Where Does Nuclear Energy Come from, and What Are Its Applications?

For centuries, scientists believed that the atom was the fundamental building block of all matter. This changed when the nucleus of an atom was split for the first time in the early nineteenth century. Nuclear physics was born! Scientists discovered that when an atom is split apart, a large amount of energy is released. This discovery led to the development of a number of applications, some of which you may be aware of, and some that will be new to you.

Mention the term “nuclear energy,” and people may think of large nuclear power reactors or perhaps nuclear weapons. The field of nuclear physics is much broader than that. Did you know, for example, that archaeologists use nuclear technology to estimate the ages of once-living fossils? Astrophysicists use similar techniques to estimate the age of moon rocks. Biologists are exploring nuclear methods to control harmful insect pest infestations. Throughout this chapter you will learn about these and other applications of nuclear technology.

Nuclear medicine is one of the fastest growing fields of research involving nuclear energy. Materials with particular nuclear properties are useful for diagnosing, and sometimes treating, certain illnesses. Technetium-99m is an artificially created material used in organ scans. These scans provide vital information to medical experts that enable them to pinpoint malignant areas of the damaged organ and plan a suitable treatment.

In this chapter you will learn about many important scientific discoveries related to nuclear energy and resulting applications. You will examine some of the issues related to the benefits and hazards of nuclear energy. As a student of science, it is your responsibility to critically examine all of the evidence available before constructing your own informed opinion on the relative merits of nuclear energy.
In a nuclear reaction, one substance spontaneously changes into another. In this investigation you will use pennies (or two-colour tiles) to simulate a nuclear reaction and analyze the speed with which the reaction occurs.

**Equipment and Materials:** 100 pennies (or 100 two-colour tiles); paper bag; graph paper

1. Place the pennies in the bag. Let heads represent the atoms of the original substance and tails the atoms of the new substance. In a moment you will pour the entire contents of the bag onto the lab bench. Predict the number of pennies that will come up heads.

2. Shake the bag and pour the pennies onto the bench. (This is Trial 1.) Count the number of heads and record your results in a table similar to Table 1. Reflect on your prediction. Account for any discrepancies.

3. Remove all of the pennies that come up tails. Put the remaining pennies back into the bag. These represent the atoms that have not yet changed.

4. Suppose you repeat this process for several trials, each time removing the pennies that come up tails and placing them back in the bag. Count the number of heads and record your results in another table similar to Table 1. Reflect on your prediction. Account for any discrepancies.

**Table 1**

<table>
<thead>
<tr>
<th>Trial number</th>
<th>Number of pennies remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

See overset Matter
the ones that come up heads back in the bag. Sketch a graph showing how you think the number of heads will decline over the next several trials. Give reasons for the shape of your graph.

5. Pour the pennies again and tally the number of heads. (This is Trial 2.) Remove the pennies that come up tails and repeat for several trials until no pennies remain.

6. Create a scatter plot of number of pennies remaining versus trial number. Draw a smooth curve of best fit through the data.

A. Describe the shape of the curve. Does it have the same shape as your prediction? Explain why it has the shape it does.

B. How many trials did it take for all of the pennies to be removed? Compare this to the results of your classmates. Account for any discrepancies.
Atoms and Isotopes

The history of atomic discovery begins with the ancient Greeks, when, around 400 BCE, the philosopher Democritus asserted that all material things are composed of extremely small irreducible particles called atoms. The science community rejected this early atomic theory for almost 2000 years! John Dalton resurrected the atomic theory of matter in the early nineteenth century by characterizing elements by their atomic structure and weight. Over the next hundred years or so, scientists continued to refine their understanding of the atom, until the advances of Niels Bohr and Ernest Rutherford.

Bohr–Rutherford Model of the Atom

Niels Bohr, a Danish scientist, and Ernest Rutherford, a New Zealand scientist, are credited with a number of discoveries that led to the development of the Bohr–Rutherford atomic model. Rutherford found that when a beam of positively charged particles was fired at a thin gold foil, most particles passed through the foil, as expected, but some were scattered in all directions. To explain this, it was proposed that the atom consists of a dense, positively charged nucleus surrounded by tiny electrons and a relatively vast region of empty space. Bohr also discovered that the electrons could only occupy certain energy levels. When these discoveries were combined, the Bohr–Rutherford model of the atom was created.

This model is illustrated in Figure 1. Note the following key features of the model:

- The dense nucleus contains the atom’s protons and neutrons.
- The relatively tiny electrons orbit the nucleus.
- The electrons only occupy certain energy levels.
- Most of the atom consists of empty space.

The model provides a visual method for describing the atomic structure of an element. The atomic structure refers to the number of protons, neutrons, and electrons in an atom and their organization within the atom. Simplified Bohr-Rutherford diagrams for helium and fluorine are shown in Figure 2.

The nucleus is the centre of the atom and consists of protons and neutrons. Protons are positively charged particles and neutrons are uncharged particles. In nuclear physics, neutrons and protons are often referred to collectively as nucleons. Protons and neutrons have approximately the same mass. Electrons are negatively charged particles that move in the space surrounding the nucleus and are extremely small compared to nucleons. Most of an atom’s mass comes from the nucleons, since electrons have a very small mass. In Figure 1, the electrons are shown arranged around the nucleus in shells, or energy levels. Figure 2 indicates that

- helium atoms have two protons, two neutrons, and two electrons
- fluorine atoms have nine protons, ten neutrons, and nine electrons

In general, an atom in its normal state has the same number of electrons as protons. In a Bohr–Rutherford diagram, electrons are placed in the lower energy levels, or shells, first, until these shells are filled. Atoms that have electrons placed in this way

atomic structure the number and arrangement of protons, neutrons, and electrons in an atom

nucleus the centre of an atom, consisting of protons and neutrons
proton a positively charged particle in the nucleus of an atom
neutron an uncharged particle in the nucleus of an atom
nucleons particles in the nucleus of an atom; protons and neutrons
electron a negatively charged particle found in the space surrounding the nucleus of an atom
are said to be in their \textbf{ground state}: the electrons are all at the lowest possible energy levels. An atom is said to be in an \textbf{excited state} if it absorbs energy that causes an electron to be raised to a higher energy level. An excited atom returns to its ground state by releasing energy as the electron drops back to its lowest available energy level. Figure 3 shows a hydrogen atom in the ground state and in an excited state.

\textbf{Figure 3} Hydrogen in (a) an excited state and (b) its ground state

According to the Bohr-Rutherford model, each energy level or shell can hold a certain number of electrons. Table 1 gives the maximum number of electrons for each shell.

\textbf{Atomic Number, Mass Number, and the Periodic Table}

The periodic table of elements lists all the elements known today. You can use a periodic table to determine the atomic structure of an element (Figure 4).

The \textit{atomic number} is the number of protons in an atom of an element. Each element has a different number of protons. The \textit{mass number} is equal to the number of nucleons in an atom. The periodic table entry shown in Figure 4 indicates that fluorine has nine protons and nine electrons. The number of neutrons is determined by subtracting the atomic number from the mass number:

\[ 19 \text{ nucleons (mass number)} - 9 \text{ protons} = 10 \text{ neutrons} \]
\[ 19 - 9 = 10 \]

\[ \text{mass number} - \text{atomic number} = \text{number of neutrons} \]
\[ (\text{protons} + \text{ neutrons}) - (\text{number of protons}) = \text{number of neutrons} \]

\textbf{Isotopes}

Carbon-12 consists of six protons and six neutrons. Most naturally occurring carbon has this atomic structure. There is, however, another form of carbon called carbon-14. Carbon-14 has six protons but eight neutrons (Figure 5).

Since carbon-14 has the same atomic number as carbon-12, but a different mass number, it is an \textit{isotope} of carbon. Different isotopes of an element have the same number of protons, but different numbers of neutrons (Figure 6). The mass number of 14 indicates that an atom of carbon-14 has two more neutrons than an atom of carbon-12:

\[ \text{number of neutrons} = \text{mass number} - \text{Vatomic number} \]
\[ n = 14 - 6 \]
\[ n = 8 \]

\textbf{Figure 6} Bohr-Rutherford models for (a) carbon-12 and (b) carbon-14

\textbf{ground state} all electrons are at their lowest possible energy levels

\textbf{excited state} one or more electrons are at higher energy levels than in the ground state

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Shell number} & \textbf{Maximum number of electrons} \\
\hline
1 & 2 \\
2 & 8 \\
3 & 18 \\
4 & 32 \\
\hline
\end{tabular}
\end{table}
As you can see, carbon-14 has eight neutrons instead of six. This isotope has some interesting properties that are useful to archaeologists and scientists. A process called carbon dating is a reasonably accurate technique for determining the age of fossils and objects made of things that were once alive. You will learn more about carbon dating in Section 7.3.

Most samples of elements consist of a number of different isotopes, some occurring naturally and others produced in laboratories. The most common isotope of hydrogen has a nucleus consisting of only one proton. There are, however, two other isotopes of hydrogen. These isotopes are important in nuclear science, so they have been given their own names: deuterium and tritium. Deuterium, which has one proton and one neutron, is a naturally occurring substance. Tritium, which has one proton and two neutrons, is only produced as a by-product of human-made nuclear reactions.

The periodic table identifies the most commonly occurring isotopes for each element. A more general table that lists atomic information for all known isotopes is called a chart of the nuclides. In the following Tutorial, you will draw, analyze, and compare Bohr–Rutherford diagrams for various isotopes. You will also identify isotopes from their given Bohr–Rutherford diagrams.

**Sample Problem 1**

Draw the Bohr–Rutherford diagram for argon.

**Step 1.** Locate argon on the periodic table. The chemical symbol for argon is Ar.

**Step 2.** Identify the atomic number and mass number of the element. The atomic number for argon is 18 and the mass number is 40.

**Step 3.** Use this information to draw a Bohr–Rutherford diagram for argon. The atomic number is 18. This means that there are 18 protons and 18 electrons. The number of neutrons is found by subtracting the atomic number from the mass number:

\[
40 - 18 = 22
\]

Therefore, there are 22 neutrons in an atom of argon.

**Figure 7**

**Step 4.** Draw the Bohr–Rutherford diagram (Figure 7).

**Practice**

1. Sketch a Bohr-Rutherford diagram for each element:
   (a) aluminum, Al
   (b) silver, Ag
   (c) two other elements of your choice
Some isotopes are unstable; that is, they spontaneously change their nuclear structure. When an isotope undergoes such a change, energy is released in the form of radiation. **Radiation** is energy released in the form of waves when an unstable isotope undergoes a structural change. When an unstable isotope spontaneously changes its nuclear structure, it becomes a **radioisotope**. This radiation can be harmful if not properly controlled. In some cases, however, these radioisotopes are beneficial. The process by which isotopes spontaneously change will be examined later in this chapter.

**Medical Applications of Radioisotopes**

**Medical Diagnosis**

An emerging application of radioisotopes is in the area of nuclear medical imaging. This diagnostic technique involves the injection of the patient with a small dose of a radioisotope, such as technetium-99m. These materials, sometimes called radioactive tracers, emit radiation that can be detected and converted into an image. Comparing radiation patterns of an unhealthy organ to those of a healthy one can help doctors pinpoint a malignancy, or tumour (Figure 8).

![Figure 8](C07-P02-OP11USB.jpg)

**Figure 8** A radioactive tracer provides a detailed image of a diseased organ.

One of the advantages of nuclear imaging over traditional X-rays is that it provides a detailed account of both hard tissues like bone and softer tissues like the liver and kidneys. X-rays are primarily useful for detecting bone fractures.

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**Research This**

**Technetium-99m**

**Skills:** Researching, Analyzing, Communicating

Technetium-99m is an unusual isotope for which medical scientists have discovered several important uses. The "m" in its name identifies it as a meta-stable isotope.

1. Research Technetium-99m (Tc-99m) on the Internet or at the library. Write a brief report of your findings that includes answers to the following questions.

A. What is a meta-stable isotope?    
B. How is Tc-99m obtained?    
C. What is it about Tc-99m that makes it particularly useful in medicine?    
D. Discuss some of the applications of Tc-99m in the medical field.    
E. Are there any drawbacks to using nuclear imaging, such as health risks, costs, or wait times?    

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**NEL**
Medical Treatments

One of the earliest medical applications of radioisotopes began in the 1950s, when iodine-131 was used to diagnose and treat thyroid disease. Sufferers of hyperthyroidism have an overactive thyroid gland: it releases more thyroid hormone than the body requires. Iodine-131 can be used to both identify a diseased thyroid gland and halt production of the hormone.

Radionuclide therapy (RNT) is a rapidly growing medical field in which the properties of certain radioactive substances are used to treat various ailments. RNT is currently used to treat certain types of tumours, bone pain, and other conditions. In cancer treatments, the fundamental idea behind RNT is to bombard rapidly dividing harmful cells with radiation. These cells tend to absorb the radiation, which prevents them from dividing further.

7.1 Summary

- The Bohr–Rutherford model of the atom illustrates the atomic structure of an element.
- You can identify the number of protons, neutrons, and electrons of an element from its Bohr–Rutherford model.
- You can identify the mass number and atomic number of an element from the periodic table.
- Isotopes of an element have the same number of protons but different numbers of neutrons.
- Radioactive isotopes are unstable and will spontaneously undergo a change in their nuclear structure.
- Some radioactive isotopes have useful applications, such as medical diagnosis and therapy.

7.1 Questions

1. Draw a Bohr–Rutherford diagram for each isotope.
   (a) oxygen-16
   (b) potassium-39
2. (a) Draw Bohr–Rutherford diagrams for hydrogen, deuterium, and tritium.
   (b) Identify their similarities and differences.
3. Identify each isotope shown in Figure 9 given its Bohr–Rutherford diagram.
4. (a) Draw a Bohr–Rutherford diagram for each isotope of beryllium.
   (i) $^7\text{Be}$
   (ii) $^9\text{Be}$
   (iii) $^{10}\text{Be}$
   (b) Explain the similarities and differences between these models.
   (c) Which isotope of beryllium is the most common in nature? Explain how you know.
5. (a) Draw a Bohr–Rutherford model for each isotope.
   (i) lithium-5, $^\text{6}\text{Li}$
   (ii) oxygen-20, $^{19}\text{O}$
   (b) Describe how each isotope compares with its most commonly occurring isotope.
6. For each Bohr–Rutherford model shown in Figure 10,
   (a) determine the atomic number and the mass number
   (b) write the chemical name of the isotope
7. An isotope has 16 protons and 22 neutrons. Identify this isotope.

8. (a) Draw a Bohr–Rutherford model for each isotope of argon.
   (i) Ar-40  (ii) Ar-44  (iii) Ar-47
   (b) Explain how these isotopes are alike and different.

   (a) Draw a Bohr–Rutherford model for each isotope.
   (b) How are these models alike? How are they different?

10. (a) Draw Bohr–Rutherford models for lithium-10, beryllium-10, and boron-10.
    (b) How are these models alike? How are they different?

11. Research nuclear medical imaging, and identify two applications not discussed in this section. Write a brief report of your findings.

12. Research radionuclide therapy. What are some diseases that can be treated? What are some diseases that cannot be treated using RNT at this time?
Radioactive Decay

A fascinating area of scientific inquiry around the turn of the twentieth century was the splitting of the atom. In 1896, Henri Becquerel observed this as a naturally occurring event when he found that a sample of uranium left an image when placed on photographic film. This eventually led to the discovery of radioactivity—the spontaneous disintegration of an atom's nucleus. The film traces were caused by particles emitted during this process.

Becquerel's accidental discovery encouraged scientists to seek ways to induce similar reactions using various materials. Ernest Rutherford used high-energy particles to bombard nitrogen and discovered that oxygen was produced. A few years later, James Chadwick performed a similar experiment with beryllium that led to the discovery of the neutron. These efforts helped scientists develop a better understanding of atomic structure at the nuclear level and formed the basis for the broad range of nuclear scientific work that followed. As you learned in Chapter 5, a reaction in which the nucleus of an atom is split into smaller pieces is known as nuclear fission.

A cyclotron, shown in Figure 1, is a machine that can accelerate particles to very high speeds. Many nuclear reactions can only occur when particles are travelling at speeds near to that of light. High-energy physics is the study of such interactions.

![Cyclotron Image](image1.png)

**Figure 1** A cyclotron is a device that accelerates particles to very high speeds approaching the speed of light. The high-energy particles that are produced can be used for research experiments as well as medical treatments.

Chemical Reactions

A chemical reaction is the interaction of substances to form new substances. The starting substances, which may be elements or compounds, are called reactants. The substances present at the end of the reaction, which also may be elements or compounds, are called products. For example, the reaction between carbon (in the form of coal) and oxygen (in the air) produces carbon dioxide. The reactants are carbon, C, and oxygen, O₂. The product is carbon dioxide, CO₂. Energy is also released in this chemical reaction.

We can represent a chemical reaction as a word equation or a chemical equation, as follows:

- word equation: carbon + oxygen → carbon dioxide + energy
- chemical equation: C + O₂ → CO₂ + energy
In a chemical reaction, the entities do not change. All of the entities that were present in the reactants are present in the products. A balanced chemical reaction clearly shows this. In the example above, there is one atom of carbon on each side of the arrow. Similarly, there are two atoms of oxygen on either side of the arrow. The identities of the elements do not change; only their organization changes. Chemical reactions obey the law of conservation of mass.

A chemical reaction, such as the example above, that releases energy is exothermic. By contrast, a chemical reaction that absorbs energy is endothermic.

## Nuclear Reactions

Nuclear reactions involve changes in the nuclei of atoms, resulting in completely new elements. As you know, the identity of an element is decided by the number of protons in its nucleus. If the number of protons changes, one or more new elements result. Examining the forces present in a nucleus will help you understand the nature of nuclear reactions and why they occur.

### Electrostatic Force and the Strong Nuclear Force

For over a hundred years, scientists have understood the electrostatic force of attraction and repulsion between electrically charged particles. Like charges repel, and opposite charges attract. This explains why the positively charged nucleus of an atom attracts negatively charged electrons. It cannot, however, explain how the nucleus itself is held together. Consider the helium nucleus shown in Figure 2. The neutrons have no electrical charge and the protons are both positively charged. What is holding the nucleus together?

A different type of force, not discovered until the 1930s, is responsible for holding the nucleus together. Like gravity, and unlike the electrostatic force, the strong nuclear force is always attractive and helps hold together the neutrons and protons in the nucleus of an atom. Protons and neutrons are attracted to each other via the strong nuclear force. The strong nuclear force is much stronger than the electrostatic force. The strong nuclear force is responsible only for holding the nucleus of an atom together.

### Stable and Unstable Isotopes

There is a delicate balance between the repulsive electrostatic force and the attractive strong nuclear force in a nucleus. When these forces are balanced, an atom is said to be stable. Atoms with higher atomic numbers (more protons) experience a greater electrostatic force of repulsion among the protons, and the protons become more separated. This separation results in a weakening of the strong nuclear force. Additional neutrons add to the strong nuclear force to balance the increasing electrostatic repulsion.

Sometimes the electrostatic forces are great enough to overcome the strong nuclear force, and the nucleus spontaneously disintegrates (breaks apart) and releases energy. An unstable atom with a nucleus that can spontaneously disintegrate is said to be radioactive. The process by which a radioactive atom spontaneously breaks apart is called radioactive decay. There are three common forms of radioactive decay: alpha decay, beta decay, and gamma decay.

### Alpha Decay

One of the most common forms of radioactive decay is alpha decay, or α-decay. In alpha decay, a helium nucleus, consisting of two protons and two neutrons, is spontaneously emitted from the nucleus. An illustration of alpha decay is shown in Figure 3.
**alpha particle** a particle emitted during alpha decay composed of a helium nucleus containing two protons and two neutrons

**parent atom** the reactant atom in a nuclear reaction

**daughter atom** the product atom in a nuclear reaction

**transmutation** a nuclear decay process in which daughter atoms are different from parent atoms

---

In Figure 3, an atom of plutonium-240 decays into uranium-236, and a helium-4 nucleus is emitted in the process. The helium-4 nucleus is called an **alpha particle**. The equation for this nuclear reaction is

$$^{240}_{94}\text{Pu} \rightarrow ^{236}_{92}\text{U} + ^{4}_{2}\text{He}$$

When a substance undergoes alpha decay, the mass number is reduced by four and the atomic number is reduced by two. Generally, this can be shown as

$$\frac{A}{Z} P \rightarrow \frac{A-4}{Z-2} D + ^{4}_{2}\text{He}$$

where P represents the **parent atom** and D represents the **daughter atom**. In a nuclear reaction, the parent atom is the reactant atom, and the daughter atom is the product atom. The atomic number changes during alpha decay, so a new atom (element) is formed. When this happens, the nuclear reaction is said to be a **transmutation**. In a transmutation, the daughter atoms are smaller and have fewer electrical charges in the nucleus. This makes the daughter atoms more stable.

In the following Tutorial, you will use your understanding of alpha decay to write the equation for a nuclear reaction.

---

**Tutorial 1** Determining the Nuclear Equation for Alpha Decay

**Sample Problem 1**

When lead-204 undergoes alpha decay, it produces a stable isotope. Determine the element and its atomic number and mass number. Write the nuclear reaction equation for this alpha decay.

**Step 1.** Use the periodic table to determine that the atomic number of lead is 82.

**Step 2.** Determine the atomic number and mass number of the new isotope. In alpha decay the atomic number is reduced by 2 and the mass number is reduced by 4. So, to determine the atomic number of the daughter atom, subtract 2 from the atomic number:

$$82 - 2 = 80$$

The periodic table tells us that the new element is an isotope of mercury.

To determine the mass number of the daughter atom, subtract 4 from the mass number of the parent atom, lead-204:

$$204 - 4 = 200$$

The new isotope is mercury-200.

**Step 3.** Write the reaction equation:

$$^{204}_{82}\text{Pb} \rightarrow ^{200}_{80}\text{Mg} + ^{4}_{2}\text{He}$$
Beta Decay

Beta decay, or $\beta$-decay, is a type of nuclear decay reaction that involves the emission or capture of a beta particle. A beta particle is either an electron or a positron. A positron is a particle exactly like an electron except that it has a positive charge instead of a negative charge. There are three main types of beta decay: beta-negative ($\beta^-$) decay, beta-positive ($\beta^+$) decay, and electron capture.

BETA-NEGATIVE DECAY

In a beta-negative decay reaction, an electron is emitted from the nucleus of a parent atom. How can this happen, since electrons are not usually found in the nucleus of an atom? When a nucleus contains too many neutrons, the strong nuclear force becomes much greater than the electrostatic force. To maintain stability, a neutron spontaneously decays into a proton and an electron, and the electron is ejected from the nucleus. An example of a beta-negative decay reaction is the decay of tritium (hydrogen-3) to helium-3, as shown in Figure 4.

The equation for this reaction is

$$ ^3_1H \rightarrow ^3_2He + _{-1}^0e $$

where $e^-$ represents an electron (the negative beta particle). In this process, the mass number of the daughter nucleus remains unchanged, but the atomic number increases by one. This process is a transmutation because the number of protons changes.

The general equation for beta-negative decay is

$$ ^A_ZP \rightarrow ^A_{Z+1}D + _{-1}^0e $$

BETA-POSITIVE DECAY

In beta-positive decay, a proton changes into a neutron and a positron, which is symbolized by $e^+$. An example of this type of nuclear reaction is when carbon-11 decays into boron-11, as shown in Figure 5.

Practice

1. Determine the element that is produced when plutonium-239 undergoes alpha decay, and write the reaction equation. [ans: uranium-235; $^{239}_{94}Pu \rightarrow ^{235}_{92}U + ^4_2He$]

2. When an unknown isotope undergoes alpha decay, neptunium-239 is produced. Determine the unknown isotope. [ans: americium-243]
**Figure 5** Beta-positive decay

The equation for this nuclear reaction is

\[ ^{11}_{5}C \rightarrow ^{11}_{5}B + ^{1}_{0}e \]

Notice that in this process, the mass number of the daughter nucleus remains unchanged, but the atomic number decreases by one. This process is a transmutation because a different type of atom is formed when a proton in the nucleus of the parent atom changes into a neutron.

The general equation for beta-positive decay is

\[ \frac{2}{2}P \rightarrow \frac{2}{2}D + \frac{1}{0}e \]

**ELECTRON CAPTURE**

Electron capture is a form of beta decay in which an electron is absorbed by a nucleus and combines with a proton to form a neutron, as shown in **Figure 6**.

**Figure 6** Electron capture

The equation for this reaction is

\[ ^{56}_{28}Ni + ^{1}_{0}e \rightarrow ^{56}_{27}Co \]

In this process the mass number of the daughter nucleus remains unchanged, but the atomic number decreases by one. This process is a transmutation because the number of protons changes.

The general equation for electron capture decay is

\[ \frac{2}{2}P + \frac{1}{0}e \rightarrow \frac{2}{2}D \]

In the following Tutorial, you will use what you have learned about beta decay to determine the unknown isotope and nuclear equation for a reaction.

**Tutorial 2** Determining the Nuclear Equation for Beta Decay

In this Sample Problem you will determine the daughter element produced by the beta-negative decay of a known element.
Sample Problem 1

When bismuth-214 undergoes beta-negative decay, it produces a stable isotope. Determine the element and its atomic number and mass number. Write the nuclear reaction equation for this beta decay.

**Step 1.** Use a periodic table to determine that the atomic number of bismuth is 83.

**Step 2.** Determine the atomic number and mass number of the new isotope. In beta decay the atomic number is increased by 1 and the mass number is unchanged, so the atomic number of the new daughter isotope is

$$83 + 1 = 84$$

The periodic table tells us that the new element is an isotope of polonium. The mass number remains 214. The new isotope is polonium-214.

**Step 3.** Write the reaction equation. In beta-negative decay a neutron changes into a proton and an electron, which is ejected from the nucleus:

$$^{214}_{82}\text{Bi} \rightarrow ^{214}_{83}\text{Po} + ^0_{-1}\text{e}$$

Practice

1. Determine the element that is produced when cerium-141 undergoes beta-negative decay and write the reaction equation. \[ \text{ans: praseodymium-141, } ^{141}_{58}\text{Ce} \rightarrow ^{141}_{59}\text{Pr} + ^0_{-1}\text{e} \]

2. Determine the element that is produced when chromium-46 undergoes beta-positive decay. Then write the reaction equation. \[ \text{ans: manganese-46, } ^{46}_{24}\text{Cr} \rightarrow ^{46}_{25}\text{Mn} + ^0_{+1}\text{e} \]

**Gamma Decay**

After a nuclear reaction such as alpha or beta decay has occurred, the daughter nucleus is in a high-energy, or excited, state. Thus, the nucleus spontaneously releases energy in the form of a gamma ray in order to return to a lower, more stable energy state. A **gamma ray** is a highly energetic form of electromagnetic radiation that is emitted as a photon. A **photon** is a particle with zero mass and a high level of energy. This process is called **gamma decay**, or \( \gamma \)-decay. For example, the helium-3 daughter resulting from the beta decay reaction above will undergo gamma decay, as shown in **Figure 7**. The general equation for gamma decay is

$$^2_3\text{He}^* \rightarrow ^3_2\text{He} + \gamma$$

**Figure 7** Gamma decay
The symbol for a photon is $\gamma$. Notice that the parent and daughter nuclei are identical. Only the energy level of the nucleus has changed. The asterisk is used to indicate that the parent in this reaction is in an excited state. Notice that the mass number and atomic number of a gamma ray are both zero. In the following Tutorial you determine the nuclear equation for a gamma decay reaction.

**Tutorial 3  Determining the Nuclear Equation for Gamma Decay**

In this Sample Problem you are given the parent element and must determine the gamma decay equation for this reaction.

**Sample Problem 1**

When dysprosium-152 undergoes gamma decay, its nucleus changes from an excited state to a stable state. Write the nuclear reaction equation for this gamma decay.

**Step 1.** Use a periodic table to determine that the atomic number of dysprosium is 66.

**Step 2.** Determine the atomic number and mass number of the new isotope. In gamma decay both the atomic number and the mass number remain unchanged.

**Step 3.** Write the reaction equation. In gamma decay a gamma ray is ejected from the nucleus. An asterisk is used to signify a nucleus in its excited state:

$$^{152}_{66}\text{Dy}^* \rightarrow ^{152}_{66}\text{Dy} + ^0_0\gamma$$

**Practice**

1. Write the reaction equation when plutonium-240 undergoes gamma decay [ans: $^{240}_{94}\text{Pu}^* \rightarrow ^{240}_{94}\text{Pu} + ^0_0\gamma$].

2. Is gamma decay an example of a transmutation? Explain why or why not.

**Characteristics of Radioactive Decay**

Alpha particles, beta particles, and gamma rays all pose a danger to living tissue because they can ionize, or strip the electrons from, atoms. Types of radiation that can ionize atoms are known as ionizing radiation. When ionizing radiation makes contact with living tissue, it can result in burns, tumours, and other harmful effects. It is important to protect tissues from exposure to ionizing radiation.

Alpha particles have a strong ionizing ability due to their positive charge and relatively high mass. Fortunately they travel a relatively short distance before becoming absorbed, so their potential danger is minimal unless they are ingested or inhaled. Beta particles and gamma rays, however, have a greater penetrating range in air and must be shielded against. Table 1 summarizes the characteristics of the three types of ionizing radiation you learned about in this section.

**Table 1  Characteristics of radioactive decay**

<table>
<thead>
<tr>
<th>Type of decay</th>
<th>Radiation</th>
<th>Electric charge</th>
<th>Emitted particle</th>
<th>Penetrating ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha decay</td>
<td>alpha particle</td>
<td>+2</td>
<td>helium nucleus ($^2_4\text{He}$)</td>
<td>can penetrate skin or paper, but is slow moving</td>
</tr>
<tr>
<td>beta decay</td>
<td>beta particle</td>
<td>−1</td>
<td>electron ($^-_1\text{e}$)</td>
<td>can penetrate a few sheets of aluminum foil</td>
</tr>
<tr>
<td>gamma decay</td>
<td>gamma rays</td>
<td>0</td>
<td>photon ($^0_0\gamma$)</td>
<td>can penetrate a few centimetres of lead</td>
</tr>
</tbody>
</table>

See overset Matter
7.2 Summary

- The strong nuclear force is responsible for holding the nucleus of an atom together by balancing the proton-proton electrostatic forces of repulsion.
- Nuclear reactions are those in which the number of protons or neutrons in the nucleus of an atom is changed.
- Radioactive decay is a process by which the nucleus of a radioisotope spontaneously changes.
- There are three common types of radioactive decay: alpha decay, beta decay, and gamma decay.
- Alpha particles, beta particles, and gamma rays are forms of ionizing radiation.

7.2 Questions

1. Write the nuclear reaction equation for each atom undergoing alpha decay.
   (a) curium-248
   (b) radium-223

2. Write the nuclear reaction equation for each atom undergoing beta-negative decay.
   (a) sulphur-35
   (b) gold-198

3. Write the nuclear reaction equation for each atom undergoing beta-positive decay.
   (a) sodium-22
   (b) calcium-39

4. The positron is a very interesting particle. Conduct some research on the positron and describe some of its properties.

5. Write nuclear reaction equations for each atom undergoing electron capture.
   (a) potassium-40
   (b) carbon-11

6. The strong nuclear force has a peculiar property. At distances less than 0.5 femtometres ($5 \times 10^{-16}$ m), the force reverses from strong attraction to strong repulsion. Suggest why this might be necessary.
Half-Life

Radioactive decay reactions have applications in a wide range of fields. For example, in 1996 the remains of a prehistoric man, shown in Figure 1, were found in Kennewick, Washington. Scientists used the properties of radioactive decay to determine that the remains belonged to a man who lived over 9000 years ago! This discovery has led to further information about North American ancestry and the evolution of humans as a species. We will explore the techniques that were used to date this fascinating artifact in this section.

Figure 1 (a) Skeleton of Kennewick Man (b) Reconstruction of Kennewick Man

Measuring the Rate of Radioactive Decay Processes: Half-Life

Radioactive decay reactions are spontaneous. There is no way to predict exactly when a particular unstable nucleus will disintegrate. However, it is possible to predict the decay rate for a large sample of an isotope. Radioactive materials decay at different rates, which can vary significantly. The average length of time it takes a radioactive material to decay to half its original mass is called the half-life.

The half-life of any given isotope is actually an average time for a particular parent atom to decay to its daughter atom. Cobalt-60, for example, has a half-life of 5.27 years. This does not mean that every atom of this isotope decays to its daughter atom 5.27 years after it is formed. Some atoms decay sooner, and some later. On average, however, it takes 5.27 years for an atom of cobalt-60 to decay. The larger the sample size, the more accurately a material decays according to its half-life.

Mini Investigation

Analyzing Half-Life

Skills: Predicting, Performing, Observing, Analyzing, Communicating

When a radioactive material decays, the amount of the parent decreases, while the amount of the daughter increases. How can these relationships be represented graphically?

Equipment and Materials: periodic table; graph paper or graphing technology; half-life simulation applet (optional)
Mathematical Models Using Half-Life

Radioactive decay is an example of an exponential relationship—as time increases, the mass of a radioactive isotope remaining in a sample decreases at an exponential rate. The rate of decay is greater in the initial stages of the process because there are more atoms to decay. The rate of decay continuously decreases as the sample gets smaller and smaller. The mass, $A$, of a radioactive material with an initial sample mass of $A_0$ is related to time, $t$, and half-life, $h$. This can be represented by the following equation:

$$A = A_0\left(\frac{1}{2}\right)^{t/h}$$

When using this equation it is important to measure the masses $A$ and $A_0$ using the same units. The same is true for $t$ and $h$. In the following Tutorial, you will apply this equation to solve problems involving the half-life of radioactive isotopes.

### Tutorial 1 Calculations Involving Half-Life

#### Sample Problem 1

Neon-19 has a half-life of 17.22 s. What mass of neon-19 will remain from a 100 mg initial sample after 30 s?

**Given:** $A_0 = 100 \text{ mg}$; $h = 17.22 \text{ s}$; $t = 30 \text{ s}$

**Required:** $A$

---

1. Carbon-15 decays to nitrogen-15 with a half-life of 2.5 s. Suppose a sample of carbon-15 has an initial mass of 256 mg. Copy and complete Table 1. Assume that mass is conserved.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Mass of carbon-15 (mg)</th>
<th>Mass of nitrogen-15 (mg)</th>
<th>Total mass (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>256</td>
<td>0</td>
<td>256</td>
</tr>
<tr>
<td>2.5</td>
<td>128</td>
<td>128</td>
<td>256</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Predict the shape of the graph of mass of carbon-15 versus time. Explain your reasoning. Plot a graph of mass of carbon-15 versus time, with time on the horizontal axis. Use a smooth curve to join the points.

3. Repeat Step 2 for the graph of the mass of nitrogen-15 versus time. Plot both graphs on the same grid.

A. What type of radioactive decay is this reaction? Explain how you know.

B. Write the nuclear reaction equation.

C. Discuss the rates of change for carbon-15 and nitrogen-15. Explain why the two graphs have the shapes that they do.

D. Interpret the point of intersection of the two graphs. Explain what each coordinate of this point represents.
Analysis: \[ A = A_0 \left( \frac{1}{2} \right)^t \]

Solution: \[ A = A_0 \left( \frac{1}{2} \right)^t \]
\[ = (100 \text{ mg}) \left( \frac{1}{2} \right)^{\frac{30}{172.2}} \]
\[ = (100 \text{ mg}) \left( \frac{1}{2} \right)^{1.7422} \]
\[ = (100 \text{ mg})(0.2989) \]
\[ = 30 \text{ mg} \]

Statement: There will be 30 mg of neon-19 remaining after 30 s.

Sample Problem 2

A 100 mg sample of magnesium-29 decays by 7% of its previous mass every minute. Determine its half-life and state the half-life decay equation.

Step 1. The decay of magnesium-29 can be modelled using a table or graph. If 7% decays during each minute, then 93% remains. Create a table similar to Table 2 to determine the mass remaining after each minute.

### Table 2 Mass of magnesium-29 remaining

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Initial mass (mg)</th>
<th>Final mass (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0.93(100) = 93</td>
</tr>
<tr>
<td>2</td>
<td>93</td>
<td>0.93(93) = 86.49</td>
</tr>
<tr>
<td>3</td>
<td>86.49</td>
<td>0.93(86.49) = 80.44</td>
</tr>
<tr>
<td>4</td>
<td>80.44</td>
<td>0.93(80.44) = 74.81</td>
</tr>
<tr>
<td>5</td>
<td>74.81</td>
<td>69.57</td>
</tr>
<tr>
<td>6</td>
<td>69.57</td>
<td>64.70</td>
</tr>
<tr>
<td>7</td>
<td>64.70</td>
<td>60.17</td>
</tr>
<tr>
<td>8</td>
<td>60.17</td>
<td>55.96</td>
</tr>
<tr>
<td>9</td>
<td>55.96</td>
<td>52.04</td>
</tr>
<tr>
<td>10</td>
<td>52.04</td>
<td>48.40</td>
</tr>
</tbody>
</table>
Applications of Half-life: Carbon Dating

The half-life of carbon-14 is 5730 years. It decays into nitrogen-14 according to the following nuclear reaction equation:

\[ ^{14}\text{C} \rightarrow ^{14}\text{N} + _{e}^{1}\text{e} \]

The half-life of C-14 makes it a useful material for measuring the age of once-living organisms. When plants absorb carbon dioxide through the process of photosynthesis, the carbon is typically a mixture of the common C-12 and relatively rare C-14 isotopes of carbon. Herbivores ingest C-14 when they eat plants, and carnivores do so when they feed on herbivores. The ratio of C-14 to C-12 is generally constant and equal in all living organisms.
7.3 Questions

1. Chlorine-38, which undergoes beta-negative decay, has a half-life of 37.24 min. (a) Construct a table that compares the mass of Cl-38 remaining after \( t \) minutes for several values of \( t \). (b) Draw a graph that illustrates this relationship. (c) What isotope does Cl-38 decay into?

2. Gold-198, with a half-life of 2.6 days, is used to diagnose and treat liver disease. (a) Write a half-life decay equation that relates the mass of Au-198 remaining to time, in days. (b) What percentage of a sample of Au-198 would remain after (i) 1 day? (ii) 1 week?

3. Cobalt-60, with a half-life of 5.3 years, has a number of applications including medical therapy and the sterilization of medical tools. Determine the mass of a 50 g sample that would remain after (a) 6 months (b) 5 years

4. What type of radioactive decay is involved in carbon dating? Explain the process of radiocarbon dating.

5. A fossil contains 70% of the relative mass of carbon-14 as a living creature. Use the half-life decay equation to determine when the creature died.

Aluminum-26, which decays to magnesium-26, has a half-life of approximately 720,000 years. Scientists can approximate the age of a sample by comparing the relative masses of Al-26 and Mg-26, in a similar fashion to carbon dating.

6. (a) What type of decay does Al-26 undergo? (b) Does Al-26 decay in the same way as C-14? Explain.

7. A moon rock is tested and it is found that its Al-26 mass has depleted to 3% of its original mass. (a) Determine the age of the moon rock. (b) Discuss any assumptions that must be made when using this method of dating.

8. Take a regular sheet of paper. Measure its length and width and determine the area. Fold the paper neatly in half. Determine the new area. Repeat until you cannot fold the paper any longer. Explain how this model can be used to describe half-life.

7.3 Summary

- The half-life of a radioactive isotope is the amount of time required for it to decay to one half of its original mass.
- Half-lives can vary from a tiny fraction of a second to millions of years.
- The decay of a radioactive isotope can be mathematically modelled using a table, a graph, or an equation.
- Some isotopes have useful applications due in part to their particular half-lives.
- Carbon-14 is a useful isotope for dating fossils and other archaeological objects.
Nuclear Fission and Nuclear Power Generation

When Ernest Rutherford split the atom for the first time in 1919, few would have predicted how profoundly our world would change. The footprint of the nuclear revolution of the twentieth century can be found in areas ranging from medical advances that save lives, to nuclear power, to devastating weaponry.

Nuclear power generation is controversial. Nuclear power reactors emit virtually no pollutants into the atmosphere, yet they produce harmful radioactive waste that must be safely contained and stored for long periods of time. Opponents of nuclear power cite the dangers of reactor meltdowns. However, Canada's reactors have enjoyed impressive safety records. Nuclear energy is a critical part of our power supply. Over 50% of Ontario's electric power is generated from Canadian Deuterium Uranium reactors or, as they are more commonly known, CANDU reactors (Figure 1).

The process by which a nuclear reactor operates is based on the work of Albert Einstein, whose famous theory of relativity consists of a number of abstract ideas. One of these is that mass and energy are actually different aspects of the same phenomenon.

Mass–Energy Equivalence

In the early twentieth century Albert Einstein proposed what is arguably the most famous equation in science:

\[ E = mc^2 \]

This simple equation challenged the foundations of physics by suggesting that energy and mass are equivalent. The equation states that the energy, \( E \), of an object at rest is equal to its mass, \( m \), multiplied by the speed of light, \( c \), squared. The speed of light is \( 3.0 \times 10^8 \) m/s.

As Einstein's theory became widely accepted, the notions of conservation of mass and conservation of energy were replaced by the more general law of conservation of mass-energy.

An isolated system is a system that is free from outside influences. No energy flows into or out of the system, and no mass is added or removed from the system. It is this relationship between mass and energy that can help explain the vast amount of energy that is released in a nuclear reaction, as you will see in Tutorial 1 below.

The atomic mass unit is commonly used in chemistry and physics as a more convenient unit of mass than the kilogram. One atomic mass unit (u) is equal to the mass of a carbon-12 nucleon, or \( 1.66 \times 10^{-27} \) kg. Table 1 lists the masses of subatomic particles in kilograms and in atomic mass units.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (kg)</th>
<th>Mass (u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>( 1.672614 \times 10^{-27} )</td>
<td>1.007276</td>
</tr>
<tr>
<td>neutron</td>
<td>( 1.674920 \times 10^{-27} )</td>
<td>1.008665</td>
</tr>
<tr>
<td>electron</td>
<td>( 9.10956 \times 10^{-31} )</td>
<td>0.000549</td>
</tr>
</tbody>
</table>
Einstein's equation allows for a deeper understanding of the nucleus. A chart of the nuclides provides the atomic number and mass number for every known isotope. A careful comparison of the mass number of an atom (as given in the periodic table) to the sum of the masses of its nucleons reveals a **mass defect**. This means that the sum of the individual masses of the nucleons of an atom is always slightly greater than the actual, measured mass of the atom's nucleus. The "missing mass" actually exists in the form of energy, which is used to hold the nucleus together. This **binding energy** is the amount of energy that would be needed to separate all of the nucleons of an atom's nucleus.

In nuclear physics, the joule is not a very convenient unit of measure to use for energy. Instead, a much smaller unit, called the mega-electron volt (MeV), is more useful. An electron-volt (eV) is defined as the amount of energy given to an electron when it is accelerated through a potential difference of 1 V: $1.602 \times 10^{-19} \text{J}$. The **mega-electron volt** is one million times this value:

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$$

In the following Tutorial you will determine the mass defect of a parent atom in a nuclear fission reaction and then use Einstein's equation to calculate the energy released in the reaction.

### Tutorial 1  Calculating the Mass Defect and Binding Energy

We can calculate the mass defect of a nucleus by comparing the total mass of its nucleons to the nucleus’s actual mass. Note that we will use delta notation in this problem. $\Delta m$ is chosen to represent the *difference* in mass between the mass of the nucleus and the mass of its component nucleons. Once the mass defect is known, we can use Einstein’s equation to calculate the corresponding binding energy that holds the nucleus together. We will use this strategy in the following Sample Problem.

#### Sample Problem 1

Determine the mass defect and binding energy of a lithium-7 nucleus, given that its atomic mass is 7.00967 u.

In this problem, the mass of a nucleus and the masses of its component nucleons are given. The difference of these represents the mass defect. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the binding energy, $\Delta m$.

**Given:** $m = 7.00967 \text{ u}$

**Required:** $E$, energy

**Analysis:** $E = \Delta mc^2$

**Solution:** A lithium-7 nucleus has three protons and four neutrons. Their total mass can be found by using the information given in Table 1:

$$3m_p + 4m_n = 3(1.007276 \text{ u}) + 4(1.008665 \text{ u}) = 7.056488 \text{ u}$$

Subtract the actual atomic mass of Li-7 to calculate the mass defect, $\Delta m$:

$$\Delta m = 7.056488 \text{ u} - 7.00967 \text{ u} = 0.046818 \text{ u}$$

Therefore, the mass defect of lithium-7 is 0.046818 u.

Multiply 0.046818 u by $1.66 \times 10^{-27} \text{ kg/u}$ to convert atomic mass units to kilograms:

$$\Delta m = (0.046818 \text{ u}) \left(1.66 \times 10^{-27} \text{ kg/u}\right) = 7.7718 \times 10^{-29} \text{ kg} \text{ (two extra digits carried)}$$
Substitute $7.7718 \times 10^{-29} \text{ kg}$ and the speed of light $(3.0 \times 10^8 \text{ m/s})$ into $E = \Delta mc^2$:

$$E = (7.7718 \times 10^{-29} \text{ kg})(3.0 \times 10^8 \text{ m/s})^2$$

$$= 6.995 \times 10^{-12} \text{ kg} \cdot \text{m}^2/\text{s}^2 \text{ (two extra digits carried)}$$

$$= 6.995 \times 10^{-12} \text{ J}$$

The binding energy of a lithium-7 nucleus is $6.995 \times 10^{-12} \text{ J}$.

We can convert this to MeV by dividing by the number of joules in a mega-electron volt:

$$E = \frac{6.995 \times 10^{-12} \text{ J}}{1.602 \times 10^{-13} \text{ J/MeV}}$$

$$= 43.7 \text{ MeV}$$

**Statement:** The binding energy of a lithium-7 nucleus is 43.7 MeV.

**Practice**

1. The mass of a helium-4 atom is 4.002603 u.
   (a) Determine the mass defect of a helium-4 atom. [ ans: 0.030377 u ]
   (b) Determine the binding energy of a helium-4 atom. [ ans: 28.3 MeV ]

---

**Nuclear Fuel**

Nuclear fuel is the radioactive material that is used to power a nuclear reactor. When nuclear fission occurs, the binding energy that gets released can be harvested. Nuclear power reactors are designed to harvest the binding energy that is released during the nuclear fission process. Some heavy radioactive isotopes, that is, those with very large mass numbers, undergo nuclear fission when struck by a neutron. For example, uranium-235 can be split into krypton-92 and barium-141, as shown in Figure 2.

![Figure 2: Nuclear fission of uranium-235](image)

The equation for this nuclear reaction is

$$^{235}_{92}\text{U} + \frac{1}{n} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3(\frac{1}{n}) + \text{energy}$$

Parent isotopes such as U-235 that can undergo nuclear fission are said to be fissionable. Some other examples of fissionable isotopes are thorium-232, uranium-233, and plutonium-239. Fissionable isotopes are the nuclear fuel used in nuclear fission reactors.

What makes nuclear fission such a desirable process for power generation is the large quantity of energy that is produced per nuclear reaction. In comparison, the amount of energy produced in a nuclear fission reaction is about seven million times as great as the energy released when the same mass of dynamite explodes.

**Chain Reactions**

The products of the nuclear fission reaction shown above include three neutrons and energy. The energy is harvested but, more important, some of the neutrons produced in the reaction are used to generate further reactions. If enough fuel is present, a chain
reaction can be established. A chain reaction is a series of reactions that can repeat and sustain itself over several cycles (Figure 3). The products of one reaction produce subsequent reactions. The amount of nuclear fuel necessary to establish a chain reaction is called the critical mass.

**Figure 3** Chain reaction induced by the fission of U-235

**Neutron Moderation**

The neutrons that are released from the fission of U-235 are typically too high in energy to be absorbed by another U-235 nucleus. They must be slowed down, or moderated. In a CANDU reactor, neutrons are moderated by surrounding the fuel elements with heavy water, which is water that contains a high level of deuterium. Heavy water, which is about 10% heavier by mass than normal water, also serves to reduce neutron leakage from a reactor core. Heavy water is about 11% denser than normal water.

Neutrons that have been slowed down using heavy water are called thermal neutrons, because their kinetic energy is at about the same level as the other materials around them. Once a high-energy neutron has been moderated, it can be absorbed by another U-235 nucleus, eventually establishing a chain reaction.

Fissionable materials that can sustain a chain reaction such as this are said to be fissile. Thus, uranium-235 is a fissile material. Plutonium-239 is another fissile fuel that is used in nuclear fission reactors. In the following Tutorial, you will calculate the energy released in a nuclear fission reaction.

**Tutorial 2 Calculating Energy Yield in a Fission Reaction**

We can calculate the energy released in a fission reaction by calculating the mass defect between the reactant and product nuclides of the reaction and then converting this to its energy equivalent using Einstein’s equation, \( E = mc^2 \).
Sample Problem 1

What is the energy yield of the following fission reaction? Use the given masses below.

\[
\frac{235}{92}\text{U} + \frac{1}{1}\text{n} \rightarrow \frac{139}{53}\text{Cs} + \frac{92}{37}\text{Rb} + 3\left(\frac{1}{1}\text{n}\right)
\]

mass of U (\(m_U\)) = 235.044 u
mass of Cs (\(m_{Cs}\)) = 139.909 u
mass of Rb (\(m_{Rb}\)) = 92.917 u
mass of neutron (\(m_n\)) = 1.009 u

In this problem, the masses of the parent and daughter nuclides are known. Calculate the mass defect and then calculate its equivalent amount of energy.

**Given:** \(m_U = 235.044\) u; \(m_{Cs} = 139.909\) u; \(m_{Rb} = 92.917\) u; \(m_n = 1.009\) u

**Required:** energy released

**Analysis:** \(E = \Delta mc^2\)

**Solution:** Note that the reaction equation can be simplified by subtracting one neutron from each side:

\[
\frac{235}{92}\text{U} + \frac{1}{1}\text{n} \rightarrow \frac{139}{53}\text{Cs} + \frac{92}{37}\text{Rb} + 3\left(\frac{1}{1}\text{n}\right)
\]

Calculate the mass defect:

\[
\Delta m = m_U - (m_{Cs} + m_{Rb} + 2m_n)
\]

\[
= 235.044\text{ u} - [139.909\text{ u} + 92.917\text{ u} + 2(1.009\text{ u})]
\]

\[
= 235.044\text{ u} - 234.844\text{ u}
\]

\[
= 0.200\text{ u}
\]

Convert to kilograms:

\[
0.200\text{ u} = 0.200\text{ u} \left(\frac{1.66 \times 10^{-27}\text{ kg}}{\text{u}}\right)
\]

\[
= 3.320 \times 10^{-28}\text{ kg}
\]

The mass of the products is \(3.320 \times 10^{-28}\) kg less than the mass of the reactants. Determine the amount of energy:

\[
E = \Delta mc^2
\]

\[
= (3.320 \times 10^{-28}\text{ kg})(3 \times 10^8\text{ m/s})^2
\]

\[
= 2.988 \times 10^{-11}\text{ kg m/s}
\]

\[
= 2.988 \times 10^{-11}\text{ J}
\]

**Statement:** The nuclear fission reaction releases \(2.99 \times 10^{-11}\text{ J}\) of energy per reaction.

**Practice**

[TO COME]

---

**CANDU Reactors**

A simplified schematic of a CANDU reactor is shown below in Figure 4.

**Components of a CANDU Reactor**

The calandria, or core, of the reactor is where the fission process occurs (Figure 5). As neutrons and thermal energy are produced, heavy water serves the dual purpose.
of moderating neutrons and absorbing thermal energy. As the heavy water cycles through the primary loop, this thermal energy is transferred to the steam generator. This cools the heavy water, which then returns to the core to repeat the cycle.

The steam generator uses the thermal energy absorbed from the heavy water in the primary loop to heat light (normal) water in the secondary loop, producing steam. This steam is sent to the steam turbine, where its high pressure causes the steam turbine to turn. An electrical energy generator is then used to convert this mechanical energy into electrical energy, which can then be delivered to the electrical power network.

Control rods are used to control the rate of nuclear reaction. These consist of highly neutron-absorbent material, such as cadmium, boron, gadolinium, or hafnium. In CANDU reactors, adjustable cadmium rods are used. Adjusting the insertion level of the rods controls the reaction rate. To slow the reactor down, the rods are inserted farther into the core, allowing for greater neutron absorption by the cadmium. To accelerate the reactor, the rods are moved out of the core, reducing the absorption rate.

**CANDU REACTOR FUEL**

CANDU reactors, as the “U” in their name implies, use uranium as their fuel. The core consists of a number of fuel bundles, as shown in Figure 6. Each fuel bundle consists of several enriched uranium fuel pellets. These fuel bundles are responsible for driving the chain reaction within the reactor core.

Only 0.72% of naturally occurring uranium is U-235. The most abundant isotope is U-238, which accounts for 99.27%. Unfortunately, pure U-238 is not useful as a fuel for CANDU reactors because it does not react in the same way as U-235. For this reason, CANDU reactors use **enriched fuel**, which contains a higher than normal percentage of U-235.
SAFETY CONSIDERATIONS

Safety is always a concern when dealing with radioactive materials. In a nuclear reactor facility it is important to ensure that workers are protected from the harmful effects of radiation. Nuclear reactor design engineers must take this into account when choosing materials for reactor core shielding.

Despite all precautions, it is inevitable that workers in a nuclear reactor facility will be exposed to some level of radiation. Tiny levels of radiation exposure are not dangerous; in fact we are all subjected to background levels of radiation in everyday life. But it is important in a nuclear facility to closely monitor exposure levels and ensure that they are kept within safe boundaries. For this reason all workers in a nuclear facility wear badges that indicate their level of radiation exposure. This badge, called a dosimeter, contains photographic film that becomes exposed when subjected to radiation.

CANDU fission reactors are famous worldwide for their safety record. One of the key design features is the way that the cadmium control rods are arranged. The rods are inserted into the core vertically from above, suspended by electrically controlled magnets. The rods are lowered into the core to reduce reaction rates, and lifted to increase them. If there is any disruption in electrical power to the reactor, the magnets automatically turn off, causing the rods to drop completely into the core. This immediately stops the chain reaction, ensuring a safe reactor shutdown.

WASTE DISPOSAL

Although nuclear reactors do not emit harmful pollutants into the atmosphere, radioactive waste must be dealt with. Radioactive waste consists of radioactive by-products of nuclear power generation that are generally not useful for other purposes. These materials must be safely stored in containers with sufficient shielding capacity, in some cases for hundreds of years.

**Research This**

**Breeder Reactors**

**Skills:** Researching, Analyzing

One way to obtain rare, but useful, isotopes to use as nuclear fuel is to produce them in a breeder reactor.

1. Research breeder reactors on the Internet or in the library. Write a brief report of your findings or design a poster that includes answers to the following questions.

   A. What is a breeding chain?  
   B. Provide an example of a breeding chain. Identify the isotope that occurs at each reaction stage.  
   C. Write reaction equations for each stage of the breeding chain. Identify the type of decay that occurs at each stage. Which of these reactions are transmutations? Explain.  
   D. Which isotopes are commonly produced in breeder reactors?
7.4 Summary

- Albert Einstein was the first person to propose that mass and energy are equivalent and related by \( E = mc^2 \).
- The law of conservation of mass and energy states that the total mass and energy in any reaction remains constant.
- Energy is released in a nuclear fission reaction; the amount of released energy is equivalent to the mass defect.
- CANDU fission reactors use enriched uranium as a fuel and heavy water as a moderator.
- Heavy water in a CANDU reactor is used to slow neutrons and absorb thermal energy from the core.
- Workers who may come into contact with radioactive materials are required to wear a dosimeter to monitor radiation exposure levels.
- Nuclear waste disposal is a complex issue whose long-term solution is still under development.

7.4 Questions

1. Determine the energy equivalent, in joules, of
   (a) an electron
   (b) a proton

2. A small sample of coal, when completely converted to energy, releases \( 4.5 \times 10^{14} \) J. Determine the original mass of the coal. Assume that the final mass is zero.

3. Calculate the energy released in the following nuclear reaction, given the known masses indicated.
   \( ^{238}\text{U} \rightarrow ^{232}\text{Th} + \frac{3}{2}\text{He} \)
   \( m_{\text{U-238}} = 236.045662 \) u
   \( m_{\text{Th-232}} = 232.038051 \) u
   \( m_{\text{He-4}} = 4.002602 \) u

4. Calculate the energy released in the following reaction, given the known masses indicated.
   \( ^{232}\text{U} \rightarrow \text{He} + ^{114}\text{Sn} + \frac{1}{2}^{}\text{Xe} + 11(\text{n}) \)
   \( m_{\text{U-238}} = 234.883 \) u
   \( m_{\text{He-90}} = 89.886 \) u
   \( m_{\text{Xe-135}} = 134.879 \) u

5. The following shows the products of a uranium-238 decay series:
   \( ^{238}\text{U} \rightarrow ^{234}\text{Th} \rightarrow ^{234}\text{Pa} \rightarrow ^{234}\text{U} \rightarrow ^{234}\text{Th} \rightarrow ^{238}\text{Ra} \)
   (a) Write a nuclear reaction equation for each stage of this series. Assume that beta decay reactions are beta-negative.
   (b) Identify each reaction by type of decay. Explain your answers.

6. Refer to Question 5. This series of reactions is part of a longer one known as the uranium-lead series.
   (a) Research this series and identify the other reactions involved.
   (b) What is the final stable isotope?

7. Summarize the safety issues related to nuclear fission reactors.

8. Explain how CANDU reactors are designed to prevent danger due to electrical power loss.

9. The following illustrates the breeding chain used to produce plutonium-239 from uranium-238 in a breeder reactor. The process is initiated by bombarding U-238 with high-energy neutrons:
   \( ^{238}\text{U} + \text{n} \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Pu} \)
   Classify the nuclear reactions occurring at each stage of this breeding cycle as alpha decay, beta decay, or electron capture. Then write a reaction equation for each stage.

10. Another breeding chain involves the transmutation of thorium-233 to uranium-233. This occurs in three stages: first a neutron is absorbed by a Th-233 nucleus, and then the daughter isotope undergoes beta-negative decay twice. Write the series of nuclear reaction equations for this breeding chain. Identify parent and daughter isotopes and their mass numbers and atomic numbers for each stage.
Nuclear Fusion

What powers the stars, such as our Sun (Figure 1)? Will stars burn forever or will they die out? A particular type of nuclear reaction powers the stars, and knowledge of these reactions can help us understand how stellar objects are formed and how they die. These reactions can also potentially provide society with a clean, renewable source of power.

Unlike fossil fuel reactors, nuclear fission reactors are very clean in the sense that they emit virtually no pollutants into the atmosphere. However, fission reactors do have some negative environmental effects. The radioactive waste products are potentially harmful if not disposed of properly. This issue has led scientists to seek a cleaner source of power in the form of nuclear fusion. **Nuclear fusion** is the fusing of two nuclei to form a heavier element. Nuclear fusion is the opposite process of nuclear fission, in which heavier nuclei split apart to form lighter products.

In order for nuclear fusion to occur, the fusing nuclei must have sufficient kinetic energy to overcome the repulsive electrostatic force between them. This allows them to get close enough to each other for the strong nuclear force to take effect. This is not an easy task to achieve in the laboratory, much less in a power reactor.

**Nuclear Stability**

Under what conditions are nuclear fission and nuclear fusion most likely to occur? To understand this, we need to consider the relative stability of heavy and light isotopes. **Figure 2** illustrates the binding energy per nucleon of all stable elements. The higher the binding energy value, the more stable is the nuclide.

![Binding energy per nucleon](image)

*Figure 2* Binding energy as a function of mass number

Notice that this binding energy graph rises sharply, reaching a maximum at \( A = 56 \), before gradually decreasing. This suggests that iron-56 is the most stable of all nuclides, with the most tightly bound nucleus.

Consider the right side of the graph: the heavier nuclides. When a heavy nuclide undergoes nuclear fission, its daughter nuclides typically have mass numbers that average around 118, which is closer to the region of maximum stability. The binding energy of the daughters of a fission reaction is therefore greater than that of the parent. The products are more stable than the reactant.

Consider the left side of the graph: the lighter nuclides. When these atoms fuse together to form a heavier nuclide, the binding energy increases sharply, with the reaction again producing a product that is closer to the region of maximum stability. The product is more stable than the reactants.

Nuclear fission is therefore more likely to occur with very heavy nuclides, while nuclear fusion is more likely to occur with very light nuclides. In both situations,
however, the total binding energy increases during the reaction. This implies that the mass defect has increased, which corresponds to a release of energy. Both fission and fusion reactions are highly exothermic.

By calculating the energy released in each type of reaction, you can make a more accurate comparison between the relative energy output of a nuclear fusion reaction and that of a nuclear fission reaction. For problems such as this, consider the energy equivalent of 1 atomic unit of mass, measured in MeV:

\[ E = mc^2 \]

\[ = (1.66 \times 10^{-27} \text{ kg})(3.0 \times 10^8 \text{ m/s})^2 \times \frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}} \]

\[ = 930 \text{ MeV} \]

Since this is the energy of 1 atomic mass unit (1 u), we can use

\[ mc^2 = (1 \text{ u})c^2 = 930 \text{ MeV} \text{ or } (1 \text{ u})c^2 = 930 \text{ MeV/u} \]

Dividing both sides by 1 u yields an alternative representation of \( c^2 \):

\[ c^2 = 930 \text{ MeV/u} \]

In the following Tutorial you will determine the mass defect and use it to calculate the energy produced in a fusion reaction and a fission reaction.

**Tutorial 1** Using the Mass Defect to Compare the Energy Output of Fusion and Fission Reactions

**Sample Problem 1**

Determine the energy released when a deuterium atom fuses with a tritium atom to form helium, according to the nuclear reaction equation

\[ ^{3}\text{H} + ^{3}\text{H} \rightarrow ^{4}\text{He} + ^{1}\text{n} + \text{energy} \]

given that

\[ m_0 = 2.01410 \text{ u} \]
\[ m_T = 3.01605 \text{ u} \]
\[ m_{\text{He}} = 4.00260 \text{ u} \]
\[ m_n = 1.00867 \text{ u} \]
\[ c^2 = 930 \text{ MeV/u} \]

In this problem, the masses of the parent and daughter nuclides of a fusion reaction are given. Since the mass defect is related to the binding energy, use \( E = \Delta mc^2 \) to calculate the energy released.

**Given:**

\[ m_0 = 2.01410 \text{ u}; m_T = 3.01605 \text{ u}; m_{\text{He}} = 4.00260 \text{ u}; m_n = 1.00867 \text{ u}; c^2 = 930 \text{ MeV/u} \]

**Required:** \( E \)

**Analysis:** \( E = \Delta mc^2 \)

**Solution:** First, calculate the mass defect, \( \Delta m \).

\[ \Delta m = (m_0 + m_T) - (m_{\text{He}} + m_n) \]
\[ = (2.01410 \text{ u} + 3.01605 \text{ u}) - (4.00260 \text{ u} + 1.00867 \text{ u}) \]
\[ = 5.03015 \text{ u} - 5.01127 \text{ u} \]
\[ = 0.01888 \text{ u} \]

Substitute 0.01888 u into \( E = \Delta mc^2 \) to determine the binding energy.

\[ E = \Delta mc^2 \]
\[ = (0.01888 \text{ u})(930 \text{ MeV/u}) \]
\[ = 17.6 \text{ MeV} \]
Statement: 17.6 MeV of energy is released when a deuterium atom fuses with a tritium atom to form helium.

Sample Problem 2
Determine the energy released when uranium-235 fissions to produce cesium-140 and zirconium-94, according to the nuclear reaction equation

\[ {}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{139}_{58}Cs + {}^{94}_{40}Zr + 2({}^{1}_{0}n) + \text{energy} \]

given that

\[ m_{U-235} = 235.0439 \text{ u} \]
\[ m_{Cs-140} = 139.9055 \text{ u} \]
\[ m_{Zr-94} = 93.9065 \text{ u} \]
\[ m_{n} = 1.00867 \text{ u} \]
\[ c^2 = 930 \text{ MeV/u} \]

In this problem, the masses of the parent and daughter nuclides of a fission reaction are given. Since the mass defect is related to the binding energy, use \( E = \Delta mc^2 \) to calculate the energy released.

Given: \( m_{U-235} = 235.0439 \text{ u} \); \( m_{Cs-140} = 139.9055 \text{ u} \); \( m_{Zr-94} = 93.9065 \text{ u} \); \( m_{n} = 1.00867 \text{ u} \);
\( c^2 = 930 \text{ MeV/u} \)

Required: \( E \)

Analysis: \( E = \Delta mc^2 \)

Solution: Calculate the mass defect. Notice that one neutron can be cancelled on either side of the reaction equation.

\[ \Delta m = m_{U-235} - (m_{Cs-140} + m_{Zr-94} + m_{n}) \]
\[ = 235.0439 \text{ u} - (139.9055 \text{ u} + 93.9065 \text{ u} + 1.00867 \text{ u}) \]
\[ = 0.22323 \text{ u} \]

Substitute into \( E = \Delta mc^2 \) to determine the binding energy.

\[ E = \Delta mc^2 \]
\[ = (0.22323 \text{ u})(930 \text{ MeV/u}) \]
\[ = 208 \text{ MeV} \]

Statement: 208 MeV of energy is released when U-235 undergoes fission to produce Cs-140 and Zr-94.

Practice
1. One type of stellar fusion reaction is the burning of helium to form carbon. The reaction equation for this process is

\[ {}^{3}_{2}\text{He} + {}^{4}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + \text{energy} \]

The masses of the parent and daughter atoms are \( m_{\text{He}} = 4.00260 \text{ u} \) and \( m_{\text{C}} = 12.00000 \text{ u} \).

(a) Calculate the mass defect for this reaction. \[ \text{[ans: 0.0078 u]} \]

(b) Determine the energy released in this reaction. \[ \text{[ans: 7.3 MeV]} \]

(c) What is the energy released per nucleon? \[ \text{[ans: 0.61 MeV/nucleon]} \]

The calculations you performed in Tutorial 1 suggest that fission produces more energy than fusion. Note, however, that the uranium-235 in the fission reaction has about 50 times more mass than the reactants in the fusion reaction. So, on a per mass basis, fusion typically yields significantly more energy than fission.
The Quest for Controlled Nuclear Fusion

Achieving nuclear fusion in a laboratory is extremely difficult. The only natural conditions that allow for nuclear fusion to occur are in the cores of stars, where the pressure, temperature, and density of nuclides are tremendous. Even under such conditions, the probability of a nuclear interaction resulting in fusion is extremely low. It is only because of the huge number of interactions that many successful fusion reactions occur.

Stellar Fusion

In the interiors of stars, temperatures and pressures can build to the extremely high levels necessary for fusion to occur. Two of the common processes in which stellar fusion occurs are described below.

PROTON-PROTON CHAIN

Fusion occurs in stars the size of the Sun and smaller through a process called the proton-proton chain. In this series of reactions, four protons eventually fuse to form one helium-4 atom. The net reaction in a proton-proton chain can be described by the following equation:

\[ 4(\text{H}) \rightarrow ^{3}\text{He} + 2(\text{e} + \text{ν}) + \text{energy} \]

Notice that two of the four protons become a neutron and an electron. Conversion of hydrogen to helium in the core of a star is just the first step in the production of all of the naturally occurring elements listed in the periodic table. In this sense, stars can be thought of as the factories of all matter. The processes of forming larger elements from smaller ones via nuclear fusion are collectively known as nucleosynthesis.

CARBON-NITROGEN-OXYGEN CYCLE

Another process occurs in stars that are significantly larger, and hotter, than the Sun. The carbon-nitrogen-oxygen cycle activates the fusion of hydrogen into helium. In this cycle, a carbon-12 nucleus undergoes a number of nuclear reactions involving fusion and decay. A summary of these is shown below. Notice that this cycle begins and ends with a carbon-12 atom.

This series of nuclear reactions produces large quantities of energy. The high-energy yield of the carbon-nitrogen-oxygen cycle has been a strong motivating factor for scientists to develop technologies for producing controlled nuclear fusion. However, another important factor makes nuclear fusion better than fission from an environmental standpoint. Nuclear fission reactors produce radioactive waste that is potentially harmful to humans and their environment. During the process of nuclear fusion, far less radioactive waste is produced. This makes nuclear fusion, theoretically at this point, our cleanest potential source of energy.

Modern Advances in Nuclear Fusion

MAGNETIC CONFINEMENT FUSION

One of the most promising methods for controlling nuclear fusion is based on the principle of magnetic confinement. Deuterium and tritium are placed in the core of the reactor and heated to an extremely high temperature, comparable to that of the Sun's core. When this happens, the materials change to the fourth state of matter, called plasma. Plasma is the fluid state of matter in which all atoms are ionized. These are the required conditions for nuclear fusion to occur.

The challenge, however, is how to confine matter that is in such a high thermal energy state. In the Sun, the enormous attractive gravitational forces due to its...
immense mass are sufficient to confine the plasma. This is not practical, however, for the masses of fuels suited to a laboratory or reactor. To achieve plasma confinement under laboratory conditions, a superconducting electromagnet is placed around the core in the shape of a toroid (donut shape) as shown in Figure 3. When a high current is passed through the coil, a very powerful magnetic field is produced, which confines the plasma.

![Figure 3 Magnetic confinement fusion reactor design](image)

Theory suggests that with the plasma state achieved, and the fuel magnetically confined, fusion can occur, resulting in the release of energy. While there have been some reports of successful trials of controlled nuclear fusion in laboratory conditions, none have yet been achieved that can sustain a chain reaction. This is the ultimate goal that must be achieved if we are to use nuclear fusion as a practical energy source.

**THE ITER PROJECT**
The ITER project is an international joint effort aimed at developing a functional nuclear fusion reactor for research purposes. The ITER reactor in Cadarache, France, is a type of magnetic confinement fusion reactor called a Tokamak (Figure 4). This very expensive project has provoked controversy from skeptics who feel that too much money will be wasted with little return on investment. Canada, originally a participant, has withdrawn due to lack of funding. Critics of the project also voice objections to the experimental nature of the facility.

![Figure 4 ITER Tokamak reactor design](image)

**LEARNING TIP**
Superconducting Electromagnets
A superconductor is a material with little to no electrical resistance. A superconducting electromagnet produces powerful magnetic fields when current is applied. You will learn more about electromagnets in Chapter 13.

**WEB LINK**
To learn more about the ITER Tokamak reactor, go to NELson Science.

**Investigation 7.5.1**
Nuclear Energy: Benefit or Hazard? [TEXT TO COME]

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**Summary**
- Nuclear fusion is the process by which lighter atoms fuse together to form heavier atoms.
- Nuclear fusion reactions are exothermic and produce significantly more energy per mass of fuel than fission reactions.
- Nuclear fusion is a potential source of clean energy, producing little pollution or waste.
- Magnetic confinement fusion is a method in which electromagnetic forces are used to confine fusion fuel that is in a very high temperature, plasma state.
- Controlled nuclear fusion has been achieved, but not in a sustainable way.
- The ITER project is the first significant international attempt to create a functioning nuclear fusion research reactor.

See overset Matter
Questions

1. Compare and contrast nuclear fission and nuclear fusion. How are these reactions alike? How are they different?

2. (a) Explain why nuclear fusion is more difficult to achieve than nuclear fission.
   (b) Why is nuclear fusion more desirable than nuclear fission for power generation?

3. Use the following values to answer parts (a) and (b).

   \[
   m_{^1H} = 1.007825 \text{ u}; \quad m_{^12C} = 12.00000 \text{ u}; \quad m_{^13C} = 13.00335 \text{ u}; \quad m_{^14N} = 14.00307 \text{ u}
   \]

   (a) Determine the amount of energy released in the third stage of the carbon-nitrogen-oxygen cycle:
   \[
   ^{12}_6C + ^1_1H \rightarrow ^{13}_7N + \text{energy}
   \]

   (b) In the first stage of the carbon-nitrogen-oxygen cycle, 1.95 MeV is produced per reaction:
   \[
   ^{13}_7N \rightarrow ^{12}_6C + ^0_1e + \text{energy}
   \]

   Use this information to determine the mass of a nitrogen-13 nucleus.

4. Refer to Tutorial 1.
   (a) Determine the energy released per nucleon for the fission and fusion reactions in Sample Problems 1 and 2.
   (b) What is illustrated by comparing these energy values?

5. Deuterium can be extracted from regular water, and tritium is a waste product of CANDU reactors. What does this suggest about the fuel availability for nuclear fusion reactors?

6. Consider the carbon-nitrogen-oxygen cycle:

   \[
   ^{12}_6C \rightarrow ^{13}_7N \rightarrow ^{12}_6C \rightarrow ^{14}_7N \rightarrow ^{15}_8O \rightarrow ^{13}_7N \rightarrow ^{12}_6C + ^1_0n
   \]

   The first two reaction equations of this cycle are given below:

   \[
   ^{13}_7N \rightarrow ^{12}_6C + ^1_0e + \text{energy}
   \]

   (a) Which of these is a fusion reaction? Explain.
   (b) Which of these is a beta-decay reaction? What type of beta-decay is it? Explain how you know.
   (c) Write the remaining reaction equations for this cycle and classify each by type of nuclear reaction. Assume that the beta decay reactions are of the same type as the one given above.

7. Perform some research on nuclear fusion techniques. What are some alternative methods for controlling nuclear fusion that have not been discussed in this section? Write a sentence or two to describe how each of these works. Include diagrams to support your explanations.

8. Conduct research on the ITER project. What advances have been made since the publication of this text?
Insect infestation can be extremely harmful in a variety of direct and indirect ways. Some insects carry and transmit diseases, which can harm, or potentially kill, humans, livestock, or crops. Think about what happens when an entire farm crop is damaged, or when a farmer's livestock is destroyed by disease. The economic and environmental consequences of uncontrolled pests can be devastating.

Chemical pesticides have been used for thousands of years to control the damaging effects of pests on crops. Recently, environmentalists have drawn attention to the harmful effects these toxins have on the environment. Some claim that the long-term costs may outweigh the short-term benefits of chemical pest control. In an effort to address these environmental issues, some jurisdictions have now banned the use of chemical pesticides. Scientists, meanwhile, look toward alternative options.

During the 1950s, a parasitic insect known as the screwworm (Figure 1) was responsible for destroying many cattle in North America. Screwworm flies lay eggs in animals such as cows. When the larvae hatch, they feed on the animal's flesh. The losses to the beef and dairy industries were devastating. Scientists turned to X-ray technology as an alternative to chemical pesticides to deal with this problem. They used X-rays to sterilize males of the species, so that when they mated, no offspring were produced. This is one of the earliest uses of radiation technology for pest control purposes. While there have been no noticeable negative side effects observed to date, the long-term consequences of removing any species from a biological system remain unknown.

The tsetse fly (Figure 2) is another pest that has been responsible for transmitting a potentially fatal disease called African trypanosomiasis, more commonly known as sleeping sickness. Prevalent in parts of Africa, this disease is responsible for approximately 40,000 human deaths per year.

**The Application**

An interesting characteristic of the tsetse fly is that the female typically mates only once in her lifetime. Scientists have used this fact to eradicate tsetse populations on the African island of Zanzibar. Large numbers of male tsetse flies are bred in the laboratory and then sterilized using radiation. These sterile males are then introduced into regions where sleeping sickness occurs. Once a female has mated with a sterile
male, she does not reproduce. This method of pest control is called the **sterile insect technique (SIT)**.

Nuclear methods for pest control represent a relatively young field of scientific study, and public awareness is not very high. Some people have voiced objections to using techniques such as SIT. The danger of exposure to nuclear radiation remains a concern whenever dealing with radioactive materials. There are also those who argue against widespread sterilization, claiming that such measures are disruptive to our natural ecological order. As with many applications of nuclear technology, the benefits must be measured against the risks and costs.

**Your Goal**

Your goal is to inform the public about the benefits, risks, and costs of nuclear methods of pest control as compared to alternative methods. Identify an area related to these techniques that may require further research or long-term monitoring.

**Research**

Conduct library or Internet research about nuclear techniques for pest control and their alternatives. What are some cases in which nuclear methods for pest control are used that were not described in this section? In each case describe

- the pest
- the danger it poses
- technique(s) used to control the pest
- any negative environmental or ecological effects resulting from the technique
- any unanticipated side effects

**Summarize**

Use the following questions to summarize your research:

- How does nuclear pest control work?
- Is it safe?
- Is it a viable alternative to other, traditional methods?
- Does everyone have access to these techniques?
- Are there conditions in which these techniques would or would not be preferred?
- What are the benefits, risks, and costs of using nuclear pest control techniques?
- Summarize how nuclear pest control compares to other pest control techniques.

**Communicate**

Summarize your findings and present them in one of the following ways:

- slide presentation
- news article
- video
- brochure
- website
- written report
- wiki
- poster
- other

**WEB LINK**

To learn more about nuclear pest control

[GO TO NELSON SCIENCE](#)
Investigation 7.5.1 CORRELATIONAL STUDY

Nuclear Energy: Benefit or Hazard?

Throughout this chapter you have learned how nuclear energy has been applied in various ways to improve our lives. You have also learned about the hazards and risks associated with using radioactive materials. Whether or not society should continue to use nuclear technology remains a controversial issue, one that you will have the opportunity to explore in this activity. What is the public opinion on uses of nuclear energy? How well informed are people about the benefits and hazards of nuclear power reactors? Are people generally aware of other applications of nuclear technology, such as medical treatments and carbon dating? Are there any differences in public opinion related to education, gender, or other variables such as nationality? Has public opinion remained constant regarding the nuclear power controversy or has it changed over time?

Purpose
In this investigation you will design and carry out a correlational study that provides insight into public awareness and public opinion regarding the uses of nuclear technology.

Variables
When conducting a correlational study, you are looking for trends or patterns between two or more variables. For example, one might ask, “Is there a relationship between support for nuclear power generation and education level?” In this case, education level is the independent variable and level of support is the dependent variable. If you explore how public opinion changes over time, then time is the independent variable.

The following are some samples of dependent and independent variables to consider. You can choose from these or use other variables for your study.
- dependent variables: support for nuclear fission reactors, support for investing in nuclear fusion research, attitudes toward nuclear medicine
- independent variables: age, gender, education level, nationality, socio-economic status, time

Study Design
In this correlational study you will collect and analyze online secondary data related to nuclear issues. Secondary data consist of data that has already been collected for another purpose by someone else, such as the Canadian Energy Research Institute. Once you have collected the data, you will use software to analyze and present your findings.

Equipment and Materials
- Internet access
- library resources
- data analysis software (optional)
- spreadsheet software (optional)
- presentation software (optional)

Procedure
1. Choose a dependent variable and an independent variable to study. Express your topic in the form of a question, such as, “Is there a correlation between education level and support for nuclear power plants?”
2. Find secondary data on the Nelson Science website or from another source of your choice. Look for any trends or patterns. You may wish to adjust your topic slightly depending on data availability and the trends that you discover.
3. Refine and restate your independent and dependent variables in the form of a question. For example, the question above could be rewritten as, “Is there a correlation between education level and support for building more nuclear power plants in Canada?”
4. Capture and insert your data into a data analysis or spreadsheet software program. Software tools such as Fathom (dynamic statistics) and spreadsheets are excellent tools for manipulating and exploring large amounts of data. Examine the data using the following strategies:
   - Create one or more graphs that relate the dependent and independent variables.
   - Identify any trends in the data.
   - Calculate the correlational coefficient, \( r \), for any linear trends (\( r \) is a measure of goodness of fit; the closer \( r \) is to 1 or \(-1\), the stronger the linear correlation).
   - Identify any outliers (points that do not fit a trend) and discuss the impact of these outliers on the results.
Analyze and Evaluate

(a) To what extent does the data provide an answer to the question that you posed? Explain.

(b) Identify some unmeasured variables that could have influenced the results.

(c) Is the data conclusive, or would additional research provide additional information?

(d) Presentation software is useful for organizing and presenting your findings in a clear and persuasive way. Use presentation software, or another tool, to create a presentation that includes the following:
   - the question that you explored
   - identification of the independent and dependent variables
   - data you found related to your research, presented in the form of tables, graphs, or other visual organizers
   - an answer to the question that you posed (note that your final evaluation may or may not provide a clear answer to the question that you posed)
   - identification of other non-measured variables and their potential impact on your findings
   - suggestions for further research that could provide additional or related information on your topic

Apply and Extend

(e) How do your friends and family feel about the issue that you researched? Design a brief survey related to the question that you explored in this investigation that you can use to obtain primary data (data that you collect yourself). Then conduct your study with a number of people that you know.

(f) Analyze your findings for Question (e) using the tools and strategies you used in the Procedure. Compare and contrast these results to those you obtained based on the secondary data obtained online. Account for any discrepancies that you observe.
Summary Questions

1. Create a study guide based on the points in the margin on page XXX. Your study guide may be in written form or in a visual format such as a graphic organizer. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.

2. Look back at the Starting Points questions on page XXX. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

atomic structure (p. XXX)  exothermic (p. XXX)  gamma ray (p. XXX)  thermal neutron (p. XXX)
nucleus (p. XXX)  endothermic (p. XXX)  photon (p. XXX)  fissile material (p. XXX)
proton (p. XXX)  nuclear reaction (p. XXX)  gamma decay (p. XXX)  enriched fuel (p. XXX)
neutron (p. XXX)  electrostatic force (p. XXX)  ionizing radiation (p. XXX)  dosimeter (p. XXX)
nucleons (p. XXX)  strong nuclear force (p. XXX)  half-life (p. XXX)  radioactive waste (p. XXX)
electron (p. XXX)  stable atom (p. XXX)  atomic mass (p. XXX)  nuclear fusion (p. XXX)
ground state (p. XXX)  radioactive atom (p. XXX)  mass defect (p. XXX)  proton-proton chain (p. XXX)
extited state (p. XXX)  radioactive decay (p. XXX)  binding energy (p. XXX)  nucleosynthesis (p. XXX)
atomic number (p. XXX)  alpha decay (p. XXX)  mega-electron volt (p. XXX)  carbon-nitrogen-oxygen cycle (p. XXX)
mass number (p. XXX)  alpha particle (p. XXX)  nuclear fuel (p. XXX)  plasma (p. XXX)
radiation (p. XXX)  parent atom (p. XXX)  fissile isotope (p. XXX)  sterile insect technique (SIT)
radioisotope (p. XXX)  daughter atom (p. XXX)  nuclear fission reactor (p. XXX)  (p. XXX)
radioactivity (p. XXX)  transmutation (p. XXX)  nuclear fission (p. XXX)  chain reaction (p. XXX)
nuclear fission (p. XXX)  beta particle (p. XXX)  critical mass (p. XXX)  heavy water (p. XXX)
chemical reaction (p. XXX)  positron (p. XXX)  nuclear operator  

Career Pathways

List the careers mentioned in this chapter. Choose two of the careers that interest you, or choose two other careers that relate to Nuclear Energy. For each of these careers, research the following information:

- skill/personality/aptitude requirements
- potential employers
- salary
- duties/responsibilities

Assemble the information you have discovered into a brochure. Your brochure should compare and contrast your two chosen careers and explain how they connect to Nuclear Energy.

GO TO NELSON SCIENCE
To do an online self-quiz, go to NELSON SCIENCE.