14.4 Nuclear Reactions

What do you think of when you hear the terms *nuclear reactions* or *nuclear science*? You might think that anything involving nuclear reactions is considered controversial. Why might that be? For starters, a great deal of energy can be produced by nuclear reactions, and humans need energy constantly. You were introduced to the structure of the atom and the forces that hold atoms together in Chapter 12. In this section, you will learn about reactions that occur within the nuclei of atoms.

Chemical vs. nuclear reactions

Chemical reactions When you mix two compounds such as calcium carbonate ($CaCO_3$) and hydrochloric acid (HCl), something happens (Figure 14.21). In this case, you get calcium chloride (CaCl), carbon dioxide (CO_2), and water (H_2O). In the transition between the reactants and the products of a chemical reaction, either energy is mostly released (as in an exothermic reaction) or used (as in an endothermic reaction). The involvement of energy in chemical reactions has to do with the breaking and forming of chemical bonds. As you have learned, these bonds involve the outermost electrons of atoms.

Introducing nuclear reactions In the case of nuclear reactions, the main events and source of energy occur in the nuclei of the atoms involved. A **nuclear reaction** involves altering the number of protons and/or neutrons in an atom. Recall from Chapter 12 that protons have a positive charge, the opposite of electrons. The charge on a proton (+*e*) and an electron (–*e*) are exactly equal and opposite. Neutrons have zero electric charge (Figure 14.22).

Energy and reactions A great deal of energy is needed to begin a nuclear reaction. However, a great deal of energy is also released by this kind of reaction. Although they can produce a lot of energy, chemical reactions fall short of producing as much energy as nuclear reactions. For example, a coal power plant uses chemical reactions to produce energy and a nuclear plant uses nuclear reactions. The fuel for a nuclear power plant, uranium-235, can produce *3.7 million* times as much energy as an equivalent amount of coal!

VOCABULARY

nuclear reaction - a reaction in which the number of protons and/or neutrons is altered in one or more atoms.

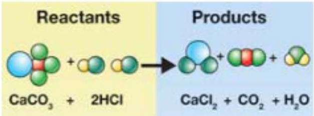


Figure 14.21: *A chemical reaction.*

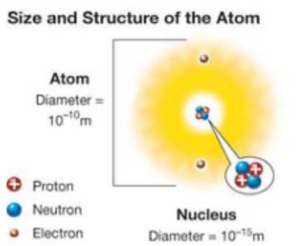


Figure 14.22: *Electrons are involved in chemical reactions. Protons and neutrons are involved in nuclear reactions.*

Radioactivity

What if there are too many neutrons? Almost all elements have one or more isotopes that are **stable**. Stable means the nucleus stays together. For complex reasons, the nucleus of an atom becomes unstable if it contains too many or too few neutrons relative to the number of protons. If the nucleus is unstable, it breaks apart. Carbon has two stable isotopes, carbon-12 and carbon-13. Carbon-14 is **radioactive** because it has an unstable nucleus. An atom of carbon-14 eventually changes into an atom of nitrogen-14.

Radioactivity If an atomic nucleus is unstable for any reason, the atom eventually changes into a more stable form. *Radioactivity* (also called *radioactive decay*) is a process in which the nucleus spontaneously emits particles or energy as it changes into a more stable isotope. Radioactivity can change one element into a completely different element.

Alpha decay When *alpha decay* occurs, the nucleus ejects two protons and two neutrons (Figure 14.23, top). Check the periodic table and you can quickly find that two protons and two neutrons are the nucleus of a helium-4 (He-4) atom. Alpha radiation is actually fast-moving He-4 nuclei. When alpha decay occurs, the atomic number is reduced by two because two protons are removed. The atomic mass is reduced by four because two neutrons go along with the two protons. For example, uranium-238 undergoes alpha decay to become thorium-234.

Beta decay *Beta decay* occurs when a neutron in the nucleus splits into a proton and an electron (Figure 14.23, middle). The proton stays in the nucleus, but the high-energy electron is ejected (this is called beta radiation). During beta decay, the atomic number increases by one because one new proton is created. The atomic mass stays the same because the atom lost a neutron but gained a proton.

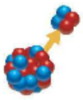
Gamma decay *Gamma decay* is how the nucleus gets rid of excess energy. In gamma decay, the nucleus emits pure energy in the form of gamma rays (Figure 14.23, bottom). The number of protons and neutrons stays the same.

VOCABULARY

stable - a term that describes an atomic nucleus that stays together.

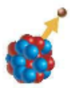
radioactive - a nucleus is radioactive if it spontaneously breaks up, emitting particles or energy in the process.

Alpha Decay
Nucleus ejects a helium-4 nucleus



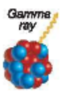
Protons	Decrease by 2
Neutrons	Decrease by 2
Atomic number	Decreases by 2
Mass number	Decreases by 4

Beta Decay
Nucleus converts a neutron to a proton and an electron, ejecting the electron.



Protons	Increase by 1
Neutrons	Decrease by 1
Atomic number	Increases by 1
Mass number	Stays the same

Gamma Decay
Nucleus emits gamma radiation and lowers its energy.



Protons	Stays the same
Neutrons	Stays the same
Atomic number	Stays the same
Mass number	Stays the same

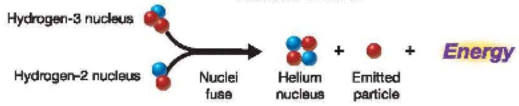
Figure 14.23: *Comparing three radioactive decay reactions.*

Two types of nuclear reactions

Getting to the nucleus of the matter As you have just learned, the nucleus of an atom can change. All by itself, an unstable isotope can experience radioactive decay and become a new, more stable isotope. Atoms that are unstable and prone to radioactive decay are useful in nuclear reactions. There are two kinds of nuclear reactions: fusion and fission.

Fusion **Nuclear fusion** is the process of combining the nuclei of lighter atoms to make heavier atoms. This process is occurring all the time in a very familiar object—the Sun. What exactly happens in nuclear fusion? The process that occurs matches its name. Two nuclei are "fused" together, a particle is emitted, and a lot of energy is released. The reaction below shows the fusion of hydrogen-3 (1 proton + 2 neutrons) with hydrogen-2 (1 proton + 1 neutron) to produce a helium nucleus, a neutron, and energy. This process occurs in the Sun and the resulting energy released provides Earth with heat and light.

Nuclear Fusion



Fission **Nuclear fission** is the process of splitting the nucleus of an atom. A fission reaction can be started when a neutron bombards a nucleus. A chain reaction results. A free neutron bombards a nucleus and the nucleus splits, releasing more neutrons. These neutrons then bombard other nuclei (Figure 14.24).

Performing fusion and fission reactions Both fusion and fission reactions can be performed in a special machine called a particle accelerator. The particle accelerator bombards particles and atoms in order to achieve these reactions. However, only a very small number of atoms can be made in this way at one time. Fission, and the resulting energy production in nuclear reactors, is controlled by releasing neutrons to start a chain reaction or by capturing neutrons to slow or stop a chain reaction. As you have just learned, the largest nuclear reactor in our solar system is the Sun.

VOCABULARY

nuclear fusion - a nuclear reaction in which the nuclei of lighter atoms are combined to make heavier atoms.

nuclear fission - a nuclear reaction in which the nuclei of heavier atoms are split to make lighter atoms.

Nuclear Fission

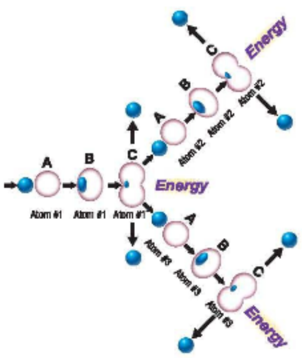


Figure 14.24: *Nuclear fission can be started when a free neutron (blue ball, step A) bombards a nucleus (step B). A chain reaction results as the nucleus splits, releasing more neutrons, which bombard other nuclei (step C).*

Using nuclear reactions in medicine and science

Half-life On this page, you will learn about why radioactive waste is harmful, but also how radioactivity is useful. Let's begin by looking at nuclear waste. The atoms that are a part of nuclear waste from nuclear reactors have long half-lives ranging from thousands (as in the case of plutonium-239) to millions of years. A **half-life** is a certain length of time after which half of the amount of radioactive element has decayed. For example, the half-life of carbon-14 (one of the radioactive isotopes of carbon) is 5,730 years. This means that if you start out with 100 atoms of carbon-14, 5,730 years from now, only 50 atoms will still be carbon-14. The rest of the carbon will have decayed to nitrogen-14 (a stable isotope). As a radioactive element decays, it emits harmful radiation such as alpha and beta particles and gamma rays. By breaking chemical bonds, radiation can damage cells and DNA. Exposure to radiation is particularly harmful if it is intense or for a long period of time.

Radioactive dating *Radioactive dating* is a process that is used to figure out the age of objects by measuring the amount of radioactive material in a substance and by knowing the half-life of that substance. For example, *carbon dating* is used to date material made from plants or animals. Much of the carbon absorbed by plants and animals is carbon-12 and carbon-13 because these are the most abundant carbon isotopes. However, some carbon-14 is also absorbed. By measuring the amount of carbon-14 remaining in a plant or animal fossil, the age of the fossils that are between 50,000 and a few thousand years old can be estimated. For older material, the amount of uranium-238 can be measured. It takes 4.5 billion years for one-half of the uranium-238 atoms in a sample to turn into lead (Figure 14.25). If a rock contains uranium-238, scientists can determine the rock's age by the ratio of uranium-238 to lead atoms in the sample. Understanding radioactive decay of uranium-238 has allowed scientists to determine that the age of Earth is 4.6 billion years old.

Radioisotopes detect problems in systems *Radioisotopes* (also called radioactive isotopes) are commonly used as tracers in medicine and science. By adding a radioactive isotope into a system (such as the human body or an underground water supply), problems can be detected. The tracer's radiation allows it to be detected using a Geiger counter or other machine and followed as it travels through the system.

VOCABULARY

half-life - a certain length of time after which half the amount of a radioactive element has undergone radioactive decay.

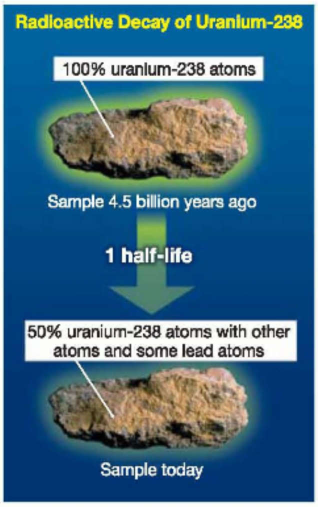


Figure 14.25: *The radioactive decay of uranium to lead. Radioactive decay is measured in half-lives. After one half-life, 50 percent of the uranium-238 atoms have decayed.*

Nuclear vs. chemical reactions

A summary of the differences between chemical and nuclear reactions is listed in the table below.

	Chemical Reactions	Nuclear Reactions
What part of the atom is involved?	Outermost electrons	Protons and neutrons in the nucleus
How is the reaction started?	Atoms are brought close together with high temperature or pressure, or catalysts, or by increasing concentrations of reactants	High temperature is required or atoms are bombarded with high-speed particles
What is the outcome of the reaction?	Atoms form ionic or covalent bonds	The number of protons and neutrons in an atom usually changes and/or energy is released
How much energy is absorbed or released?	A small amount	A huge amount
What are some examples?	Burning fossil fuels, digesting food, making medicines and commercial products	Generating nuclear energy, treating cancer, irradiating food to sterilize it, the Sun generating heat and light

SCIENCE FACT

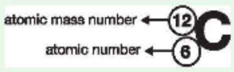
Radiation Is All Around

Because you cannot see or feel radiation, you might not be aware that it is all around you. Many common objects contain radioactive isotopes. Exposure to radiation can come from space (radiation entering Earth's atmosphere), an X-ray, brick or stone buildings, or even Brazil nuts! Fortunately, exposure to radiation from these sources is very low.

STUDY SKILLS

Isotope Notation

Isotope notation is a way to write the atomic mass number and atomic number of the isotope of an element. This particular notation is useful for tracking whether a radioactive isotope has undergone alpha, beta, or gamma decay.



Section 14.4 Review

1. Why is so much energy required and released in a nuclear reaction?
2. Gold-185 decays to iridium-181. Is this an example of alpha or beta decay?
3. What has to happen, in terms of radioactive decay, for carbon-14 to decay to nitrogen-14?
4. How is gamma decay different from alpha or beta decay?
5. In your own words, describe the difference between fusion and fission. Why do certain elements undergo fusion or fission?
6. Which type of nuclear reaction is used in modern-day nuclear reactors? Why is the other type of nuclear reaction NOT used in modern-day energy production?
7. When an atom of beryllium-9 is bombarded by an alpha particle, an atom of carbon-12 is produced and a neutron is emitted. What kind of nuclear reaction has just occurred?
8. What is the half-life of each of these radioactive isotopes?
   a. A radioactive isotope decreased to one-half its original amount in 18 months.
   b. A radioactive isotope decreased to one-fourth its original amount in 100 years.
9. For each scenario below, indicate whether a chemical reaction or a nuclear reaction is occurring.
   a. When two compounds are combined, heat is released.
   b. A sample of galium-68 is reduced to one-half of its original amount in 68.3 minutes.
   c. Radium-226 decays to radon-222.
   d. A spark of energy is used to begin the combustion of methane gas.
   e. Hydrogen nuclei are fused in the Sun to make helium atoms.

BIOGRAPHY

Irene Joliot-Curie

Irene Joliot-Curie was a remarkable woman. She was the oldest daughter of Marie and Pierre Curie. Irene studied both mathematics (her forte) and physics at the University of Sorbonne in Paris. However, her education was interrupted by World War I. Irene joined her mother in military hospitals and on the battlefield. Marie had developed portable X-ray machines that she set up and used to treat wounded soldiers. For her service, Irene was awarded France's Military Medal. By 1925, Irene had earned her Ph.D., studying alpha rays of the element polonium, which was discovered by her parents. Around this time, she also met her future husband and scientific collaborator, Frederic Joliot. Frederic and Irene were both passionate about science and also shared interests in politics, art, and sports. The couple married in 1926 and had two children. They earned the Nobel Prize in 1935 for discovering that nonradioactive elements could be turned into radioactive isotopes using alpha particles.