4.4 Simple Nuclear Reactions

Section Preview/ Specific Expectations

In this section, you will

- **balance** simple nuclear equations
- **communicate** your understanding of the following terms: *nuclear reactions, nuclear equation, alpha* (α) *particle emission, beta* (β) *decay, beta particle, gamma* (γ) *radiation, nuclear fission, nuclear fusion*

Figure 4.18 This patient is about to undergo radiation therapy.

Media LINK

The media are full of references to radioactivity. For example, the comic book hero Spiderman gained the abilities of a spider after being bitten by a radioactive spider. Bart Simpson reads *Radioactive Man* comics. Can you think of any other references to radioactivity in popular culture? What kind of reputation do radioactivity and nuclear reactions have? Do you think this reputation is deserved?

You have seen some chemical reactions that involve the formation and decomposition of different compounds. These reactions involve the rearrangement of atoms due to the breaking and formation of chemical bonds. Chemical bonds involve the interactions between the electrons of various atoms. There is another class of reactions, however, that are not *chemical*. These reactions involve changes that occur within the nucleus of atoms. These reactions are called **nuclear reactions**.

We know that nuclear weapons are capable of mass destruction, yet radiation therapy, shown in Figure 4.18, is a proven cancer fighter. Smoke detectors, required by law in all homes, rely on the radioactive decay of americium-241. The human body itself is radioactive, due to the presence of radioactive isotopes including carbon-14, phosphorus-32, and potassium-40. Most people view radioactivity and nuclear reactions with a mixture of fascination, awe, and fear. Since radioactivity is all around us, it is important to understand what it is, how it arises, and how we can deal with it safely.

Types of Radioactive Decay and Balancing Nuclear Equations

There are three main types of radioactive decay: alpha particle emission, beta particle emission, and the emission of gamma radiation. When an unstable isotope undergoes radioactive decay, it produces one or more different isotopes. We represent radioactive decay using a **nuclear equation.** Two rules for balancing nuclear equations are given below.

Rules for Balancing Nuclear Equations

1. The sum of the mass numbers (written as superscripts) on each side of the equation must balance.
2. The sum of the atomic numbers (written as subscripts) on each side of the equation must balance.

Alpha Decay

Alpha (α) particle emission, or alpha decay, involves the loss of one alpha particle. An α particle is a helium nucleus, ${}^{4}_{2}\text{He}$, composed of two protons and two neutrons. Since it has no electrons, an alpha particle carries a charge of +2.

One example of alpha particle emission is the decay of radium. This decay is shown in the following equation:

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

Notice that the sum of the mass numbers on the right (222 + 4) equals the mass on the left (226). As well, the atomic numbers balance (88 = 86 + 2). Thus, this nuclear equation is balanced.

In another example of alpha particle emission, Berkelium-248 is formed by the decay of a certain radioisotope according to the balanced nuclear equation:

$$^{a}_{b}X \rightarrow {}^{248}_{97}\mathrm{Bk} + {}^{4}_{2}\mathrm{He}$$

Given this information, what is $^{a}_{b}X$? You can use your knowledge of how to balance a nuclear equation to determine the identity of a radioisotope undergoing alpha particle decay.

The total of the atomic masses on the right side is $(248 + 4) = 252$. The total of the atomic numbers on the right is $(97 + 2) = 99$. Therefore, $a = 252$ and $b = 99$. From the periodic table, you see that element number 99 is Es, einsteinium. The missing atom is $^{252}_{99}\mathrm{Es}$, so the balanced nuclear equation is:

$$^{252}_{99}\mathrm{Es} \rightarrow {}^{248}_{97}\mathrm{Bk} + {}^{4}_{2}\mathrm{He}$$

Try the following problems to practise balancing alpha emission nuclear reactions.

Practice Problems

29. Uranium was the first element shown to be radioactive. Complete the following reaction representing the alpha decay of uranium-238.

$$^{238}_{92}\mathrm{U} \rightarrow \underline{\qquad\qquad} + {}^{4}_{2}\mathrm{He}$$

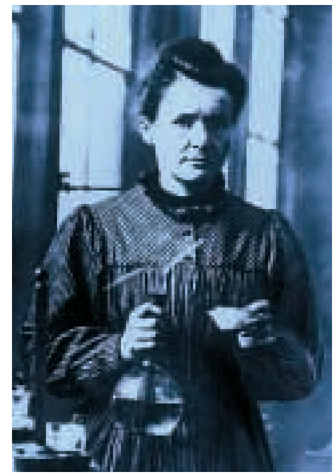
30. Radon-222, $^{222}_{86}\mathrm{Rn}$, is known to decay by alpha particle emission. Write a balanced nuclear equation and name the element produced in this decay process.

31. Plutonium-242 decays by emitting an alpha particle. Write the balanced nuclear equation for this reaction.

32. Neodymium-144, $^{144}_{60}\mathrm{Nd}$, decays by alpha particle emission. Write the balanced nuclear equation for this nuclear decay.

History LINK

Marie Curie discovered the element polonium, Po, in 1898. She named polonium after Poland, her homeland. Curie won two Nobel Prizes, one in Physics (1903) for sharing in the discovery of radioactivity, and one in Chemistry (1911) for the discovery of radium, which has been used to treat cancer. Radium-226 undergoes alpha decay to yield radon-222.



Beta Decay

Beta (*β*) decay occurs when an isotope emits an electron, called a **beta particle**. Because of its tiny mass and –1 charge, a beta particle, is represented as $^{0}_{-1}\mathrm{e}$. For example, hydrogen-3, or tritium, emits a beta particle to form helium-3 as illustrated by the equation:

$$^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\mathrm{e}$$

Notice that the total of the atomic masses and the total of the atomic numbers on each side of the nuclear equation balance. What is happening, however to the hydrogen-3 nucleus as this change occurs? In effect, the emission of a beta particle is accompanied by the conversion, inside the nucleus, of a neutron into a proton:

$$\underset{\text{neutron}}{^{1}_{0}\mathrm{n}} \rightarrow \underset{\text{proton}}{^{1}_{1}\mathrm{H}} + \underset{\text{electron }(\beta\text{ particle})}{^{0}_{-1}\mathrm{e}}$$

CHEM FACT

One of the most harmful potential sources of radiation in the home is radon gas. Radon-222 is a product of the decay of uranium-containing rocks beneath Earth's surface. Since radon is denser than air, it can build up to dangerous levels in basements when it seeps through cracks in walls and floors. Simple radon detectors can be purchased at hardware stores.

CHEM FACT

The nucleus of the most common isotope of hydrogen consists of one proton. Therefore, a proton can be represented by H^+ or $^{1}_{1}H$.

Carbon-14 is a radioactive isotope of carbon. Its nucleus emits a beta, particle to form a nitrogen-14 nucleus, according to the balanced nuclear equation shown below in Figure 4.19.

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

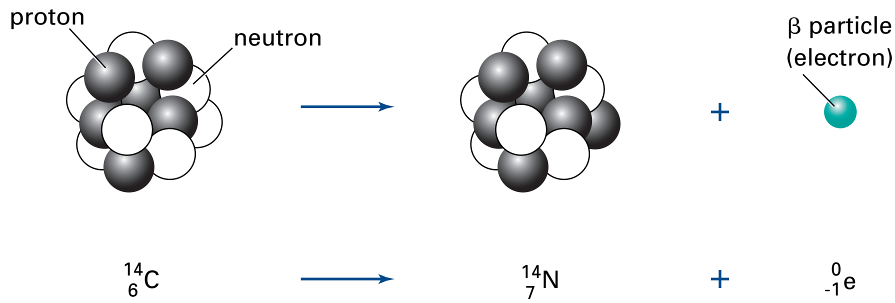


Figure 4.19 **Carbon-14 decays by emitting a beta particle and converting to nitrogen-14. Notice that a neutron in the nucleus of carbon is converted to a protron as the β particle is emitted.**

CHEM FACT

The terms radiation and radioactivity are often confused. Radiation refers to electromagnetic radiation—everything from gamma rays, to X-rays, to visible light, to microwaves, to radio and television signals. Radioactivity, on the other hand, involves the emission of particles or energy from an unstable nucleus.

Radioactive waste from certain nuclear power plants and from weapons testing can lead to health problems. For example, ions of the radioactive isotope strontium-90, an alkali metal, exhibit chemical behaviour similar to calcium ions. This leads to incorporation of the ions in bone tissue, sending ionizing radiation into bone marrow, and possibly causing leukemia. Given the following equation for the decay of strontium-90, how would you complete it?

$$^{90}_{38}Sr \rightarrow \boxed{} + {}^{0}_{-1}e$$

Since both atomic numbers and mass numbers must balance, you can find the other product.

The mass number of the unknown element is equal to 90 + 0 = 90. The atomic number of the unknown element is equal to 38 – (–1) = 39. From the periodic table, you can see that element 39 is yttrium, Y. The balanced nuclear equation is therefore

$$^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}e$$

You can check your answer by ensuring that the total mass number and the total atomic number on each side of the equation are the same.

Mass numbers balance: 90 = 90 + 0

Atomic numbers balance: 38 = 39 + (–1)

Try the following problems to practise balancing beta emission equations.

Practice Problems

33. Write the balanced nuclear equation for the radioactive decay of potassium-40 by emission of a β particle.

34. What radioisotope decays by β particle emission to form $^{47}_{21}Sc$?

35. Complete the following nuclear equation:

$$^{73}_{31}Ga \rightarrow {}^{0}_{-1}e + \boxed{}$$

Canadians in Chemistry

Harriet Brooks

It was the Nobel that just missed being Canadian. In 1907, Ernest Rutherford left Montréal's McGill University for a position in England. The following year, he received the Nobel Prize for Chemistry for his investigations of the chemistry of radioactive substances. Most of the work, however, had been done in Montréal. Moreover, one young Canadian woman had played an important role in putting it on the right track.

Harriet Brooks is nearly forgotten today, even though she helped to show that elements could be transformed. For over a century, chemists had rejected the dream of the ancient alchemists who thought that they might turn lead into gold with the help of the philosopher's stone. They believed that elements were forever fixed and unchangeable.

Then Harriet Brooks arrived on the scene. When she joined Rutherford's team, she was asked to measure the atomic mass of the isotopes that make up the mysterious vapour given off by radium. She determined that its atomic mass was between 40 and 100, whereas radium was known to have an atomic mass of over 140. Surely this was not just a gaseous form of radium. Somehow radium was turning into another element!

It turned out that Brooks' result was a mistake. Radon—as the mystery gas is now known—has almost the same atomic mass as radium. Brooks' result was a fruitful mistake, however. Her experiment led to a basic understanding of radioactivity and isotopes.

Why did Rutherford win a Nobel Prize for Chemistry? Both he and Brooks worked as physicists. By proving that elements transformed, Rutherford, Brooks, and their co-workers revolutionized traditional chemistry.

Gamma Radiation

Gamma (γ) radiation is high energy electromagnetic radiation. It often accompanies either alpha or beta particle emission. Since gamma radiation has neither mass nor charge, it is represented as ${}^{0}_{0}\gamma$, or simply γ. For example, cesium-137 is a radioactive isotope that is found in nuclear fall-out. It decays with the emission of a beta particle and gamma radiation, according to the equation

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

How is gamma radiation produced in a radioactive decay? When a radioactive nucleus emits an alpha or beta particle, the nucleus is often left in an unstable, high-energy state. The "relaxation" of the nucleus to a more stable state is accompanied by the emission of gamma radiation.

Nuclear Fission and Fusion

All cases of radioactive decay involve the atom's nucleus. Since these processes do not involve the atom's electrons, they occur regardless of the chemical environment of the nucleus. For example, radioactive hydrogen-3, or tritium, will decay by β particle emission whether it is contained in a water molecule or hydrogen gas, or in a complex protein.

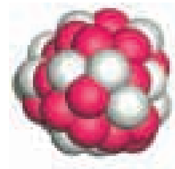
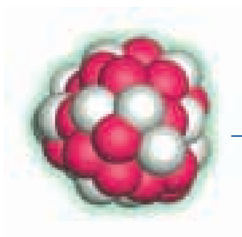
Mode	Emission	Decay					Change in …		
							Mass numbers	Atomic numbers	Number of neutrons
α Decay	α ($^{4}_{2}$He)	 reactant	→	 product	+	 α expelled	−4	−2	−2
β Decay	$^{0}_{-1}\beta$	$^{1}_{0}$n  in nucleus	→	$^{1}_{1}$p  in nucleus	+	$^{0}_{-1}\beta$  β expelled	0	+1	−1
γ Emission	$^{0}_{0}\gamma$	 excited nucleus	→	 stable nucleus	+	$^{0}_{0}\gamma$ γ photon radiated	0	0	0

Figure 4.20 A summary of alpha decay, beta decay, and gamma emission

Many chemical reactions, once begun, can be stopped. For example, a combustion reaction, such as a fire, can be extinguished before it burns itself out. Nuclear decay processes, on the other hand, cannot be stopped.

The principles of balancing nuclear equations apply to all nuclear reactions. **Nuclear fission** occurs when a highly unstable isotope splits into smaller particles. Nuclear fission usually has to be induced in a particle accelerator. Here, an atom can absorb a stream of high-energy particles such as neutrons, $^{1}_{0}$n. This will cause the atom to split into smaller fragments.

For example, when uranium-235 absorbs a high energy neutron, $^{1}_{0}$n, it breaks up, or undergoes fission as follows:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{87}_{35}\text{Br} + \boxed{} + 3{}^{1}_{0}\text{n}$$

How would you identify the missing particle? Notice that three neutrons, $^{1}_{0}$n, have a mass number of 3 and a total atomic number of 0. The total atomic mass on the left side is (235 + 1) = 236. On the right we have (87 + 3(1)) = 90, and so (236 − 90) = 146 remains. The missing particle must have a mass number of 146.

The total atomic number on the left is 92. The total atomic number on the right, not including the missing particle, is 35. This means that (92 − 35) = 57 is the atomic number of the missing particle. From the periodic table, atomic number 57 corresponds to La, lanthanum. The balanced nuclear equation is

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{87}_{35}\text{Br} + {}^{146}_{57}\text{La} + 3{}^{1}_{0}\text{n}$$

Check your answer by noting that the total mass number and the total atomic number are the same on both sides.

Nuclear fusion occurs when a target nucleus absorbs an accelerated particle. The reaction that takes place in a hydrogen bomb is a fusion reaction, as are the reactions that take place within the Sun, shown in Figure 4.21. Fusion reactions require very high temperatures to proceed but produce enormous amounts of energy. The fusion reaction that takes place in a hydrogen bomb is represented by the following equation:

$$^{6}_{3}\text{Li} + ^{1}_{0}\text{n} \rightarrow ^{3}_{1}\text{H} + ^{4}_{2}\text{He}$$

Notice that the total mass numbers and the total atomic numbers are the same on both sides.

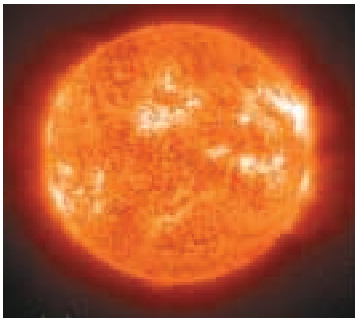


Figure 4.21 The Sun's interior has a temperature of about 15 000 000 °C, due to the energy provided by nuclear fusion reactions.

Practice Problems

36. Astatine can be produced by the bombardment of a certain atom with alpha particles, as follows:

$\_\_\_\_ + ^{4}_{2}\text{He} \rightarrow ^{211}_{85}\text{At} + 2^{1}_{0}\text{n}$

Identify the atom.

37. Balance the following equation by adding a coefficient.

$^{252}_{96}\text{Cf} + ^{10}_{5}\text{B} \rightarrow ^{257}_{101}\text{Md} + \_\_\_\_\ ^{1}_{0}\text{n}$

38. How many neutrons are produced when U-238 is bombarded with C-12 nuclei in a particle accelerator? Balance the following equation.

$^{238}_{92}\text{U} + ^{12}_{6}\text{C} \rightarrow ^{246}_{98}\text{Cf} + \_\_\_\_\ ^{1}_{0}\text{n}$

39. Aluminum-27, when it collides with a certain nucleus, transforms into phosphorus-30 along with a neutron. Write a balanced nuclear equation for this reaction.

Section Wrap-Up

In this chapter, you learned how atoms can interact with each other and how unstable isotopes behave. In the first three sections, you learned about chemical reactions. In section 4.4, you learned about different types of nuclear reactions: reactions in which atoms of one element change into atoms of another element. In Unit 2, you will learn how stable isotopes contribute to an indirect counting method for atoms and molecules.

Section Review

1 K/U Draw a chart in your notebook to show alpha decay, beta decay, gamma decay, nuclear fusion, and nuclear fission. Write a description and give an example of each type of reaction. Illustrate each example with a drawing.

2 K/U Complete each nuclear equation. Then state the type of nuclear reaction that each equation represents.

(a) $^{232}_{90}\text{Th} + \_\_\_\_ \rightarrow ^{233}_{90}\text{Th}$

(b) $^{233}_{91}\text{Pa} \rightarrow ^{233}_{92}\text{U} + \_\_\_\_$

(c) $^{226}_{88}\text{Ra} \rightarrow \_\_\_\_ + ^{4}_{2}\text{He}$

(d) $^{210}_{83}\text{Bi} \rightarrow ^{206}_{81}\text{Tl} + \_\_\_\_$

(e) $^{210}_{83}\text{Bi} \rightarrow + ^{206}_{81}\text{Tl} +$ ____

(f) ____ $+ ^{1}_{0}\text{n} \rightarrow ^{90}_{38}\text{Sr} + ^{143}_{54}\text{Xe} + 3^{1}_{0}\text{n}$

(g) $^{6}_{3}\text{Li} + ^{2}_{1}\text{H} \rightarrow 2$ ____

3 **MC** Nuclear reactors have complex cooling systems that absorb the heat given off by the fission reaction. The absorbed heat is used to produce steam to drive a generator, thus producing electrical energy. Cooling the steam for re-use requires a large amount of cool water, which is usually obtained from a nearby river or lake. A large amount of hot water is then released into the river or lake. Do you think this is a form of pollution? What kinds of problems might warm water cause?

4 **K/U** Alpha or beta particle emission from a radioactive nucleus is often, but not always, accompanied by gamma rays. Why does the presence of gamma rays *not* affect how a nuclear equation of this type is balanced?

5 **K/U** Write a balanced nuclear equation to describe each of the following statements. Classify the reactions.

(a) Radon-222 undergoes alpha decay, forming polonium-218.

(b) When hydrogen-2 (deuterium) and hydrogen-3 (tritium) react, they form an alpha particle and a subatomic particle.

(c) Bismuth-214 undergoes beta decay, emitting one electron and forming a different nucleus.

(d) When a neutron collides with uranium-235, it forms krypton-92 and one other nucleus.

(e) Polonium-218 decays to lead-214, emitting one other particle.

(f) Strontium-90 emits a subatomic particle, forming yttrium-90.