Pearson

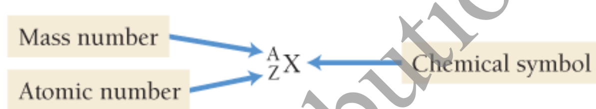
20.3: Types of Radioactivity

Key Concept Video **Types of Radioactivity**

While Curie focused her work on discovering the different kinds of radioactive elements, Ernest Rutherford (1871–1937) and others focused on characterizing the radioactivity itself. These scientists found that the emissions are produced by the nuclei of radioactive atoms. Such nuclei are unstable and spontaneously decompose, emitting small pieces of themselves to gain stability. These fragments are the radioactivity that Becquerel and Curie detected. Natural radioactivity can be categorized into several different types, including *alpha* (α) *decay*, *beta* (β) *decay*, *gamma* (γ) *ray emission*, and *positron emission*. In addition, some unstable atomic nuclei can attain greater stability by absorbing an electron from one of the atom's own orbitals, a process called *electron capture*.

> Element 96 is named curium in honor of Marie Curie and her contributions to our understanding of radioactivity.

In order to understand these different types of radioactivity, we must briefly review the notation for symbolizing isotopes from Section 1.8. Recall that we can represent any isotope with the following notation:

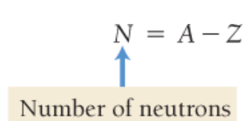


mass number (A) = the sum of the number of protons and number of neutrons in the nucleus

atomic number (Z) = the number of protons in the nucleus

Radium, discovered by Marie Curie, is so radioactive that it glows visibly and emits heat.

A represents the sum of the number of protons and neutrons, and Z represents the number of protons, so the number of neutrons in the nucleus (N) is $A - Z$.



For example, the symbol $^{21}_{10}Ne$ represents the neon isotope containing 10 protons and 11 neutrons. The symbol $^{20}_{10}Ne$ represents the neon isotope containing 10 protons and 10 neutrons. Remember that most elements have several different isotopes. When we are discussing nuclear properties, we often refer to a particular isotope (or species) of an element as a **nuclide**.

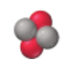
We represent the main subatomic particles—protons, neutrons, and electrons—with similar notation.

$$\text{proton symbol } {}^{1}_{1}\text{P} \quad \text{neutron symbol } {}^{1}_{0}\text{n} \quad \text{electron symbol } {}^{0}_{-1}\text{e}$$

The 1 in the lower left of the proton symbol represents 1 proton, and the 0 in the lower left corner of the neutron symbol represents 0 protons. The −1 in the lower left corner of the electron symbol is a bit different from the other atomic numbers; it will make sense when we see it in the context of nuclear decay a bit later in this section.

Alpha (α) Decay

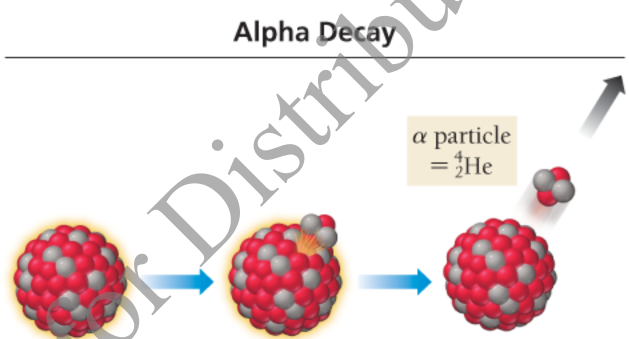
Alpha α decay occurs when an unstable nucleus emits a particle composed of two protons and two neutrons (Figure 20.2). Since two protons and two neutrons combined are identical to a helium-4 nucleus, the symbol for alpha radiation is the symbol for helium-4:

alpha (α) particle $\quad {}^{4}_{2}\text{He}$ 

> As we discuss in Section 20.4, nuclei are unstable when they are too large or when they contain an unbalanced ratio of neutrons to protons.

Figure 20.2 Alpha Decay

In alpha decay, a nucleus emits a particle composed of two protons and two neutrons (a helium-4 nucleus).



When an element emits an alpha particle, the number of protons in its nucleus changes, transforming the element into a different element. We symbolize this phenomenon with a **nuclear equation**, an equation that represents nuclear processes such as radioactivity. For example, the nuclear equation for the alpha decay of uranium-238 is:

$$\underbrace{{}^{238}_{92}\text{U}}_{\text{Parent nuclide}} \longrightarrow \underbrace{{}^{234}_{90}\text{Th}}_{\text{Daughter nuclide}} + {}^{4}_{2}\text{He}$$

> In nuclear chemistry, we are primarily interested in changes within the nucleus; therefore, the 2+ charge that we would normally write for a helium nucleus is omitted for an alpha particle.

We call the original atom the *parent nuclide* and the product of the decay the *daughter nuclide*. In this case, uranium-238 (the parent nuclide) becomes thorium-234 (the daughter nuclide). Unlike a chemical reaction, in which elements retain their identities, in a nuclear reaction elements often change their identities. Like a chemical equation, however, a nuclear equation must be balanced. *The sum of the atomic numbers on both sides of a nuclear equation must be equal, and the sum of the mass numbers on both sides must also be equal.*

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

Reactants	Products
sum of mass numbers = 238	sum of mass numbers = 234 + 4 = 238
sum of atomic numbers = 92	sum of atomic numbers = 90 + 2 = 92

We can deduce the identity and symbol of the daughter nuclide in any alpha decay from the mass and atomic number of the parent nuclide. During alpha decay, the mass number decreases by 4 and the atomic number decreases by 2, as shown in Example 20.1.

Example 20.1 Writing Nuclear Equations for Alpha Decay

Write the nuclear equation for the alpha decay of Ra-224.

SOLUTION Begin with the symbol for Ra-224 on the left side of the equation and the symbol for an alpha particle on the right side.

$$^{224}_{88}\mathrm{Ra} \rightarrow {}^{?}_{?}? + {}^{4}_{2}\mathrm{He}$$

Equalize the sum of the mass numbers and the sum of the atomic numbers on both sides of the equation by writing the appropriate mass number and atomic number for the unknown daughter nuclide.

$$^{224}_{88}\mathrm{Ra} \rightarrow {}^{220}_{86}? + {}^{4}_{2}\mathrm{He}$$

Refer to the periodic table to deduce the identity of the unknown daughter nuclide from its atomic number and write its symbol. The atomic number is 86, so the daughter nuclide is radon (Rn).

$$^{224}_{88}\mathrm{Ra} \rightarrow {}^{220}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

FOR PRACTICE 20.1 Write the nuclear equation for the alpha decay of Po-216.

Interactive Worked Example 20.1 **Writing Nuclear Equations for Alpha Decay**

Alpha radiation is the 18-wheeler truck of radioactivity. The alpha particle is by far the most massive of all particles commonly emitted by radioactive nuclei. Consequently, alpha radiation has the most potential to interact with and damage other molecules, including biological ones. Highly energetic radiation interacts with other molecules and atoms by ionizing them. When radiation ionizes molecules within the cells of living organisms, the cells can usually repair the damage. However, in some cases, the cells can die or begin to reproduce abnormally. The ability of radiation to ionize molecules and atoms is called its **ionizing power**. Of all types of radioactivity, alpha radiation has the highest ionizing power.

However, alpha particles, because of their large size, have the lowest **penetrating power**—the ability to penetrate matter. (Imagine a semitruck trying to get through a traffic jam.) In order for radiation to damage important molecules within living cells, it must penetrate into the cell. Alpha radiation does not easily penetrate into cells because it can be stopped by a sheet of paper, by clothing, or even by air. Consequently, a low-level alpha emitter that remains outside the body is relatively safe. If an alpha emitter is ingested in significant amounts, however, it becomes dangerous because the alpha particles then have direct access to the molecules that compose organs and tissues.

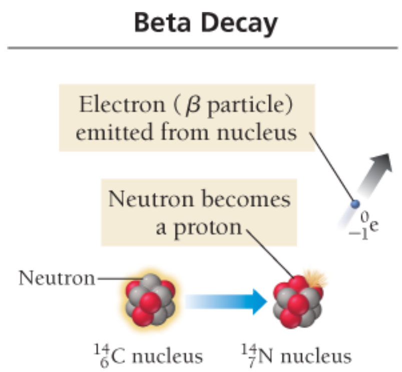
Beta (β) Decay

Beta *β* decay occurs when an unstable nucleus emits an electron (Figure 20.3). How does a nucleus, which contains only protons and neutrons, emit an electron? In some unstable nuclei, a neutron changes into a proton and emits an electron.

$$\textbf{beta decay} \quad \text{neutron} \rightarrow \text{proton} + \text{emitted electron}$$

Figure 20.3 **Beta Decay**

In beta decay, a neutron emits an electron and becomes a proton.



The symbol for a beta (*β*) particle in a nuclear equation is:

$$\textbf{beta }(\boldsymbol{\beta})\textbf{ particle} \quad {}^{0}_{-1}\mathrm{e}$$

We can represent beta decay with a nuclear equation:

$${}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e}$$

The –1 reflects the charge of the electron, which is equivalent to an atomic number of –1 in a nuclear equation. When an atom emits a beta particle, its atomic number increases by 1 because it now has an additional proton. For example, the nuclear equation for the beta decay of radium-228 is:

$${}^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}\mathrm{e}$$

Notice that the nuclear equation is balanced—the sum of the mass numbers on both sides is equal, and the sum of the atomic numbers on both sides is equal.

Beta radiation is the four-door sedan of radioactivity. Beta particles are much less massive than alpha particles and consequently have a lower ionizing power. However, because of their smaller size, beta particles have a higher penetrating power and only something as substantive as a sheet of metal or a thick piece of wood stops them. Consequently, a beta emitter outside of the body poses a higher risk than an alpha emitter. If ingested, however, the beta emitter does less damage than an alpha emitter.

> This kind of beta radiation is also called beta minus (β^{-}) radiation due to its negative charge.

Gamma (γ) Ray Emission

Gamma *γ* ray emission is significantly different from alpha or beta radiation. Gamma radiation is a form of *electromagnetic* radiation (see Section 2.2). Gamma rays are high-energy (short-wavelength) photons. The symbol for a gamma ray is:

$$\textbf{gamma }(\boldsymbol{\gamma})\textbf{ ray} \quad {}^{0}_{0}\gamma$$

A gamma ray has no charge and no mass. When a gamma-ray photon is emitted from a radioactive atom, it does not change the mass number or the atomic number of the element. Gamma rays are usually emitted from nuclei in excited states or in conjunction with other types of radiation. For example, the alpha emission of U-238 (discussed previously) is accompanied by the emission of a gamma ray:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} + {}^{0}_{0}\gamma$$

The emission of gamma rays in conjunction with other types of radiation is so common that it is often left out of nuclear equations. Nuclear chemists simply understand that the gamma rays are emitted along with the other types of decay. However, in some instances, there can be a delay between the initial decay and the subsequent emission of gamma rays. The initial decay leaves the daughter nucleus in *metastable* state (an unstable state that can exist for a prolonged period of time). The daughter then emits a gamma particle at a later time. For example, technetium-99 has a gamma-emitting metastable state:

$$^{99\mathrm{m}}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + {}^{0}_{0}\gamma$$

The m next to the mass number stands for metastable.

Gamma rays are the motorbikes of radioactivity. They have the lowest ionizing power but the highest penetrating power. (Imagine a motorbike zipping through a traffic jam.) Shielding gamma rays requires several inches of lead or thick slabs of concrete.

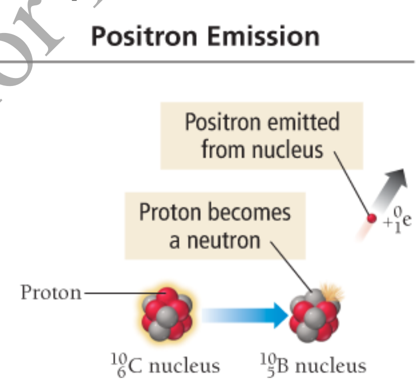
Positron Emission

Positron emission occurs when an unstable nucleus emits a positron (Figure 20.4). A **positron** is the *antiparticle* of the electron; it has the same mass as an electron but the opposite charge. If a positron collides with an electron, the two particles annihilate each other, releasing energy in the form of gamma rays. In positron emission, a proton becomes a neutron and emits a positron.

positron emission proton → neutron + emitted positron

Figure 20.4 **Positron Emission**

In positron emission, a proton emits a positron and becomes a neutron.



The symbol for a positron in a nuclear equation is:

positron $^{0}_{+1}\mathrm{e}$

We can represent positron emission with this nuclear equation:

$$^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{+1}\mathrm{e}$$

> Positron emission can be thought of as a type of beta emission and is sometimes referred to as beta plus emission (β^{+}).

beta plus emission (β^+).

When an atom emits a positron, its atomic number *decreases* by 1 because it has one less proton after emission. Consider the nuclear equation for the positron emission of phosphorus-30 as an example:

$$ {}^{30}_{15}\mathrm{P} \rightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\mathrm{e} $$

We can determine the identity and symbol of the daughter nuclide in any positron emission in a manner similar to that used for alpha and beta decay, as shown in Example 20.2. Positrons are similar to beta particles in their ionizing and penetrating power.

Example 20.2 Writing Nuclear Equations for Beta Decay, Positron Emission, and Electron Capture

Write the nuclear equation for each type of decay.

a. beta decay in Bk-249
b. positron emission in O-15
c. electron capture in I-111

SOLUTION

a. In beta decay, the atomic number *increases* by 1 and the mass number remains unchanged. The daughter nuclide is element number 98, californium.

$$ {}^{249}_{97}\mathrm{Bk} \rightarrow {}^{249}_{98}? + {}^{0}_{-1}\mathrm{e} $$
$$ {}^{249}_{97}\mathrm{Bk} \rightarrow {}^{249}_{98}\mathrm{Cf} + {}^{0}_{-1}\mathrm{e} $$

b. In positron emission, the atomic number *decreases* by 1 and the mass number remains unchanged. The daughter nuclide is element number 7, nitrogen.

$$ {}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}? + {}^{0}_{-1}\mathrm{e} $$
$$ {}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} $$

c. In electron capture, the atomic number also *decreases* by 1 and the mass number remains unchanged. The daughter nuclide is element number 52, tellurium.

$$ {}^{111}_{53}\mathrm{I} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{111}_{52}? $$
$$ {}^{111}_{53}\mathrm{I} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{111}_{52}\mathrm{Te} $$

FOR PRACTICE 20.2

a. Write three nuclear equations to represent the nuclear decay sequence that begins with the alpha decay of U-235 followed by a beta decay of the daughter nuclide and then another alpha decay.
b. Write the nuclear equation for the positron emission of Na-22.
c. Write the nuclear equation for electron capture in Kr-76.

FOR MORE PRACTICE 20.2

Potassium-40 decays to produce Ar-40. What is the method of decay? Write the nuclear equation for this decay.

Interactive Worked Example 20.2 **Writing Nuclear Equations for Beta Decay, Positron Emission, and Electron Capture**

Electron Capture

Unlike the forms of radioactive decay discussed so far, electron capture involves a particle being *absorbed by* instead of *emitted from* an unstable nucleus. **Electron capture** occurs when a nucleus assimilates an electron from an inner orbital of its electron cloud. Like positron emission, the net effect of electron capture is the conversion of a proton into a neutron.

electron capture proton + electron → neutron

We can represent electron capture with this nuclear equation:

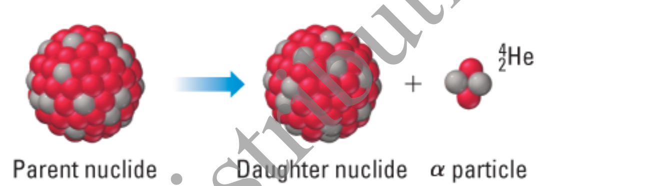
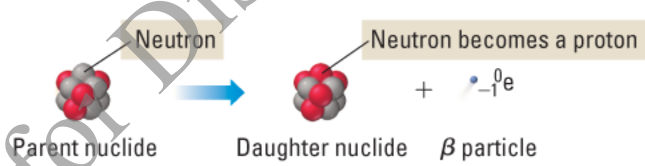
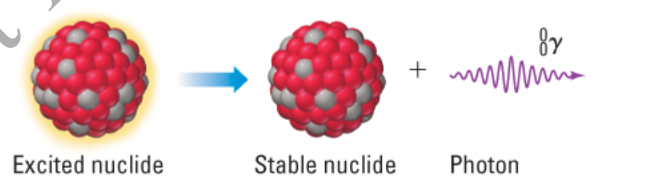
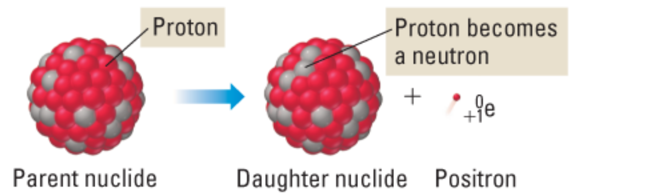
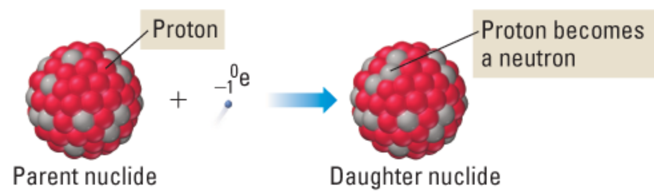
$$^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{1}_{0}\mathrm{n}$$

When an atom undergoes electron capture, its atomic number decreases by 1 because it has one less proton. For example, when Ru-92 undergoes electron capture, its atomic number changes from 44 to 43:

$$^{92}_{44}\mathrm{Ru} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{92}_{43}\mathrm{Tc}$$

Table 20.1 summarizes the different kinds of radiation.

Table 20.1 **Modes of Radioactive Decay**

Decay Mode	Process	Change in: A	Z	N/Z*	Exa
α		−4	−2	Increase	$^{238}_{92}$
β		0	+1	Decrease	$^{228}_{88}$R
γ		0	0	None	$^{99m}_{43}$T
Positron emission		0	−1	Increase	$^{30}_{15}$
Electron capture		0	−1	Increase	$^{92}_{44}$R

* Neutron-to-proton ratio

Conceptual Connection 20.1 **Alpha and Beta Decay**

Interactive