

# Radioactive Decay

## 7.2

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 device 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.

**radioactivity** a process by which the nucleus of an atom spontaneously disintegrates

**nuclear fission** the decomposition of large, unstable nuclei into smaller, more stable nuclei



**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 initial 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 and oxygen produces carbon dioxide. The reactants are carbon, C, and oxygen, O<sub>2</sub>. The product is carbon dioxide, CO<sub>2</sub>. Energy is also released during 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:  $C + O_2 \rightarrow CO_2 + \text{energy}$

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 previous example, 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 previous example, that releases energy is exothermic. By contrast, a chemical reaction that absorbs energy is endothermic.

## Nuclear Reactions

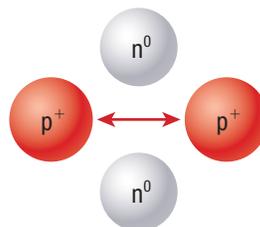
**nuclear reaction** the process by which the nucleus of an atom sometimes changes

**Nuclear reactions** involve changes in the nuclei of atoms, sometimes resulting in completely new elements. The identity of an element is determined by examining the number of protons in its nucleus. If the number of protons changes, one or more new elements result. By examining the forces present in a nucleus, it is possible to understand the nature of nuclear reactions and why they occur.

### Electrostatic Force and the Strong Nuclear Force

**electrostatic force** the force of attraction or repulsion due to electric charges

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?



**Figure 2** The nucleons in a helium nucleus

**strong nuclear force** the very strong force of attraction between nucleons

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. 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

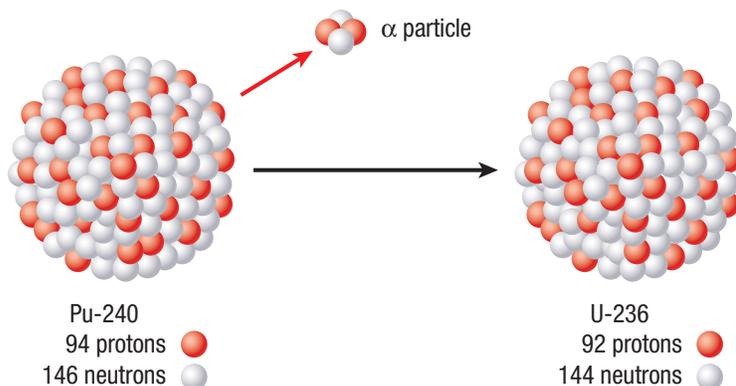
There is a delicate balance between the repulsive electrostatic force and the attractive strong nuclear force in a nucleus. When these forces are balanced, an atom is said to be stable. Atoms with higher atomic numbers (more protons) experience a greater electrostatic force of repulsion among the protons, 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 to form smaller atoms is called **radioactive decay**. There are three common forms of radioactive decay: alpha decay, beta decay, and gamma decay.

**radioactive decay** the process by which a radioactive atom's nucleus breaks apart and forms different atoms

## Alpha Decay

One of the most common forms of radioactive decay is **alpha decay**, or  $\alpha$ -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**.

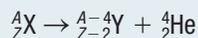


**Figure 3** Alpha decay of plutonium-240

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



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



In a nuclear reaction, the **parent atom** ( $X$ ) is the reactant atom, and the **daughter atom** ( $Y$ ) 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 the following Tutorial, you will use your understanding of alpha decay to write the equation for a nuclear reaction.

**alpha ( $\alpha$ ) decay** nuclear reaction in which an alpha particle is emitted

**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 elements from parent atoms

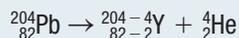
### Tutorial 1 Determining the Nuclear Equation for Alpha Decay

#### 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 using the equation for alpha decay.



We can see that the new element has the atomic number 80 and mass number 200.



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

The daughter atom is mercury-200.

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



#### Practice

- Determine the element that is produced when plutonium-239 undergoes alpha decay, and write the reaction equation. **T/I C** [ans: uranium-235;  ${}_{94}^{239}\text{Pu} \rightarrow {}_{92}^{235}\text{U} + {}_2^4\text{He}$ ]
- When an unknown isotope undergoes alpha decay, neptunium-239 is produced. Determine the unknown isotope. **T/I** [ans: americium-243]

**beta ( $\beta$ ) decay** nuclear reaction in which a beta particle is emitted or captured

**beta particle** a high-energy electron or positron ejected or captured by a nucleus during beta decay

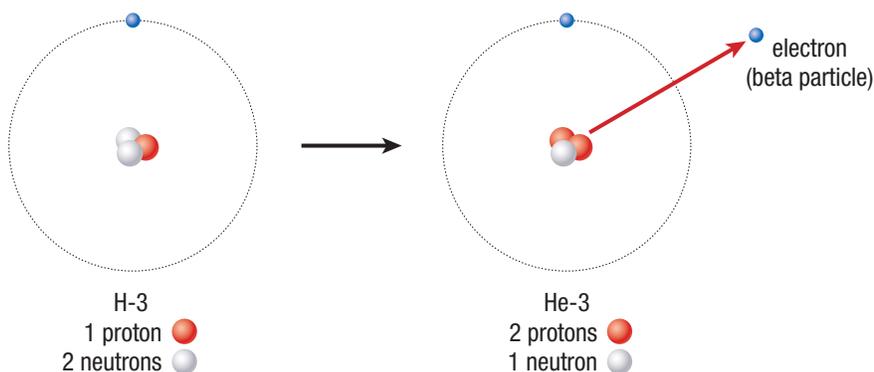
**positron** a particle with a positive charge and the same mass as an electron

## 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 similar to 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**.

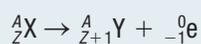


**Figure 4** Beta-negative decay of tritium (H-3)

The equation for this reaction is

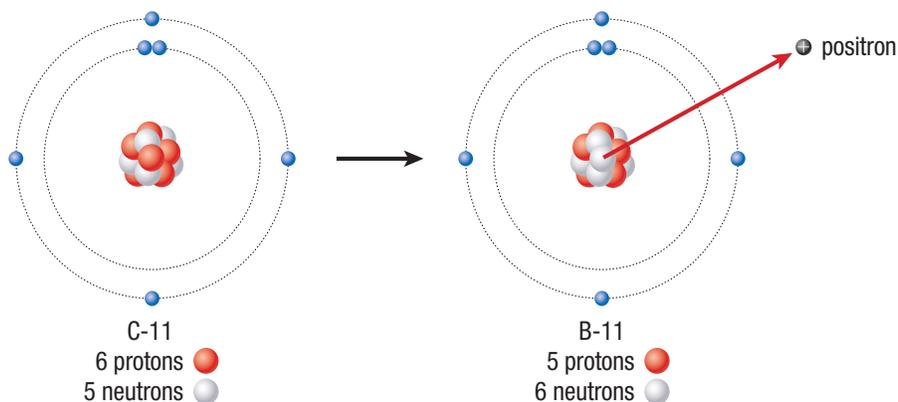


where  ${}^0_{-1}\text{e}$  represents an electron (the negative beta particle). In this process, the mass number of the daughter nucleus remains unchanged, but the atomic number increases by one. This process is a transmutation because the number of protons changes. The general equation for beta-negative decay is



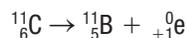
### BETA-POSITIVE DECAY

In beta-positive decay, a proton changes into a neutron and a positron, which is symbolized by  ${}^0_{+1}\text{e}$ . An example of this type of nuclear reaction is the decay of carbon-11 into boron-11, as shown in **Figure 5**.

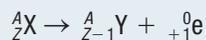


**Figure 5** Beta-positive decay of carbon-11

The equation for this nuclear reaction is

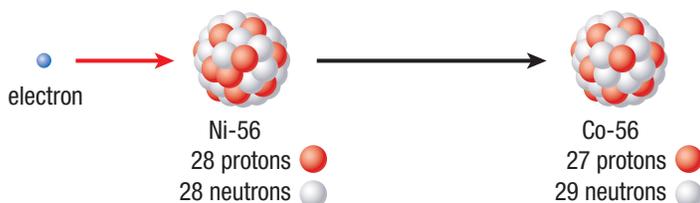


Notice that in this process, the mass number of the daughter nucleus remains unchanged, but the atomic number decreases by one. This process is a transmutation because a different type of element is formed when a proton in the nucleus of the parent atom changes into a neutron. The general equation for beta-positive decay is



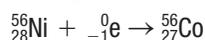
## ELECTRON CAPTURE

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**.

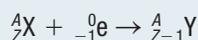


**Figure 6** Electron capture

The equation for this reaction is



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



In the following Tutorial, you will use what you have learned about beta decay to determine an unknown isotope and a 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 using the equation for beta-negative decay.



We can see that the new element has the atomic number 84 and mass number 214.



The periodic table tells us that the new element is polonium-214.

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



### Practice

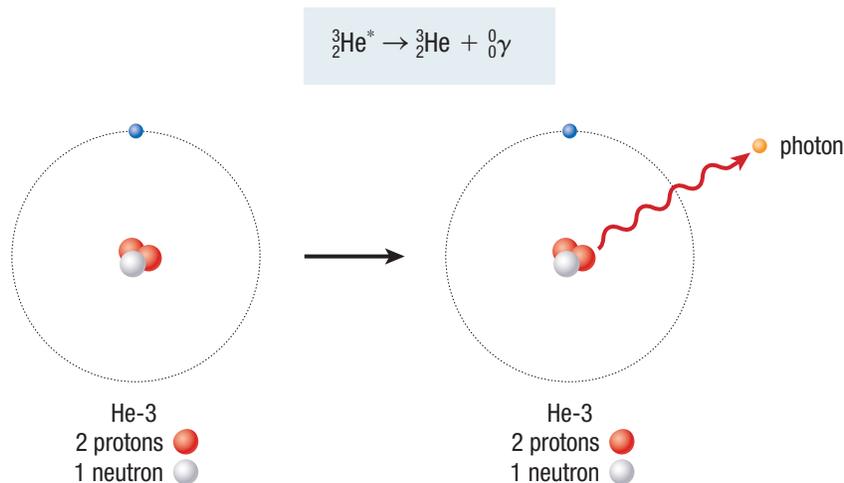
- Determine the element that is produced when cerium-141 undergoes beta-negative decay and write the reaction equation. **T/I C** [ans: praseodymium-141;  ${}_{58}^{141}\text{Ce} \rightarrow {}_{59}^{141}\text{Pr} + {}_{-1}^{0}\text{e}$ ]
- Determine the element that is produced when chromium-46 undergoes beta-positive decay. Then write the reaction equation. **T/I C** [ans: vanadium-46;  ${}_{24}^{46}\text{Cr} \rightarrow {}_{23}^{46}\text{V} + {}_{+1}^{0}\text{e}$ ]

**photon** a high-energy particle with no mass

**gamma ( $\gamma$ ) decay** a reaction in which an excited nucleus returns to a lower, more stable energy state, releasing a very high-energy gamma ray in the process

## 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. As a result, 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 in Figure 4 will undergo gamma decay, as shown in **Figure 7**. The general equation for gamma decay is



**Figure 7** Gamma decay of helium-3

The symbol for a photon is  ${}^0_0\gamma$ . 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 will 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.



#### Practice

1. Write the reaction equation when plutonium-240 undergoes gamma

decay. [T/I](#) [C](#) [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. [K/U](#)

## 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

Type of decay	Radiation	Emitted particle	Electric charge	Penetrating ability
alpha decay	alpha particle	helium nucleus ( ${}^4_2\text{He}$ )	+2	can penetrate skin or paper, but is slow moving
beta-negative decay	beta particle	electron ( ${}_{-1}^0\text{e}$ )	-1	can penetrate a few sheets of aluminum foil
beta-positive decay	beta particle	positron ( ${}_{+1}^0\text{e}$ )	+1	
electron capture	—	no particle is emitted	—	not applicable
gamma decay	gamma rays	photon ( ${}^0_0\gamma$ )	0	can penetrate a few centimetres of lead

### 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 reactions that involve the nucleus of an atom, where high-energy electromagnetic radiation is either emitted or absorbed.
- 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

- Write the nuclear reaction equation for each atom undergoing alpha decay (refer to the periodic table). **K/U**
  - curium-248
  - radium-223
- Write the nuclear reaction equation for each atom undergoing beta-negative decay (refer to the periodic table). **K/U**
  - sulfur-35
  - gold-198
- Write the nuclear reaction equation for each atom undergoing beta-positive decay (refer to the periodic table). **K/U**
  - sodium-22
  - calcium-39
- The positron is a very interesting particle. Conduct some research on the positron and describe some of its properties. Summarize your findings in a one-page report. **T/I C**
- Write nuclear reaction equations for each atom undergoing electron capture (refer to the periodic table). **K/U**
  - potassium-40
  - carbon-11
- 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. **T/I C A**

