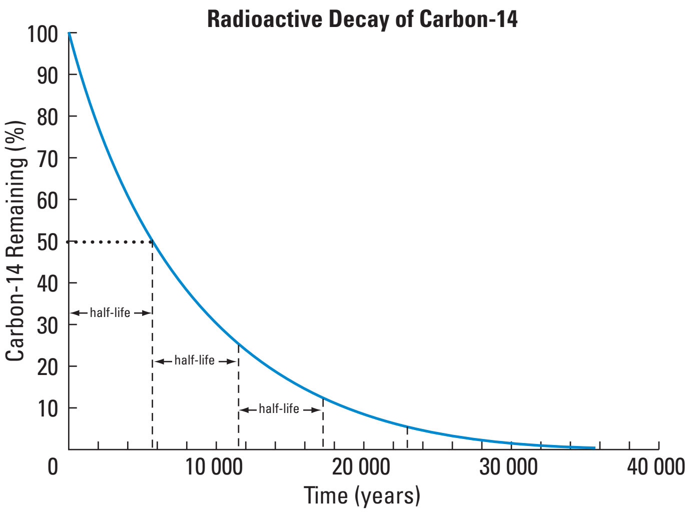


Figure 8.16 Carbon-14 content as a function of the age of an artefact

For archaeologists, bone fragments and other artefacts found at buffalo jumps are like clocks that show when the living matter stopped absorbing carbon. Suppose, for example, that the portion of carbon-14 in a bone fragment is about 40 percent of that in living tissue. Assuming that the ratio of carbon-14 to carbon-12 in the atmosphere is the same now as when the bison was alive, you can see from the graph that the age of the bone fragment is roughly 1.3 half-lives, or $1.3 \times 5730 \approx 7500$ years. Accurate estimates require more detailed calculations that take into account factors such as variations in the proportion of carbon-14 in the atmosphere through the ages.

Geologists estimate the age of rocks and geological formations using calculations based on isotopes with much longer half-lives. Useful decays include uranium-235 into lead-207, uranium-238 into lead-206, rubidium-87 into strontium-87, and calcium-40 into argon-40. Radioactive dating is one method that scientists use to estimate the age of Earth and the Solar System.

PHYSICS•SOURCE

Take It Further

Archaeometry is the application of physical science and engineering techniques to archaeological materials. The development of carbon dating in the 1950s was the start of modern archaeometry. Today, mass spectroscopy, fission-track dating, luminescence dating, potassium-argon dating, and dendrochronology are just a few of the tools in an archaeometrist's bag. Investigate how one of these techniques has been used to solve a dating, provenance, or authenticity puzzle. Organize your findings into a short presentation.

C13 Quick Lab

PHYSICS•SOURCE

Building Nuclei

Purpose

To investigate the composition of several nuclei and to visualize some nuclear reactions

Activity Overview

In this activity you will build models of nuclei out of coloured clay protons and neutrons. You will compare several isotopes of hydrogen and helium. Using your nuclei, you will model the reactions that create carbon-14 in the atmosphere and its later decay into nitrogen-14. You will also mimic fusion reactions of the early universe and the Sun.

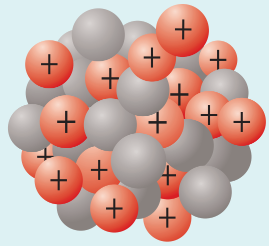


Figure 8.17 A model of a nucleus

Prelab Questions

Consider the questions below before beginning this activity.

1. Which subatomic particles make up atoms? Which subatomic particles make up nuclei?

2. Compare the size of an atom to the size of its nucleus.

C14 Quick Lab

PHYSICS•SOURCE

Half-Life of Dice

Purpose

To determine the half-life of a virtual radioactive isotope

Activity Overview

In this activity you will model the radioactive decay of a nucleus. You and your classmates will each represent individual nuclei. Your fate is determined by the roll of a die. As the simulation proceeds, you will record how many nuclei have or haven't decayed. When all of the nuclei have decayed, you will plot a decay graph and determine the half-life of the virtual isotope you modelled.

Prelab Questions

Consider the questions below before beginning this activity.

1. How many faces are there on an ordinary die? What is the probability of rolling a "6" with one roll of an ordinary die?

2. How many times do you think you will roll an ordinary die before you get a "6"? Explain.

Figure 8.18 Dice can be used to simulate the random decay of radioisotopes.

8.1 Check and Reflect

Key Concept Review

1. Describe how electrons, protons, and neutrons are arranged in an atom.
2. (a) How does the size of a nucleus compare to that of its atom?
   (b) How does the mass of a nucleus compare to that of its atom?
3. Explain the meaning of the following quantities: Z, N, and A.
4. What does it mean for two atoms to be different isotopes of the same element?
5. State Z, N, and A for the following nuclei:
   (a) ${}^{60}_{28}\text{Ni}$ (b) ${}^{40}_{19}\text{K}$ (c) ${}^{208}_{82}\text{Pb}$
6. Write the names of the following isotopes in nuclear notation:
   (a) carbon-14 (b) iron-56 (c) uranium-238
7. Write the names of the following isotopes in nuclear notation:
   (a) $Z = 80$, $N = 121$ (b) $Z = 14$, $N = 16$
8. (a) What is ionizing radiation?
   (b) Why is ionizing radiation dangerous?
9. Name three types of nuclear radiation.
10. Compare the masses and charges of the three types of nuclear radiation.
11. (a) Which type of nuclear radiation has the greatest penetration ability?
    (b) Which type of nuclear radiation has the greatest ionization ability?
12. What happens to the parent nucleus during each of the three types of radioactive decay?
13. What is nuclear transmutation? Illustrate your answer with an example.
14. A radioactive isotope has a half-life of 2.5 days. You start with 100 μg of the material. How much will be left after 2.5 days, 5.0 days, and 10 days?

Connect Your Understanding

15. Compare the structure of an atom to the structure of a nucleus. Include a description of the particles involved, the energy levels, and the type of radiation emitted during a change of energy level.
16. Explain why the value of Z gives the charge on the nucleus. What are the units of measurement?
17. Explain why the value of A is very close to the mass of the nucleus. What are the units of measurement?
18. Give two reasons why the atomic mass is usually not exactly the whole number A. Which element is the exception?
19. Identify the types of the following decays:
    (a) ${}^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra}^* + {}^{4}_{2}\alpha$
    (b) ${}^{228}_{88}\text{Ra}^* \rightarrow {}^{228}_{88}\text{Ra} + {}^{0}_{0}\gamma$
    (c) ${}^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta + \bar{v}$
    (d) ${}^{243}_{95}\text{Am} \rightarrow {}^{239}_{93}\text{Np} + {}^{4}_{2}\alpha$
    (e) ${}^{39}_{18}\text{Ar} \rightarrow {}^{39}_{19}\text{K} + {}^{0}_{-1}\beta + \bar{v}$
20. Write the equation for the alpha decay of
    (a) ${}^{64}_{29}\text{Cu}$ (b) ${}^{239}_{94}\text{Pu}$ (c) ${}^{8}_{4}\text{Be}$
21. Write the equation for the beta decay of
    (a) ${}^{19}_{8}\text{O}$ (b) ${}^{35}_{16}\text{S}$ (c) ${}^{131}_{53}\text{I}$
22. Explain how naturally occurring radioactive decays deep inside Earth produce geothermal energy.
23. Uranium-235 has a much shorter half-life than uranium-238. These two isotopes occurred in equal abundance when Earth was formed. Compare their relative abundance today.
24. A radioactive tracer used in a medical test has a half-life of 2.4 h. What fraction of this tracer will remain after 12 h?
25. An archaeologist finds a wooden arrow shaft with a proportion of carbon-14 that is about 25 percent of that in a living tree. Estimate the age of the arrow. Hint: Refer to Figure 8.16 on page 257.
26. Describe some sources of ionizing radiation in your daily life. Which exposures do you think are likely to affect your health in time? Justify your response.

Reflection

27. There are strong similarities between alpha and beta decay. Describe how you would help a fellow student understand the differences between these decays. For example, would you draw a sketch of the nucleus? Would you work with reaction equations?

For more questions, go to PHYSICS•SOURCE

8.2 Fission, Fusion, and Other Nuclear Processes

Section Summary

- Einstein's formula $E = mc^2$ is used to calculate mass-energy equivalence.
- Nuclear reactions conserve mass-energy, charge, and nucleon number.
- In nuclear fission, a massive nucleus splits into two or more lighter nuclei.
- Nuclear reactors use fission to produce energy.
- In nuclear fusion, two lighter nuclei join to form a more massive nucleus.
- Fusion reactions produce the Sun's energy.
- Nuclear technologies produce radioisotopes for medical use.

Figure 8.19 Fusion reactions power the stars. Almost all of the chemical elements were made in fusion reactions in stars or supernovas. A supernova explosion created the Cygnus Loop nebula (above).

Fusion means the merging together of different elements to make a new element. Rock and roll originally developed as a fusion of blues, gospel, and country music. Fusion cuisine blends ingredients from various cuisines in a single dish. In **nuclear fusion**, two nuclei combine to form a more massive nucleus.

Fission means breaking something up into parts. In **nuclear fission**, a massive nucleus splits into two lighter nuclei. Alpha decay is a type of fission. The atomic bombs dropped on Hiroshima and Nagasaki at the end of World War II were fission bombs, and nuclear reactors are powered by fission.

In both nuclear fusion and nuclear fission, energy is released. The energy released by fission is a million times greater than that released in chemical reactions, and the energy released by fusion is greater still (Figure 8.19). Where this immense energy comes from involves the relationship between mass and energy represented by the famous equation $E = mc^2$.

Mass–Energy Equivalence

In the nucleus the strong interaction binds the nucleons tightly together. When nucleons are bound together by the strong interaction, their energy is reduced — they go into a low-energy state. You saw a hint of this with gamma decay. If a nucleus is left in an excited state by an alpha or beta decay, its nucleons are loosely bound. By emitting energy as a gamma ray, the nucleus settles into a lower-energy, more stable state.

The **binding energy** of a nucleus is the energy required to break up the nucleus into its individual protons and neutrons. The bigger a nucleus is, the greater its binding energy.

The law of conservation of mass says that mass is never created or destroyed. Therefore, it is surprising that accurate measurements show that a bit of mass disappears when nuclei form from their individual nucleons: the mass of a nucleus is less than the sum of the masses of the individual protons and neutrons that make up the nucleus. This missing mass is called the **mass defect** (Figure 8.20).

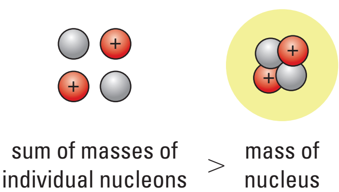


Figure 8.20 The individual protons and neutrons that make up a nucleus have more mass than the nucleus itself.

Unravelling the mystery of the mass defect required an idea from special relativity. In 1905, physicist Albert Einstein (1879–1955) was thinking about how particles moving close to the speed of light act as if they are more massive as their energy increases. He suggested that particles have an energy equivalent to their mass and proposed his famous formula:

$$E = mc^2$$

where E is energy in J, m is mass in kg, and c is the speed of light in a vacuum in m/s. Later, other physicists began to interpret the equation $E = mc^2$ as showing that energy and mass are truly equivalent and interchangeable.

Mass can be transformed into energy and energy can be transformed into mass. This explains the mass defect: when nucleons are bound together, their energy is reduced, so their mass is also reduced. The binding energy of a nucleus is the mass-energy equivalent of its mass defect.

Although we now know that mass is a form of energy, scientists cannot yet explain why a particle has a certain mass. Physicists have theorized that there is a particle, or set of particles, that interacts with other particles to give them mass. They call this particle the Higgs boson. The Higgs boson has not been observed, but physicists from around the world are working together to find it, using the gigantic particle accelerators at the Large Hadron Collider near Geneva and at Fermilab in Illinois.

The equation $E = mc^2$ also shows that a small amount of mass can be converted into a huge amount of energy: 1 g of mass is equivalent to about 25 GW·h, about 10 times the electrical energy generated by Niagara Falls in an hour. This means that nuclear reactions can produce very large amounts of energy from very small amounts of fuel. Just as the discovery that thermal energy could be transferred as heat led to new technologies that transformed heat into mechanical energy, the discovery of the **mass-energy equivalence** led to nuclear technologies that transform mass into energy.

PHYSICS•SOURCE

Explore More

How does the binding energy of a nucleus vary with the size of the nucleus?

PHYSICS INSIGHT

Any attractive force can create stable bound states. The definition of binding energy is the same: the amount of energy needed to take the bound structure apart. Chemical molecular bonds form due to attractive forces between atoms and energy is needed to break the bonds of stable molecules. The Solar System formed under the attractive force of gravity. The more tightly bound a system is, the more energy is required to free its pieces.

Example 8.4

Determine the mass-energy equivalent of 1.0 kg of gasoline.

Given

$m = 1.0$ kg

Required

mass-energy equivalent (E)

Analysis and Solution

Use Einstein's relation $E = mc^2$.

$c = 2.998 \times 10^8$ m/s

$$\begin{aligned} E &= mc^2 \\ &= (1.0\ \text{kg})\left(2.998 \times 10^8\ \frac{\text{m}}{\text{s}}\right)^2 \\ &= 8.988 \times 10^{16}\ \text{J} \\ &= 9.0 \times 10^{16}\ \text{J} \end{aligned}$$

Paraphrase

The mass-energy equivalent of 1.0 kg of gasoline is about 9.0×10^{16} J. This is enormous compared with the chemical energy stored in 1.0 kg of gasoline, about 4.8×10^7 J.

Practice Problems

1. What is the mass-energy equivalent of the mass of one electron?
2. What is the mass-energy equivalent of a 1500-kg car?
3. How much mass must be converted to energy for a nuclear reaction to release 3.6×10^6 J (1 kW·h) of thermal energy?

Answers

1. 8.188×10^{-14} J
2. 1.348×10^{20} J
3. 4.0×10^{-11} kg

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Suggested Activity

- C15 Quick Lab Activity Overview on page 268

Gasoline is called a fuel because its chemical energy can be transformed into thermal energy by combustion. Its energy content is 4.8×10^7 J/kg. Similarly, uranium and hydrogen are considered nuclear fuels because their nuclear energy can be transformed into thermal energy by nuclear reactions such as fission and fusion. The energy content of nuclear fuels is vastly higher than the energy content of chemical fuels. The fission of uranium releases about 8×10^{13} J/kg and the fusion of hydrogen releases about 7×10^{14} J/kg. These values depend somewhat on the particular fission or fusion reaction followed.

Conservation Laws for Nuclear Reactions

Einstein's theory of relativity united the concepts of conservation of mass and conservation of energy. Particles that have mass can be converted to energy, and energy can be converted to particles that have mass, but the sum of energy and the energy equivalent of mass must be constant.

Consider the process of beta decay. The mass of a neutron is slightly greater than the combined mass of a proton, an electron, and an antineutrino. The missing mass is transformed into the kinetic energy of the electron and the antineutrino emitted from the nucleus. Similarly in alpha decay, the mass of the parent nucleus is greater than the mass of the daughter nucleus and the alpha particle — the missing mass becomes kinetic energy of the products.

In all nuclear reactions, mass-energy, charge, and nucleon number are conserved. These three conservation laws are listed in Table 8.4.

Table 8.4 Conservation Rules for Nuclear Reactions

Conservation Law	Statement	Relation
Mass-energy	The total mass-energy is constant throughout a reaction.	The energy released in a reaction is $\Delta E = (m_{\text{initial}} - m_{\text{final}})c^2$
Charge	The total charge is constant throughout a reaction. The charge of all of the protons and all of the electrons together doesn't change.	The total value of Z is the same before and after the reaction.
Nucleon number	The total number of neutrons and protons remains constant. The total mass is very nearly constant.	The total value of A is the same before and after the reaction.

Concept Check

1. Define the binding energy of a nucleus. How is it related to the nuclear mass defect?
2. What is mass-energy equivalence?
3. Describe three quantities that are conserved in nuclear reactions.

Nuclear Fission

Fission is the reaction in which a massive nucleus splits into two or more lighter nuclei. This is the reaction used in nuclear reactors to produce thermal energy and then electricity.

Spontaneous Fission

Spontaneous fission is a form of nuclear fission characteristic of very heavy isotopes. It is only seen in nuclei with atomic mass numbers above 230 (elements near thorium). Spontaneous fission occurs when an unstable isotope splits into two or more smaller nuclei without any external interaction. Figure 8.21 shows one of the ways that uranium-235 can split into two lighter nuclei:

$${}^{235}_{92}\text{U} \rightarrow {}^{140}_{54}\text{Xe} + {}^{95}_{38}\text{Sr}$$

The lighter nuclei that result when a nucleus undergoes fission are called the **fission products**. In the reaction above, the fission products are xenon-140 and strontium-95.

A large amount of energy is released when a nucleus is broken apart. This energy is the difference between the binding energy of the original nucleus and the binding energies of the fission products. The liberated energy takes the form of kinetic energy in the fission products.

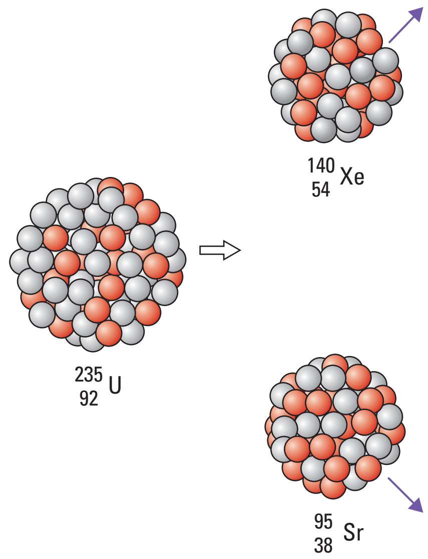

Figure 8.21 Spontaneous fission of uranium-235

Induced Fission

A fission reaction can also be started by a slowly moving neutron. Neutrons are usually found only in atomic nuclei. A **free neutron** is a neutron that is not bound in an atomic nucleus. A free neutron is not stable; it beta decays with a half-life of about 10 min. While a neutron is not a chemical element, it does have a nuclear notation: it is denoted by ${}^{1}_{0}\text{n}$ to show that it has a mass number of 1 and an atomic number of 0.

Because they have no charge, free neutrons travel easily through the electron clouds of atoms and may collide with atomic nuclei, inducing fission. In **induced fission**, a nucleus absorbs a neutron, forming a highly unstable isotope that breaks up almost instantly into two lighter nuclei, one of which is often nearly half the mass of the other. This reaction also emits two or more neutrons, which carry off most of the large amount of energy liberated by the reaction. Gamma rays are also commonly produced.

Figure 8.22 shows one of the ways that uranium-235 can split into two lighter nuclei:

$${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

The fission products of this reaction are the two lighter nuclei and the three free neutrons. After fission, some of the fission products may undergo alpha, beta, or gamma decay.

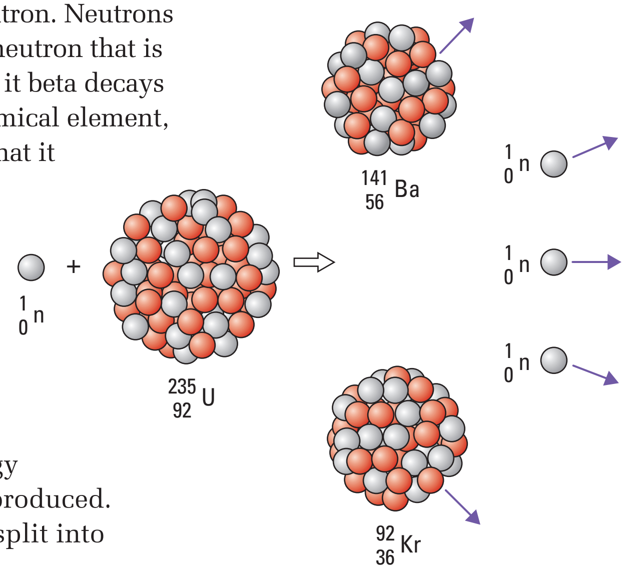

Figure 8.22 Absorbing a neutron causes uranium-235 to undergo fission.

PHYSICS • SOURCE

Radioactive Decay Series

The radiation danger of nuclear fission comes from the fission products. The neutrons and gamma rays pose a high immediate hazard. But it is the lighter fission-product nuclei that set up a series of reactions that may produce radiation for thousands of years.

Often, a radioactive nucleus will decay into a daughter nucleus that is itself radioactive. The daughter nucleus may then decay into yet another unstable nucleus. This process of successive decays continues until the nucleus becomes stable, with energy released at every step. Such a process is called a **radioactive decay series**.

PHYSICS INSIGHT

Alpha decay is a special case of fission in which a helium nucleus is one of the product nuclei. Since alpha decay was observed decades before other fission reactions, scientists usually treat it as a separate reaction.

The dots in Figure 8.23 represent nuclei that are part of the decay series for uranium-238. A decay series can have several branches that lead to the same final product. Figure 8.23 shows that $^{218}_{84}Po$ can transmute into $^{214}_{84}Po$ by three different combinations of decays. All of the intermediate isotopes in a decay series are unstable, but the degree of instability is different for each isotope. For example, $^{218}_{86}Rn$ usually lasts for only a fraction of a second, whereas $^{222}_{86}Rn$ takes several days to decay, and $^{230}_{90}Th$ takes thousands of years. Although not shown in Figure 8.23, many of the intermediate isotopes undergo gamma decay.

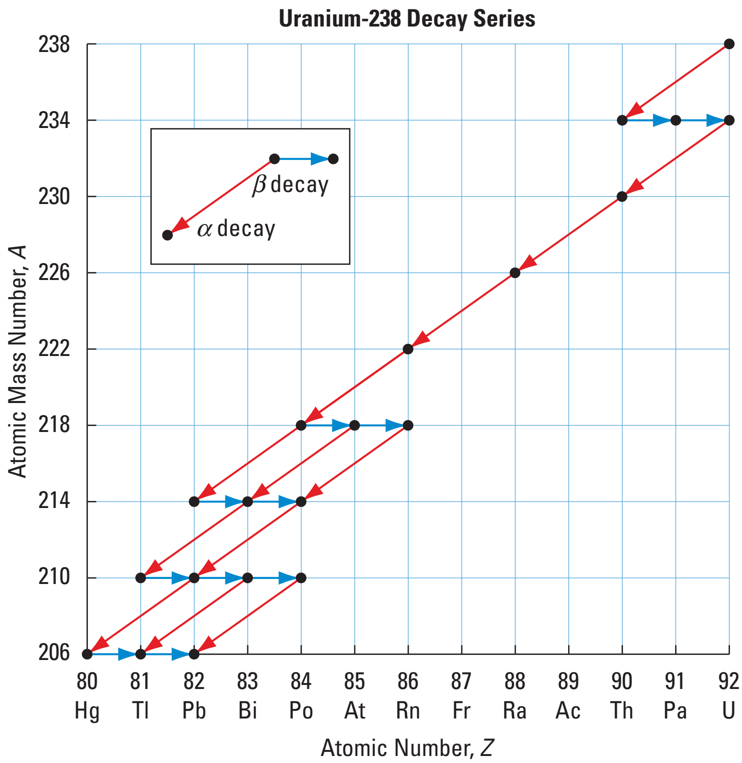

Figure 8.23 Uranium-238 undergoes many alpha and beta decays before reaching the stable isotope lead-206.

Only three decay series for the heavy isotopes are found in nature: the uranium-238, uranium-235, and thorium-232 series.

Nuclear fission produces nuclei that may be too short-lived to be found naturally on Earth. These nuclei are often the beginnings of radioactive decay series seen only in the fallout from nuclear bombs and in the waste from nuclear reactors. Some of the nuclei in these decay series are short-lived, and some last for many thousands of years. As a result, the remnants from nuclear bombs and nuclear reactors pose a radiation risk for a much longer time than the original fission process.

Concept Check

1. What is the difference between spontaneous and induced fission?
2. Consider $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$. Why are three neutrons produced?
3. Explain why uranium-235 can have a variety of fission products.

Example 8.5

Thorium-230 decays to polonium-218 by three alpha decays. Write the equations for the reactions. Use a periodic table.

Analysis and Solution

Write the alpha decay reaction for thorium-230 and identify the daughter nucleus:

$$^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\alpha$$
$$^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Y} + {}^{4}_{2}\alpha$$
$$^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$$

Write the alpha decay reaction for radium-226 and identify the daughter nucleus:

$$^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\alpha$$
$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Y} + {}^{4}_{2}\alpha$$
$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$$

Write the alpha decay reaction for radon-222:

$$^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\alpha$$
$$^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Y} + {}^{4}_{2}\alpha$$
$$^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\alpha$$

Paraphrase

The three reactions are: $^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$, $^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$, and $^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\alpha$

Practice Problems

Use a periodic table.

1. Uranium-235 decays by α decay, β decay, α decay, and then β decay. Write the equations for the reactions.
2. Americium-241 decays by α decay, α decay, and then β decay. State the intermediate isotopes and the final isotope in the decay series.
3. Lead-212 decays by β decay, β decay, and then α decay. State the intermediate isotopes and the final isotope in the decay series.

Answers

1. $^{235}_{92}\text{U} \rightarrow {}^{231}_{90}\text{Th} + {}^{4}_{2}\alpha$
   $^{231}_{90}\text{Th} \rightarrow {}^{231}_{91}\text{Pa} + {}^{0}_{-1}\beta + \bar{\upsilon}$,
   $^{231}_{91}\text{Pa} \rightarrow {}^{227}_{89}\text{Ac} + {}^{4}_{2}\alpha$,
   $^{227}_{89}\text{Ac} \rightarrow {}^{227}_{90}\text{Th} + {}^{0}_{-1}\beta + \bar{\upsilon}$
2. neptunium-237, protactinium-233, uranium-233
3. bismuth-212, polonium-212, lead-208

Nuclear Fusion

In nuclear fusion, smaller nuclei join together to form a larger nucleus. To do this, they must get close enough to feel the strong interaction. This is extremely difficult, because nuclei are positively charged and are repelled by the electromagnetic interaction. In nature, fusion happens in the centres of stars, where high temperatures give nuclei huge kinetic energy, resulting in tremendous collisions that push the nuclei close enough together to cause them to fuse. The nuclei must have enough kinetic energy to overcome the electrostatic repulsion between them. On Earth, fusion has been achieved in bombs, but sustained controlled fusion has not yet been achieved.

PHYSICS•SOURCE

Explore More

How did fusion create nuclei in the early universe? Where were the elements on Earth today formed?

The Proton-Proton Chain

Several different fusion reactions occur in stars. The dominant fusion reaction in stars the size of our Sun or smaller is the **proton-proton chain**. The Sun and smaller stars are made up mostly of hydrogen nuclei, which are protons. In the proton-proton chain reaction, four hydrogen nuclei interact to form a helium nucleus. First, two hydrogen nuclei combine to form deuterium (hydrogen-2), a positron (antielectron), and a neutrino. Next, another hydrogen nucleus combines with the deuterium nucleus to produce a helium-3 nucleus and a gamma ray. Then, two of the helium-3 nuclei combine to produce a helium-4 nucleus, two hydrogen nuclei, and a gamma ray. In the final step, annihilation of two positron-electron pairs occurs. Each annihilation produces a pair of gamma photons.

Energy is released in this fusion reaction, illustrated in Figure 8.24, because a helium atom has less mass than four hydrogen atoms. The difference in mass, though extremely small, represents a huge amount of energy (Table 8.5).

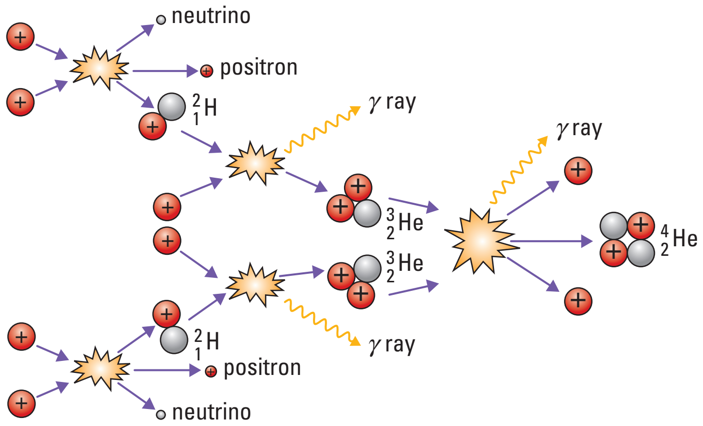

Figure 8.24 The proton-proton chain. Note that this diagram does not show step 4, annihilation of the two positrons by two electrons and the two resulting pairs of gamma rays.

Table 8.5 Steps in the Proton-Proton Chain

Step	Reaction	Energy Released ($\times 10^{-13}$ J)
1	$2\,^{1}_{1}\text{H} \rightarrow \,^{2}_{1}\text{H} + \,^{0}_{+1}\beta + v$ (twice)	0.67 (twice)
2	$^{1}_{1}\text{H} + \,^{2}_{1}\text{H} \rightarrow \,^{3}_{2}\text{He} + \gamma$ (twice)	8.78 (twice)
3	$2\,^{3}_{2}\text{He} \rightarrow \,^{4}_{2}\text{He} + 2\,^{1}_{1}\text{H} + \gamma$	20.56
4	$^{0}_{+1}\beta + \,^{0}_{-1}\beta \rightarrow 2\gamma$ (twice)	1.63 (twice)
Total	$4\,^{1}_{1}\text{H} \rightarrow \,^{4}_{2}\text{He} + 2\,^{0}_{+1}\beta + 2v + 7\gamma$	42.72

Concept Check

1. Why can fusion reactions occur only at extremely high temperatures?
2. Which fusion reaction occurs in stars similar to our Sun?
3. What are the products of the reaction in question 2?

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Suggested Activity

- C16 Decision-Making Analysis, Activity Overview on page 268

Other Nuclear Processes

Nuclear medicine is the use of radioactive isotopes in medicine. Radioactive isotopes used in medicine are called **radio-pharmaceuticals** or **medical isotopes**. Many modern medical isotopes are **artificial isotopes**; they do not occur in nature. Some methods used to create artificial isotopes are described below. Many other methods are under development.

Neutron Absorption

Cobalt-60 decays by beta decay followed by two gamma decays. Sources of gamma radiation are used in diagnostic imaging and in radiation therapy (Figure 8.25). A gamma source can be injected into the body, and its radiation produces pictures of specific areas. Due to its short half-life of 5.27 years, cobalt-60 is not found in nature. It must be produced artificially.

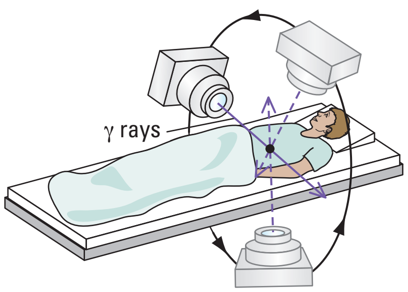

Figure 8.25 Cobalt-60 is an artificial isotope used in radiation therapy and industrial radiography.

Cobalt-60 is made by **neutron absorption**, in which a nucleus is hit with a slow-moving neutron that becomes part of the nucleus. Neutron absorption reactions can be written as:

$$^{A}_{Z}\text{X} + \,^{1}_{0}\text{n} \rightarrow \,^{A+1}_{Z}\text{X}$$

To make cobalt-60, naturally occurring cobalt-59 is placed in a source of neutrons, usually a nuclear reactor. The neutron absorption reaction is:

$$^{59}_{27}\text{Co} + \,^{1}_{0}\text{n} \rightarrow \,^{60}_{27}\text{Co}$$

A half-life of 5.27 years is long enough so that the cobalt-60 can be stored and shipped to hospitals and labs in relatively small amounts as needed.

Harvesting Fission Products

The products of fission in nuclear reactors are a source of both natural and artificial radioisotopes. For example, molybdenum-99, a radioisotope used in medical imaging, is a fission product of the nuclear reactor fuel uranium-235. Currently molybdenum-99 is made by placing uranium foil near a small reactor where neutrons can induce fission in the uranium-235. The foil can be harvested remotely and processed with solvents to separate out the molybdenum-99.

Radionuclide generators

Radioisotopes with a short half-life cannot be shipped over long distances. Hospitals need to be able to produce these radioisotopes on the spot. A **radionuclide generator** is a device used to extract a radioisotope from its parent isotope. For example, molybdenum-99 is the parent of technetium-99, which accounts for 80 percent of the radioisotopes used in nuclear medicine today. Molybdenum-99 has a half-life of 66 h and beta decays into technetium-99, whose half-life is only 6 h. The generator in which molybdenum-99 is delivered to medical centres is a glass vial stored in a lead pot. When needed, technetium-99 is washed out of the vial with a saline solution.

Exchange Reactions

Positron emission is a type of beta decay, sometimes referred to as beta plus ($\beta+$) decay. In beta plus decay, a proton in the nucleus transforms into a neutron, a positron (the antiparticle of an electron), and a neutrino. The positron is often called a beta plus particle and is written as ${}^{0}_{+1}\beta$. For example, beta plus decay of fluorine produces oxygen-18, and the equation is:

$${}^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{+1}\beta + v$$

The positrons emitted in beta plus decay are used in positron emission tomography (PET imaging), a type of medical imaging. Fluorine-18 is an important source of positrons for PET imaging.

Several **exchange reactions** (reactions with two reactants and two products) can be used to make fluorine-18. For example, a proton can be exchanged for a neutron, or a deuterium nucleus can be exchanged for an alpha particle:

$${}^{18}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n}$$
$${}^{20}_{10}\mathrm{Ne} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{4}_{2}\alpha$$

A **cyclotron** is a type of particle accelerator that can make beams of high-energy protons. These protons can be used to bombard nuclear targets to produce positron-emitting isotopes such as fluorine-18. The world's largest cyclotron is housed at TRIUMF (TRI University Meson Factory), located at the University of British Columbia in Vancouver.

Concept Check

1. What happens in a neutron absorption reaction?
2. How is cobalt-60 used in radiation therapy?
3. Why is molybdenum-99 an important medical isotope?

PHYSICS•SOURCE

Explore More

What happens in a nucleus when it undergoes beta plus (positron) decay?

PHYSICS•SOURCE

Explore More

What nuclear medicine research and innovative industrial partnership activities occur at TRIUMF in Vancouver?

PHYSICS•SOURCE

Take It Further

The experiments at the Large Hadron Collider at CERN are trying to unravel some of the remaining mysteries of mass and energy. The physicists hope to see the Higgs boson and explain the observed masses of subatomic particles. They are also looking for clues into the nature of dark matter and dark energy. Research one of the LHC experiments and prepare a poster explaining its purpose and its method.

C15 Quick Lab

PHYSICS•SOURCE

Energy Content of Nuclear and Chemical Fuels

Purpose

To compare the energy released in a variety of nuclear and chemical reactions

Activity Overview

In this activity, you will compare the energy available from a variety of chemical and nuclear fuels. The largest challenge for a consumer trying to understand reports about energy sources and energy consumption is the mixed usage of units of measurement. Here you will encounter energy measured in joules, calories, and kilowatt·hours. Quantities may be bush cords, litres, tonnes, or kilograms. You will make sense of it all by quoting energy contents in joules per kilogram.

Prelab Questions

Consider the questions below before beginning this activity.

1. List some common units for measuring energy.
2. List some common ways of measuring the quantity of a material.
3. List some common processes that produce thermal energy from potential energy.

Figure 8.26 Chemical energy in natural gas is transformed into thermal energy, light, and sound by a Bunsen burner. How much thermal energy is produced per kilogram of natural gas?

C16 Decision-Making Analysis

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REQUIRED SKILLS

- Gathering information
- Recording information sources

Shortage of Medical Isotopes

Issue

Who should be responsible for producing medical isotopes?

Activity Overview

Medical isotopes are used for the diagnosis and treatment of cancer. Due to their short half-lives, they can't be stockpiled and they can't be transported over long distances. Shortages of these critical drugs are common. What should government agencies, university research groups, and specialized production companies do to ensure a dependable supply of medical isotopes? Your task is to research the methods of production and the production shortage of medical isotopes. You will prepare a report summarizing options to ensure an appropriate supply of these materials and to recommend a course of action for Canada.

Prelab Questions

Consider the questions below before beginning this activity.

1. Describe how ionizing radiation can kill a cell. How can this be useful?
2. Describe some possible dangers of radioactive isotopes released into the atmosphere or the water table.

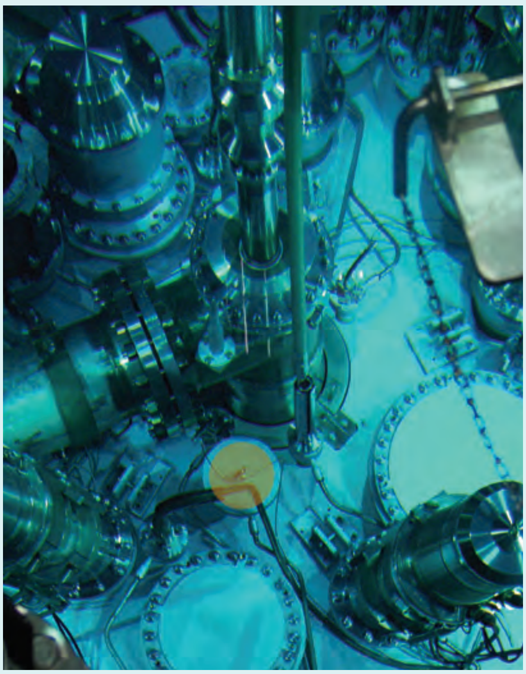


Figure 8.27 The reactor pool of FRM II, a research reactor in which molybdenum-99 will be produced

8.2 Check and Reflect

Key Concept Review

1. Calculate the energy equivalent of the mass of a proton.
2. Verify that the units of mc^2 simplify to the units of energy.
3. Give an example of mass transforming into energy.
4. List the three rules obeyed in all nuclear reactions.
5. Which of the following reactions satisfy the Z and A rules? Suggest a correction for the equations that violate a Z or A rule.
   (a) ${}^{235}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n}$
   (b) ${}^{227}_{89}\mathrm{Ac} \rightarrow {}^{227}_{90}\mathrm{Th} + {}^{0}_{-1}\beta + \bar{v}$
   (c) ${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{224}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha$
   (d) ${}^{6}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\mathrm{He}$
6. What is the difference between nuclear fission and nuclear fusion?
7. How do spontaneous and induced fission differ? How are they similar?
8. Write a balanced reaction for boron-10 absorbing a neutron and splitting into lithium-7 and an alpha particle.
9. What is a radioactive decay series?
10. Why is it hard to start a fusion reaction?
11. What are the reactants and the products of the fusion reaction in the Sun?
12. Describe three ways of producing radioisotopes.

Connect Your Understanding

13. Explain why the mass defect contradicts the law of conservation of mass.
14. How is conservation of atomic mass number similar to the law of conservation of mass?
15. Describe under what circumstances the law of conservation of mass is true. Under what circumstances do you need to use the extended law of conservation of mass-energy?
16. Molybdenum-99 is created in cyclotrons. It decays to make technetium-99, a medical tracer isotope. Write a possible decay equation.
17. An electron and positron (antielectron) collide and their mass is transformed into energy.
   (a) Calculate the energy released.
   (b) Calculate the energy released per kilogram of initial mass.
18. Bismuth-213 decays by alpha decay followed by two beta decays. Write the reaction equations for the series.
19. Tritium is made in a CANDU nuclear reactor when deuterium (hydrogen-2) absorbs a neutron. Write the reaction equation.
20. (a) Describe several ways that writing chemical and nuclear reactions are similar. Illustrate your answer with examples.
   (b) Suggest how you might use these similarities to help explain nuclear fission to a student who is having difficulty.
21. Describe three new nuclear reactions or processes you learned about in this section. Select one of these and explain how it can have a beneficial effect on society.

Reflection

22. What is one thing that surprised you about nuclear fission? Nuclear fusion?
23. Explain why it is important for you to learn about nuclear processes.

Question 16 Used in particle physics experiments, the cyclotron at TRIUMF also produces radioisotopes for medical use.

For more questions, go to PHYSICS•SOURCE

8.3 Nuclear Technologies

Section Summary

- Nuclear power is produced from controlled nuclear chain reactions.
- A nuclear chain reaction transforms nuclear energy into thermal energy.
- Nuclear power plants use this thermal energy to generate electricity.
- CANDU reactors use natural (unenriched) uranium for fuel, and heavy water for the moderator and coolant.
- Nuclear technologies are used in medicine and industry.
- All nuclear technologies involve risk and require rigorous safety protocols.

The idea of a nuclear chain reaction was first conceived by Hungarian physicist Leo Szilard (1898–1964) while on his way to work in London in 1933. When, in 1938, a successful nuclear fission experiment using uranium was conducted in Nazi Germany, Szilard and other physicists quickly realized that uranium could be used for enormously devastating bombs. Fearing that the Germans would develop such bombs, Szilárd asked his friend Albert Einstein to help him persuade American president Franklin Roosevelt that the United States should begin work immediately to develop nuclear weapons capability (Figure 8.28). Einstein was a pacifist, but he too feared that Hitler might be the first to develop a fission bomb. Einstein wrote to Roosevelt in 1939,

Figure 8.28 Physicist Leo Szilárd explained the dangers of nuclear chain reactions to Einstein.

> Some recent work by E. Fermi and L. Szilard… leads me to expect that… a nuclear chain reaction in a large mass of uranium, by which vast amounts of power… would be generated… could be achieved in the immediate future… extremely powerful bombs of a new type may thus be constructed …

Einstein recommended that Roosevelt "speed up the experimental work." In late 1941, work began that would evolve into the Manhattan Project that developed the first atomic bomb. Two atomic bombs were dropped on Japan at the end of World War II, causing enormous damage and the loss of from 150 000 to 250 000 lives. Numerous bombs were then tested until, in 1963, most countries agreed to stop testing nuclear weapons in the atmosphere, underwater, or in space.

Figure 8.29 A hydrogen test-bomb. The energy released in the first hydrogen bomb was about 12 TW·h, equivalent to the electrical energy generated in Ontario in about one month.

Nuclear Chain Reactions

A **nuclear chain reaction** is a series of nuclear fissions that starts with one fission reaction (often spontaneous) that produces free neutrons. These neutrons carry away the energy released by fission. What happens next depends on the number and kinetic energy of these neutrons. If enough neutrons are present, the fission reaction may spread to other nuclei, and more and more fission will occur, uncontrollably, at a faster and faster rate, releasing more and more energy, as it does in a nuclear bomb (Figures 8.29 and 8.30). If there are too few neutrons, a chain reaction will not start. **Nuclear power** is electricity produced from controlled nuclear chain reactions.

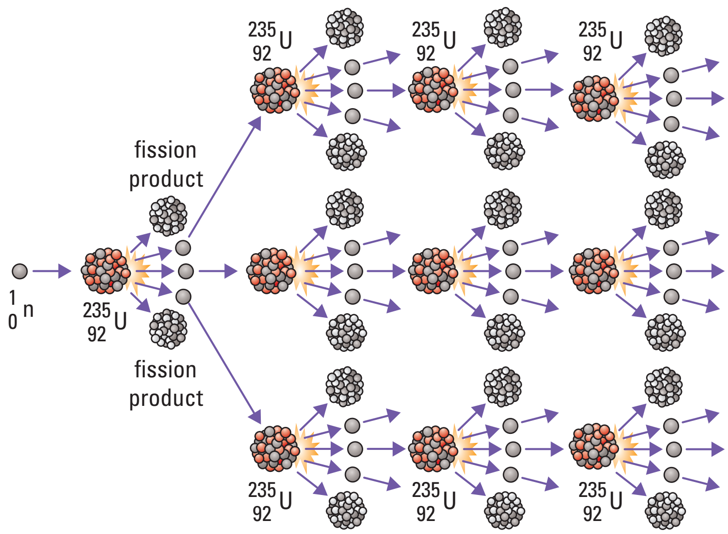


Figure 8.30 In a nuclear chain reaction, the neutrons from one fission reaction induce more fission reactions. If the chain reaction were not controlled, the third column in this diagram would actually have nine $^{235}_{92}$U and the fourth column would have twenty-seven $^{235}_{92}$U.

Thermonuclear Reactors

A **thermonuclear generating station** uses energy produced by fission in a thermonuclear reactor. A **nuclear reactor** is a device in which nuclear chain reactions are initiated and controlled. The nuclear reactions heat water to produce steam that is then used to generate electricity.

All reactor designs have the same basic components: fuel; mechanisms to control and moderate nuclear chain reactions; and a coolant, such as water, to carry the thermal energy produced to the boiler. As shown in Figure 8.31, the process is then the same as in any thermal power plant: the boiler boils water and produces steam that turns a turbine, that turns a generator, that transforms kinetic energy into electrical energy.

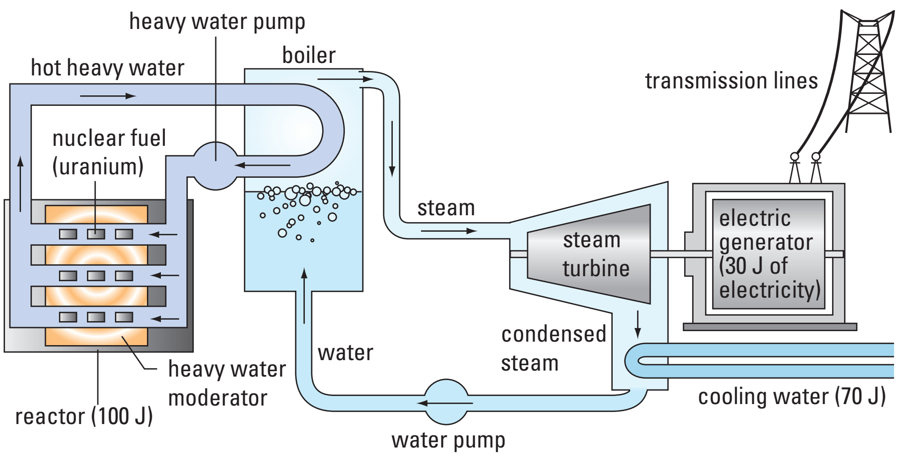


Figure 8.31 Simplified diagram of a thermonuclear generating station

Fuel Rods

Fissionable materials are those that can undergo nuclear fission. However, only some fissionable materials can start a nuclear chain reaction and keep it going. These are called **fissile** materials. For example, uranium-235 is fissile, but uranium-238 is merely fissionable. Nuclear fuel needs to be fissile. Uranium-235 is the only fissile isotope existing in nature.

Figure 8.32 A single nuclear fuel pellet can power an average home for six weeks.

Natural uranium is mostly uranium-238. It contains less than 1 percent uranium-235. The fuel for nuclear reactors usually requires a higher concentration of fissile material, so natural uranium is enriched using high-speed centrifuges to increase the concentration of uranium-235 to between 3 and 5 percent. Most reactor designs use **enriched uranium**. Because enriched uranium is also used in nuclear weapons, it must be rigorously controlled.

The enriched uranium is pressed into small pellets (Figure 8.32). The **fuel pellets** are dropped into hollow metal cylinders, called **fuel rods**, which are then grouped and inserted into the core of the reactor. The fission takes place in the fuel pellets.

Control Rods

In fission, a uranium nucleus absorbs a neutron and is then unstable. It splits into two lighter nuclei, releasing kinetic energy, gamma rays, and free neutrons, some of which may be absorbed by other uranium nuclei, causing further fission. In a **stable chain reaction**, each fission causes only one more fission. The central process in a nuclear reactor is setting up a stable chain reaction in the fuel.

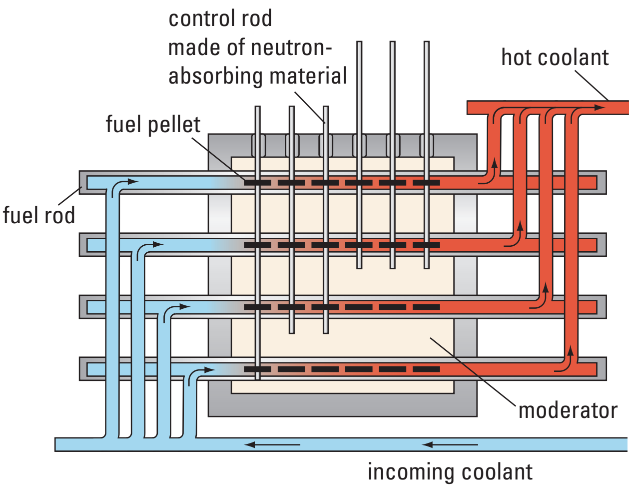


Figure 8.33 A nuclear reactor core

Control rods control the rate of fission in a reactor. They are made of an element that absorbs neutrons without undergoing fission, such as cadmium or boron. As shown in Figure 8.33, the control rods can be inserted into the reactor to absorb neutrons and slow down the chain reaction. When the rods are removed, the neutrons can move freely.

Fission produces a lot of thermal energy, increasing the temperature of the reactor. The kinetic energy of the fission products is transformed into thermal energy when these nuclei collide with others. The reactor absorbs some of the gamma rays emitted in fission, and their energy also becomes thermal energy. Radioactive decay of fission products and neutron absorption also produce some heat. The temperature in a reactor core is monitored carefully. If the core temperature begins to rise, the control rods are inserted to reduce the amount of fission.

As a safety measure, the control rods are held above and moved into the reactor by electromagnets. If there is a power outage in the plant, gravity will pull the rods down into the reactor and stop the fission process. Because there is no mechanical linkage moving the rods, there is no way the rods can get stuck above the reactor.

Moderator

Fast neutrons bounce right off most nuclei; they aren't absorbed and they don't cause fission. To set up a chain reaction, the neutrons have to be slowed by colliding with other particles. The substance in a reactor that slows fast neutrons is called the **moderator**.

The hydrogen nuclei (protons) in water molecules are effective at slowing neutrons. Ordinary water is a common moderator. Some reactors use **heavy water** as a moderator. Heavy water, or D_2O, is water that contains a high proportion of the isotope deuterium (hydrogen-2). When a fast neutron collides with a deuterium atom in a heavy water molecule, it gives up a lot of energy. It then can go on to split a uranium nucleus. Many reactors, including those in the United States, use light water for a moderator. Light water is cheap and readily available, but it has a tendency to absorb neutrons instead of slowing them.

Coolant

The **coolant** flows into, through, and out of the reactor core, removing thermal energy from the core by conduction. The coolant then transfers that energy to the boiler to make steam. This system keeps the reactor contents isolated from the steam system, so the water in the steam turbine does not become radioactive. Many reactor designs use light water as a coolant. In newer reactors, the water is pumped at high pressure, which increases the efficiency of the heat transfer.

Like all power plants that use steam turbines, nuclear power plants need water to cool and condense the steam by absorbing its thermal energy. When possible, water is circulated from a nearby lake, river, or ocean. Otherwise, cooling towers must be used. The same thermal pollution issues apply to thermonuclear plants as to fossil-fuel steam plants.

The efficiency of a thermonuclear plant is mostly determined by the transformation of heat into electricity. Modern designs have efficiencies around 30 to 35 percent, producing electricity with a large cogeneration or district heating potential that may also be tapped.

Figure 8.34 Located on the shore of Lake Ontario just east of Toronto is one of the world's largest nuclear generating facilities. Pickering Nuclear Generating Station has six operating CANDU reactors.

CANDU Reactors

The first **CANDU** (CANada Deuterium Uranium) **reactor** was designed and built by Atomic Energy Canada Ltd. in the 1950s. All of the nuclear power plants in Canada still use the basic CANDU design — a design that has made Canada a leader in the international reactor market (Figure 8.34). A number of features distinguish the CANDU reactor from other reactor designs.

CANDU reactors use natural uranium, rather than the more costly enriched uranium, in their fuel pellets. They can also make their own fuel in a neutron absorption breeding process: uranium-238 occasionally absorbs a slow neutron, becoming uranium-239. It then beta decays twice to become plutonium-239, which is fissile.

The amount of plutonium in a CANDU fuel bundle builds up in the reactor over the first year or so (Figure 8.35). By the time the fuel bundles are changed (every 5 to 7 years), fission of plutonium contributes more than 50 percent of the reactor's output power. Ontario nuclear plants actually contract to dispose of weapons-grade fissionable materials — they just put in it the reactor and make electricity.

Figure 8.35 CANDU fuel bundles

Heavy water is the moderator in CANDU reactors — the "D" in CANDU is for deuterium. Heavy water absorbs fewer neutrons than light water, making it possible to sustain a chain reaction even in unenriched fuel. Canada has developed a heavy water industry to supply its nuclear reactors. In the atmosphere, about 1 in 3250 water molecules contains deuterium. This gives us mostly light water (H_2O), some semi-heavy water (HDO), and a very little heavy water (D_2O). The mass difference of the three molecules means they can be separated by evaporation. In addition, recombination techniques can make heavy water from semi-heavy water.

The original CANDU design also uses heavy water as a coolant. Heavy water has a slightly higher heat capacity and boiling point than light water. The CANDU reactor uses separate systems for the moderator and the coolant. With this design, the moderator can be dumped to stop the chain reaction without losing cooling. In addition, draining the moderator from only a part of the reactor allows individual fuel bundles to be removed without taking the reactor off-line.

Concept Check

1. What are the two common isotopes of uranium? Which one is fissile?
2. What is heavy water? What is it used for in the CANDU system?
3. Explain why removing the moderator from a reactor stops the fission chain reaction.

Nuclear Power Hazards and Safety

PHYSICS•SOURCE

Suggested Activity

- C17 Quick Lab Activity Overview on page 281

Radioactive contamination can occur if radioactive materials are released into an environment through an accident or carelessness. Radiation cannot be detected by human senses. A variety of handheld and laboratory instruments is available for detecting and measuring radiation (Figure 8.36).

The radiation safety issues for nuclear power fall into three broad categories: mining and processing the fuel, plant design and operation, and handling the spent fuel.

Mining and Processing

Figure 8.36 A Geiger counter is one of a variety of instruments that measure the intensity of radiation. It was the original radiation detector used by uranium prospectors. Geiger counters have applications in nuclear physics and nuclear medicine as well as in mining.

Canada has vast uranium ore resources and currently produces about 20 percent of the world's supply of uranium. Debates about radiation safety in uranium mines are ongoing (Figure 8.37). Miners in general suffer increased lung disease because of dust inhalation. The problems are substantially worse when the dust is both toxic and radioactive.

Close to each mine is a mill that crushes the rock and separates out the uranium, resulting in piles of tailings (gravel and dust) and chemical sludge ponds. Both the tailings and the sludge ponds pose a radiation hazard to the surrounding environment. While these waste areas are strictly controlled and monitored, a small leak into the water table is hard to notice and could affect life for hundreds of kilometres around. It is primarily the quantity of uranium ore handled that makes the problem so difficult to resolve. A nuclear power plant may only use 20 t of fuel each year, but it takes 20 000 t of ore to make that fuel, resulting in more than 20 000 t of toxic radioactive waste.

After mining and milling, the extracted uranium, called *yellowcake*, undergoes many chemical transformations. In Canada, it is trucked to Ontario, where refineries convert it into uranium dioxide, for use as fuel in CANDU reactors, or into uranium hexafluoride, for use in light-water reactors.

The refined uranium then goes to plants in the United States, France, or Britain for subsequent enrichment. Enriched uranium is needed for almost all research reactors, most non-Canadian reactors, and nuclear weapons. Finally, the uranium is manufactured into fuel pellets.

The processes from mining the ore to making the fuel pellets are called the "front end" of the nuclear fuel cycle.

Figure 8.37 MacArthur River uranium mine in northern Saskatchewan, shown here, is the largest uranium mine in the world, with enormous reserves of high-grade ore. Today, Saskatchewan is the only province in Canada mining uranium.

Nuclear Reactor Accidents

A nuclear accident can give people and animals large doses of radiation that will quickly kill them or make them very ill. The worst potential nuclear accident is a runaway nuclear chain reaction in fissile material. This is what happened in the worst nuclear accident in history at Chernobyl in the Ukraine in 1986, when the reactor at a nuclear power plant exploded. Four workers were killed instantly. A cloud of highly radioactive fallout — 400 times more than was released by the atomic bomb dropped on Hiroshima at the end of World War II — shot up into the atmosphere and drifted away, contaminating large areas in Ukraine, Belarus, and Russia. More than 300 000 people had to be evacuated and resettled. The United Nations is now overseeing recovery of the affected area.

Partial meltdowns of reactor cores and other nuclear accidents have happened on a handful of other occasions, including at Three Mile Island in Pennsylvania in 1979 and at Chalk River near Ottawa in 1952. No deaths resulted from either of these accidents.

Today, reactor safety is taken very seriously. You are far more likely to die or be harmed by dozens of activities you engage in daily — walking to school, riding in a car, sledding down a hill, or going for a swim than by the effects of a nuclear accident.

Plant Safety

Safety in a reactor facility is much more manageable than at a mine. Effective engineering and skilled operators are key — and both are readily available in Canada. In the nuclear industry, safety is often referred to as the *Three C's*: control, containment, and cooling. The concept is to build multiple levels of control into every process.

For example, you can shut down the fission reaction by removing the moderator, dropping neutron-absorbing control rods into the reactor, or bathing the reactor in a neutron-absorbing liquid.

All radioactive materials are contained by both pressure and shielding. The areas of the reactor facility with the highest radiation hazard are kept at the lowest air pressure, so no bits of radioactive dust or gases can escape through the air.

The fission reaction and the decay series in the fission by-products can produce enough heat to structurally damage the reactors or spent-fuel containers. Cooling keeps the temperature under control and so helps prevent radiation leaks.

CANDU reactors have two separate fast-acting safety shutdown systems. Shutoff rods penetrate the housing of the reactor core vertically and lower into the core in the case of a safety-system trip. A second shutdown system injects a high-pressure solution that acts as a neutron poison (neutron absorber) directly into the moderator.

The *Three C's* also underlie the safety technologies for the transportation and storage of nuclear materials and nuclear waste.

Nuclear Reactor Waste

Nuclear power generation does not rely on fossil fuels. Ontario generates more than 50 percent of its electricity by nuclear means. This represents a huge reduction in our carbon footprint. Worldwide, nuclear and hydro each account for about 15 percent of electrical energy. With modern nuclear plants running at 35 to 40 percent efficiency, nuclear power is expected to be a huge growth industry.

More nuclear power will mean more nuclear waste, and greater probability of accidents. The volume of highly radioactive waste produced today is tiny on industrial and geographic scales, but the problem of how to store this waste safely for many thousands of years is still unsolved, and the volume of waste will grow if nuclear energy becomes more widely used.

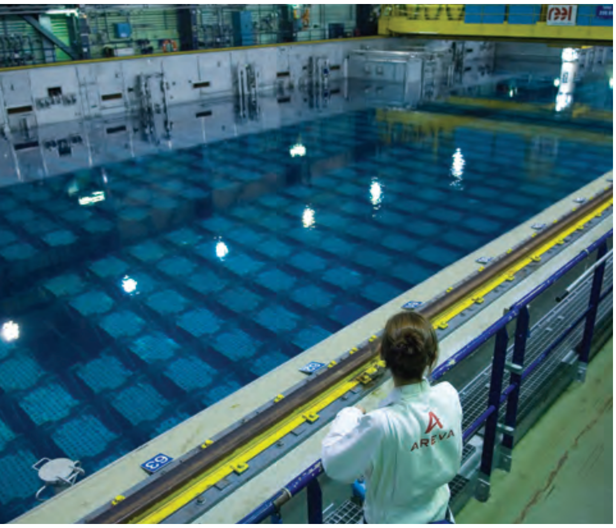


Figure 8.38 The cooling pools for spent uranium fuel glow an unearthly blue. Beta particles from the spent fuel slow quickly in the water and their kinetic energy is transformed into light.

The processing of spent fuel that comes out of a reactor is referred to as the "back end" of the nuclear fuel cycle. When spent fuel rods are taken out of a reactor, they are stored underwater in large pools of water (Figure 8.38). The water cools the spent fuel and shields workers from its radiation. The fission products in the spent fuel are usually radioactive, each isotope initiating its own long decay series. The result is a continually changing mixture of radioactive isotopes. The short-lived isotopes are highly radioactive for a short time from their creation, and the long-lived ones are mildly radioactive for millennia. The fission waste is essentially "hot" forever.

After a few years, it is possible to remove the spent fuel safely from the pools. It is then stored in concrete containers. In Ontario, the containers are shipped to a dedicated storage facility near Kincardine. Extreme care must be taken to avoid a leak while transporting or storing nuclear waste, and the concrete containers are closely monitored. It is believed that nuclear waste can be left safely in such containers for at least 50 years. What to do after that has not yet been decided.

Several countries, such as Finland and Sweden, are developing permanent storage sites deep underground, and Ontario is investigating this possibility as well. A possible disadvantage of this storage method is that nuclear waste buried underground could eventually contaminate the environment.

Concept Check

1. How much uranium ore is needed to make 1 t of uranium fuel?
2. Explain why *coolant* is one of the *Three C's* of nuclear safety.
3. Why do nuclear reactions continue after the fuel has been removed from the reactor?

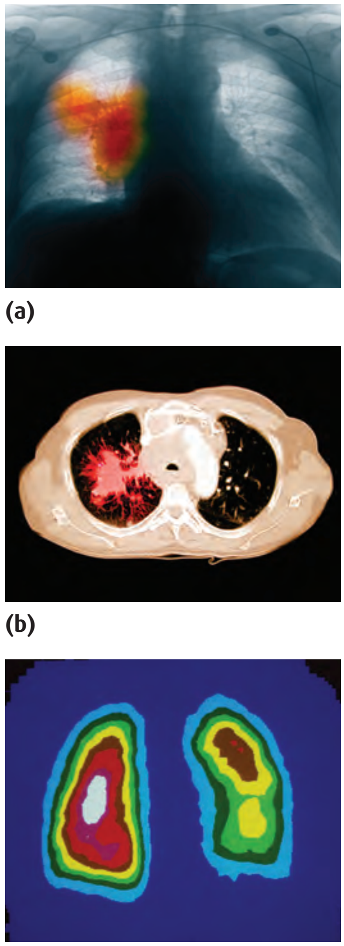
Nuclear Medicine

X-rays were the first form of electromagnetic radiation used to see inside the body. Hard tissue, such as bones and dense tumours, absorbs X-rays, while soft tissue allows X-rays to pass unchanged. A camera on the other side of the patient records on film the pattern of X-ray light that has passed through the patient's body, creating a (negative) image of the hard tissue, as shown in Figure 8.39(a).

Special X-ray scanners can be used to produce multiple images of the inside of the body that can then be seen as a three-dimensional image on a computer. This type of medical image is called a computed tomography (CT) scan. CT scans of internal organs, soft tissue, and blood vessels are much clearer and more detailed than regular X-rays, but they are most effective for imaging hard tissue (Figure 8.39(b)).

Gamma rays are now also commonly used in medical imaging as in the image shown in Figure 8.39(c). Whereas X-rays are usually emitted by atoms in excited states, gamma rays are emitted by the nucleus.

The use of radioactive isotopes in medicine allows us to see and travel deep inside the human body, providing powerful new ways to diagnose and treat many diseases.



(a)

(b)

(c)

Figure 8.39 (a) A chest X-ray showing lung cancer (b) A CT scan showing lung cancer (c) A SPECT scan of lungs, produced using the radiotracer technetium-99.

Radiotracers

Medical imaging that uses radioisotopes is non-invasive and painless. The radioisotopes used in this type of imaging are called **radiotracers**. Most radiotracers are isotopes of elements normally found in the body, such as oxygen, carbon, and fluorine. This is because isotopes of an element have similar chemical properties, so most biological processes treat them in an almost identical way. Radiotracers also have short half-lives; they will stay in the body just long enough for a diagnosis to be made.

Tracers are attached to chemical compounds that concentrate in specific organs of the body or move through specific metabolic paths. The patient is given the tracer orally, by injection, or by inhalation. Once the radiotracer has been taken into the body, a camera or scanner records the gamma radiation over time and builds up an image for analysis. A computer uses this data to measure the amount of tracer absorbed and produce detailed images of organs and tissues.

Using a tracer allows medical staff to see organs that don't show up in X-ray images. Radiotracers can be used to evaluate how well organs are functioning, to track the passage of substances through the body, to see how the body absorbs certain substances, and to locate and measure tumours. These tracers often eliminate the need for exploratory surgery.

Two main types of imaging detect gamma rays produced by radiotracers: SPECT (single photon emission computed tomography) and PET (positron emission tomography). In SPECT, the tracer emits gamma radiation which is recorded. The resulting image is somewhat fuzzy because it is hard to determine exactly where each gamma ray was emitted (Figure 8.39(c)).

In PET, a radioisotope that decays by positron emission (beta plus decay) is used as a tracer. Usually this radioisotope is fluorine-18. Each positron is annihilated by combining with an electron, producing two gamma rays shooting off in opposite directions. A PET camera looks for these gamma-ray pairs and determines very accurately where they came from.

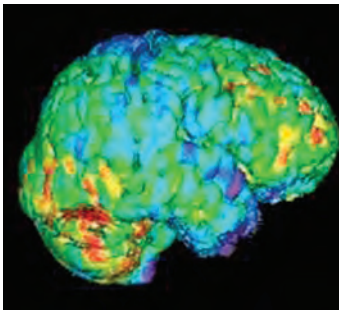


Figure 8.40 A brain PET scan

The result is a very detailed three-dimensional image (Figure 8.40). PET is used in the diagnosis of cancer because it is accurate and not invasive. It is also used in cardiac and brain imaging.

The amount of radiation you are exposed to from an X-ray, CT scan, or PET or SPECT scan is low — just a fraction of the amount of natural background radiation you receive in a year.

Brachytherapy

The most frequently used form of radiation therapy uses an external beam to deliver radiation to the cancer. In another form of treatment, known as **brachytherapy**, a radioactive source is placed inside the cancerous tissue. The source might be in the form of a surgically implanted "seed" that produces short-range radiation (Figure 8.41). In most cases, it is beta radiation that causes the destruction of the damaged cells.

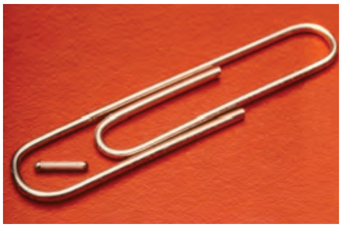


Figure 8.41 A radioactive iodine-125 seed

In one version of this therapy, the radiologist inserts a catheter (small tube) into the target area. A thin wire with a radiation source at the tip is threaded through the catheter to the tumour. The source stays in position for a short while and is then removed. The treatment is repeated as necessary.

Brachytherapy avoids exposing a large part of the body to radiation, and it is better suited than external beam-type radiotherapy to some parts of the body, such as the prostate (Figure 8.42). It has been proven to be very effective and safe, providing a good alternative to surgical removal of the prostate, breast, and cervix, while reducing the risk of some long-term side effects.

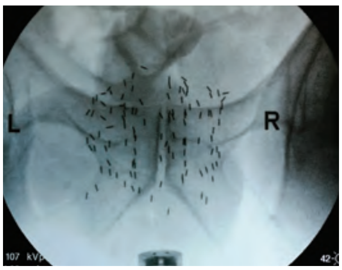


Figure 8.42 X-ray of male pelvis with radioactive iodine seeds treating prostate cancer

Less time is needed to complete a session of brachytherapy than other types of radiation therapy. This reduces the likelihood that surviving cancer cells will divide and grow in the intervals between each dose. Brachytherapy can be performed on an outpatient basis, making it accessible and convenient.

Nuclear medicine research is well funded, and innovative new diagnostic and treatment procedures appear every year. One idea is to modify antibodies so that they carry a radiotracer. Since antibodies attach themselves to the cells of specific tissues, this could make it possible to design extremely accurate treatments. Research into new applications of radioisotope technology is also ongoing. Procedures show promise for treating liver cancer, non-Hodgkin's lymphoma, and brain cancer.

Accidental Exposure to Nuclear Radiation

In 1987 a junkyard dealer in Goiania, Brazil, broke open an abandoned radiation therapy machine and removed a small chunk of material made with cesium-137, a highly radioactive isotope. Children, attracted to the bright blue of the radioactive material, touched it and rubbed it on their skin. Several city blocks were contaminated and had to be demolished. Four people were killed, 29 were severely affected, and over 200 cases of radiation poisoning were detected.

Medical radioisotopes provide many benefits, but they must be handled with extreme care. Accidents can be caused by human error and equipment failure. Another concern is the quantity of radioisotopes that end up in the environment (especially water systems) after leaving patients' bodies and before decaying.

The international radiation-warning symbol (Figure 8.43(a)) is posted wherever radioactive materials are handled or radiation-producing equipment is used, such as in the nuclear medicine area of a hospital. In 2007, the United Nations introduced a new symbol (Figure 8.43(b)) to help reduce accidental exposure to large radioactive sources. The new symbol will not be visible under normal use, only if someone attempts to disassemble a device that is a source of dangerous radiation. It is hoped that this symbol will help to prevent the type of accident that happened in the junkyard in Goiania.

(a) (b)

Figure 8.43 Signage for radiation hazard (a) nuclear radiation (b) large source of ionizing radiation

Concept Check

1. What are the important characteristics of a radiotracer?
2. Describe what happens to the positron in the PET process.
3. Why is brachytherapy more effective than ordinary radiation treatment? Why does it produce fewer and less-serious side-effects?

Commercial and Industrial Applications

Commercial uses of nuclear radiation are based on its ionizing ability, or its penetration ability, or both.

PHYSICS•SOURCE

Suggested Activity

- C18 Decision-Making Analysis Activity Overview on page 281

Ionization Smoke Detectors

Most household smoke detectors contain a small amount of americium-241 (Figure 8.44). This isotope emits alpha particles, which ionize air molecules between two metal plates within the detector. One of the plates has a positive charge, and the other has a negative charge. The plates attract the ions, so a small current flows between the plates.

If smoke particles enter the smoke detector, they absorb some of the alpha particles. The alpha radiation ionizes fewer air molecules, and the current between the metal plates decreases. This drop in current triggers the alarm circuit in the smoke detector.

On your wall, this radioactive material poses little threat, but if a detector were broken open, alpha particles could be inhaled or ingested. These smoke detectors should never be smashed or taken apart. Ionization detectors can be returned to the manufacturer for disposal as hazardous waste. Alternatively, most municipalities have guidelines for their disposal.

Figure 8.44 This smoke detector uses alpha radiation to sense smoke particles.

Industrial Radiography

Manufacturers of sheet materials such as paper, plastics, and metal foils often monitor the thickness of the material with a gauge that measures how much of the beta radiation from a calibrated source passes through the material. Unlike mechanical thickness gauges, such gauges need not touch the material they measure, so they do not get worn down and there is less risk of marking the material.

Gamma rays can pass through thick metal parts to expose a photographic plate. The resulting image can reveal hidden air bubbles or hairline cracks, similar to the way X-rays produce images of the inside of a patient's body.

PHYSICS•SOURCE

Explore More

How are radiotracers used to monitor the toxicity of shellfish?

Figure 8.45 Irradiated peaches (in front) and peaches not irradiated and showing rot (in back) after two weeks

Gamma-ray photographs are a non-destructive way of testing items that X-rays cannot penetrate, including structural materials, jet engines, and welded joints in pipelines.

Irradiation

Food irradiation is used to kill insects, bacteria, and other micro-organisms that cause spoilage or food poisoning. It slows the sprouting of root vegetables after harvesting and the ripening of stored fruits and vegetables, extending their shelf life (Figure 8.45).

Much like luggage that passes through an airport X-ray unit, irradiated food passes through a machine with a strong gamma ray source such as cobalt-60. The ionizing effect of the gamma rays damages living cells and especially disrupts DNA required for germination or reproduction.

Food irradiation is also used at national borders to ensure that insect pests are not transported across, and astronauts in space dine on irradiated food. Many of the spices used in Canada are irradiated, and Health Canada is studying requests to apply the process to poultry and red meat.

Irradiation using a cobalt-60 source is used in hospitals to sterilize operating rooms and medical equipment and supplies. Pharmaceutical and cosmetics companies use irradiation to sterilize heat-sensitive products.

Concept Check

1. Why is alpha radiation particularly dangerous if it comes from inside your body?
2. How are gamma rays used to find structural faults in metal objects?
3. Explain how irradiation makes food safer.

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Take It Further

The World Nuclear Organization says: "The Chernobyl accident in 1986 was the result of a flawed reactor design that was operated with inadequately trained personnel and without proper regard for safety." Did they violate all of the *Three C's*? Investigate the details of the accident and create a visual organizer describing how the accident occurred.

The Future of Nuclear Energy

Ours is an energy-hungry society and our demand for electricity is not likely to decrease in the near future. At present, Ontario generates 53 percent of its electricity from nuclear energy; worldwide, the figure is about 14 percent. As fossil fuels become scarce, expensive, and the cause of political tension, and as we recognize the environmental impact of using them, nuclear power offers a more nearly "green" option for electricity. With our supply of uranium ore and our technical experience, Canada's role in nuclear power is certain to increase.

Sterilizing insects, analyzing pollutants, powering batteries, destroying skin cancer cells using radioactive patches — these are just a few of the many other ways that the energy of nuclear reactions is being used today. New applications are continually being discovered in dozens of fields. Despite the dangers of radiation, our use of nuclear energy may increase significantly in the years to come. As with every type of energy transformation, the key to using this energy well is to understand the interactions and processes that transform and transfer it. Maybe you yourself will use the energy of nuclear reactions some day to discover a new particle or invent a new technology.

The *Three C's* of Nuclear Reactor Safety

Purpose
To relate safety procedures at a CANDU power plant to the reactor processes

Activity Overview
The hazards of nuclear radiation are real. In this activity, you will examine the safety issues in a CANDU thermonuclear plant. As you explore how accidents and exposure to radiation are prevented, you will connect safety techniques to the basic operation of a nuclear reactor.

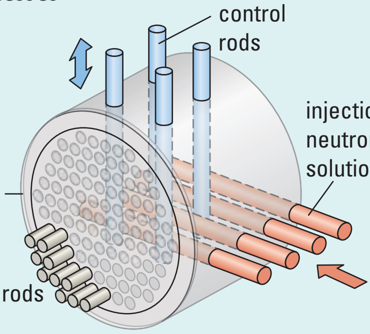


Figure 8.46 Modern CANDU reactors have two independent emergency shutdown systems: insertion of control rods that absorb neutrons and injection of a neutron-absorbing solution. Each system stops the nuclear chain reaction.

Prelab Questions
Consider the questions below before beginning this activity.

1. What is a nuclear chain reaction?

2. How can a nuclear chain reaction be controlled?

3. What are the dangers if the chain reaction in a nuclear reactor gets out of control?

DI Key Activity

C18 Decision-Making Analysis PHYSICS•SOURCE

REQUIRED SKILLS
- Selecting media
- Summarizing information

Food Irradiation

Issue
We rely on safe food for nutrition, enjoyment, and upholding our traditions. In the food industry, nuclear radiation is increasingly being used to preserve food and to extend its shelf-life. Is this a beneficial technology that we should support and encourage?

Figure 8.47 International symbol of food irradiation

Activity Overview
Bacterial infection or infestations can cause food to spoil, make us sick, and even lead to death. Scientists from the food industry are continually searching for effective methods to reduce spoilage and make food safer, while keeping it wholesome for us to eat. Food irradiation is a process that uses ionizing radiation to help preserve food by killing bacteria, fungi, parasites, and insects.

At present, irradiated foods are allowed in Canada to only a very limited degree. What should Canada's position on irradiated foods be? Should we be irradiating more, fewer, or no foods?

Your task is to research this issue and present your findings, along with your recommendations for Canadian policy on food irradiation.

Prelab Questions
Consider the questions below before beginning this activity.

1. Have you, or anyone you know, ever had food poisoning?

2. Which types of food spoil most easily? Explain.

3. Do you trust the safety of foods produced in Canada? Do you trust the safety of imported foods? Explain.

8.3 Check and Reflect

Key Concept Review

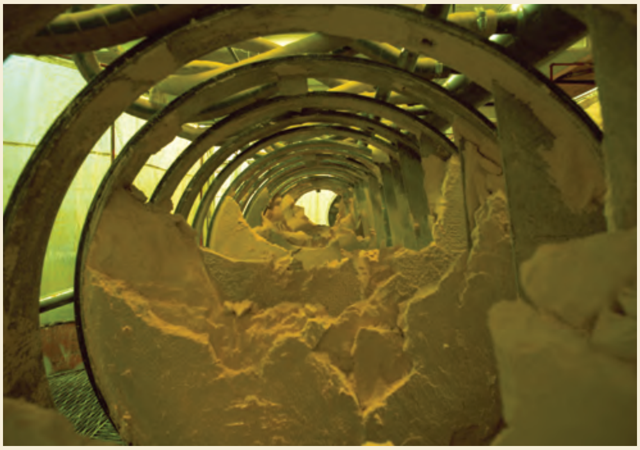
1. What is a nuclear fission chain reaction?
2. What happens in a chain reaction if there are too many neutrons?
3. What is a thermonuclear reactor?
4. What do the letters in CANDU represent?
5. What type of fuel is used in most reactors? Why?
6. What type of fuel is used in a CANDU reactor?
7. What is the purpose of a moderator in a nuclear reactor?
8. What is the purpose of the control rods?
9. What are the *Three C's* of nuclear safety?
10. Describe the methods used to store nuclear reactor waste in Canada.
11. What method of long-term storage is being investigated in other countries and in Ontario? What is the potential danger of this approach?
12. Compare an ordinary X-ray image with a CT-scan image.
13. Describe two medical imaging techniques that use gamma rays.
14. Describe what happens in brachytherapy.
15. Which type of nuclear radiation is used in an ionization smoke detector? Which radioactive isotope do these smoke detectors contain?
16. Describe two benefits of food irradiation.

Connect Your Understanding

17. Describe the energy transformations that occur in a thermonuclear plant, from a uranium-235 nucleus to electrical energy.
18. Describe the stages in producing fuel for nuclear reactors, from the mining of uranium ore to the production of fuel pellets.
19. A CANDU power plant has four different water systems (Figure 8.31): one in the reactor, one connecting the reactor to the steam plant, and two in the steam plant. Explain the function of each of these systems.
20. A CANDU reactor "breeds" some of its own fuel, starting from non-fissionable uranium-238.
    (a) Write the reaction equations for uranium-238 absorbing a neutron, followed by two beta decays.
    (b) What is the fissionable isotope resulting from the beta decays?
21. Why is spent fuel very radioactive? What precautions are taken with spent fuel?
22. Suggest what sorts of nuclear waste might come from nuclear medical applications.
23. Explain why irradiating foods with gamma rays kills micro-organisms.
24. Suggest what sorts of nuclear waste might come from industrial applications.
25. Describe the types of medical imaging you or someone close to you have experienced. Explain any precautions or warnings you were given.

Reflection

26. After learning about CANDU nuclear reactors, what concerns you most about Ontario's use of nuclear power? In what ways are you more comfortable about nuclear energy?



Question 18 Yellowcake is the bright yellow uranium powder produced when raw uranium ore is crushed and purified. Yellowcake is not a usable form of uranium; it needs to be refined before it is used as nuclear fuel. The bulk of the yellowcake produced in Canada is processed outside of Canada.

For more questions, go to PHYSICS•SOURCE

Great CANADIANS in Physics Ursula Franklin

Ursula Franklin is a person who makes change happen. In 1967, Franklin was the first woman appointed to the Department of Metallurgy and Materials Science at the University of Toronto, and in 1984 she was the first woman to be appointed University Professor.

In the 1950s, Franklin pioneered the field of archaeometry, the analysis of ancient materials using techniques from modern physics. She continues to consult on the dating of copper, bronze, and ceramic artefacts from prehistoric peoples in Canada.

Franklin gained public recognition in the 1960s when she measured the accumulation of strontium-90 from nuclear fallout by collecting and analyzing Canadian children's teeth. The work was instrumental in the decision by the United States to ban atmospheric nuclear testing.

Today Franklin's life revolves around issues of peace and social justice. She has received many awards and honours, including the Pearson Medal of Peace and the Order of Canada. She is a tireless role model for young woman seeking non-traditional careers and an active speaker and writer about the interaction of technology and society.

Figure 8.48 Ursula Franklin

Figure 8.49 The cover of Franklin's 2006 book on pacifism, feminism, technology, teaching, and learning

Physics CAREERS Renewable Energy Technician

Renewable energy technician (or energy systems technician) is one career in the expanding field of sustainable energy development and green building design.

The work may involve advising homeowners by performing energy audits, modelling heating and cooling systems, and recommending improvements for energy saving. In the building trades, an energy technician may be involved in planning, installing, and maintaining solar, wind, or geothermal energy systems. Many energy technicians consult with architects and industrial designers involved in sustainable planning.

A renewable energy technician uses a balance of technical and business skills to meet clients' energy needs in a field of constant change and innovation.

Figure 8.50 A renewable energy technician testing solar panels

To find out more, visit PHYSICS•SOURCE

CHAPTER 8 CHAPTER REVIEW

Key Concept Review

1. Define the following: atom, ion, nucleus, nucleon. k
2. What do the quantities A, Z, and N represent? What is the mathematical relationship among A, Z, and N? k
3. Use an example to explain the difference between ionizing and non-ionizing radiation. k
4. Define radioactive decay. k
5. What are the three main types of nuclear radiation? k
6. Compare the penetrating abilities of the three types of nuclear radiation. k
7. Describe what happens to a nucleus during
   (a) alpha decay k
   (b) beta decay k
   (c) gamma decay k
8. Define the half-life of an isotope. k
9. Describe how scientists use half-life to date artefacts. k
10. Describe the mass defect. k
11. What is the relationship between mass defect and binding energy? k
12. List and give an example of the three conservation laws for nuclear reactions. k
13. Explain the difference between fission and fusion. k
14. Describe how a free neutron can induce fission in uranium-235. k
15. What is meant by the *energy content* of a fuel? k
16. Give an example of a decay series. k
17. How is cobalt-60 made? What is it used for? k
18. What is a radio-pharmaceutical? k
19. Why is molybdenum-99 so important? k
20. Describe the two types of uranium found in nuclear reactors. k
21. How does a CANDU reactor use deuterium? k
22. Explain the role of the moderator in a nuclear reaction. k
23. Why do some reactors have separate systems for the moderator and the coolant? k
24. List the *Three C's* of nuclear safety. k
25. Compare the efficiencies of hydroelectric, fossil-fuel thermal, and thermonuclear power generation. k
26. Describe a medical application of nuclear technology. k
27. Describe an industrial application of nuclear technology. k

Connect Your Understanding

28. State A, Z, and N for
    (a) $^{56}_{26}\text{Fe}$ a
    (b) $^{39}_{18}\text{Ar}$ a
    (c) $^{199}_{84}\text{Po}$ a
29. Write the names for the following atoms in nuclear notation:
    (a) carbon-13 a
    (b) $Z = 74$, $N = 110$ a
    (c) $N = 66$, $A = 115$ a
30. Write the alpha decay reaction for:
    (a) $^{150}_{64}\text{Gd}$ a
    (b) $^{203}_{86}\text{Rn}$ a
    (c) $^{147}_{63}\text{Eu}$ a
31. Write the beta decay reaction for:
    (a) $^{1}_{0}\text{n}$ a
    (b) $^{141}_{53}\text{I}$ a
    (c) $^{102}_{41}\text{Nb}$ a
32. Write the reaction series for $^{152}_{63}\text{Eu}$ undergoing beta decay, followed by three alpha decays. a
33. Draw a chart similar to Figure 8.23 (radioactive decay series). Show three possible decay series starting at $^{215}_{83}\text{Bi}$ and ending with $^{207}_{82}\text{Pb}$. a
34. Uranium-237 has a half-life of 6.75 days. What percentage of an initial sample of uranium-237
    (a) decays over 13.5 days? a
    (b) remains after 27 days? a

ACHIEVEMENT CHART CATEGORIES

k Knowledge and understanding
t Thinking and investigation
c Communication
a Application

35. Explain why a group of particles in a bound state has lower energy than the same particles when free. a

36. Imagine building an atom from a nucleus and some free electrons. Is there a mass defect between the atom and its free particles? Explain why or why not. a

37. The proton-proton chain fusion reaction starts with four protons and produces 42.7×10^{-13} J of energy. Calculate the energy produced per kilogram of initial mass. a

38. Canada produced 600 TW·h of electricity in 2008. Find the mass equivalent of this energy. a

39. The top energy of the proton beam at the LHC is 362.0 MJ. Calculate the speed (in m/s and km/h) of a 3200-kg car with this kinetic energy. a

40. Verify that the *A* and *Z* conservation laws hold in the following reactions:

(a) ${}^{18}_{8}\text{O} + {}^{1}_{1}\text{H} \rightarrow {}^{18}_{9}\text{F} + {}^{1}_{0}\text{n}$ a

(b) ${}^{20}_{10}\text{Ne} + {}^{2}_{1}\text{H} \rightarrow {}^{18}_{9}\text{F} + {}^{4}_{2}\alpha$ a

41. Describe and explain how neutrons in a nuclear reactor

(a) help maintain the fission reaction a

(b) transfer and transform energy a

42. One design for a CANDU reactor produces 1.6×10^{8} kW·h of electrical energy from 1 tonne of natural uranium.

(a) Calculate the usable energy content of natural uranium in J/kg. a

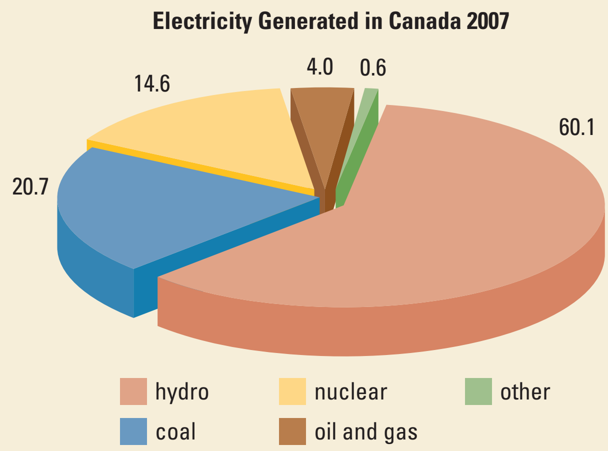
(b) Calculate the mass-energy equivalent of 1.0 t of uranium. a

(c) Explain any difference in the answers of parts (a) and (b). a

43. Describe three environmental issues related to nuclear power. For each issue, outline a possible solution. a

44. (a) How do you think the graph shown at the top of this page is likely to change in your lifetime? Explain your thinking. t

(b) Which methods of generating electricity would you prefer to see used more and less in Ontario? Explain why. t



Question 44

45. Describe the nuclear medicine technology that you believe has made the most important improvement in people's lives. Justify your choice. c

46. Nuclear waste is produced whenever radioactive materials are used. List six of the non-reactor applications of radioactivity from this chapter. For each use, describe what waste is created and how you think it should be handled. c

Reflection

47. Write a paragraph describing what you have learned about radiation in this unit that you didn't know previously. Include examples to illustrate your answer. c

Unit Task Link

It has just been announced that a uranium mine will be built about 25 km from the intended location of the retreat centre. The developer of the centre seeks your analysis of the safety and environmental issues concerning uranium mines. You must make a recommendation on whether to relocate the retreat, modify the planned air and water systems, or keep your existing design. Summarize your research and decision in a letter to your client.

For more questions, go to PHYSICS•SOURCE