10.3 Radioactive Decay

10A — Investigation

Penetrating Ability of Nuclear Radiation

To perform this investigation, turn to page 298.

In this investigation, you will look at radioactive decay.

Henri Becquerel, and Pierre and Marie Curie found that uranium, radium, and polonium were radioactive. We now know that there are other naturally occurring radioactive elements including astatine, radon, and francium. The nuclei of some isotopes are unstable and emit radiation. Such isotopes are called radioactive isotopes, or radioisotopes. An unstable nucleus that emits radiation is undergoing **radioactive decay**. There are three main types of radioactive decay: alpha decay, beta decay, and gamma decay. Table 1 and Figure 1 summarize their characteristics. 10A — *Investigation*

Table 1 Three Main Types of Radioactive Decay

Method of decay	Radiation	Radiation symbol	Electric charge	Mass (electron = 1)	What is it?	Characteristics
alpha decay	alpha particle	α	+2	7000	a helium nucleus $^{4}_{2}He$	• slow moving • can only penetrate a piece of paper or skin
beta decay	beta particle	β	−1	1	an electron $^{0}_{-1}e$	• can only penetrate a few sheets of aluminum foil
gamma decay	gamma rays	γ	0	0	energetic "light" $^{0}_{0}\gamma$	• can only penetrate a few centimetres of lead

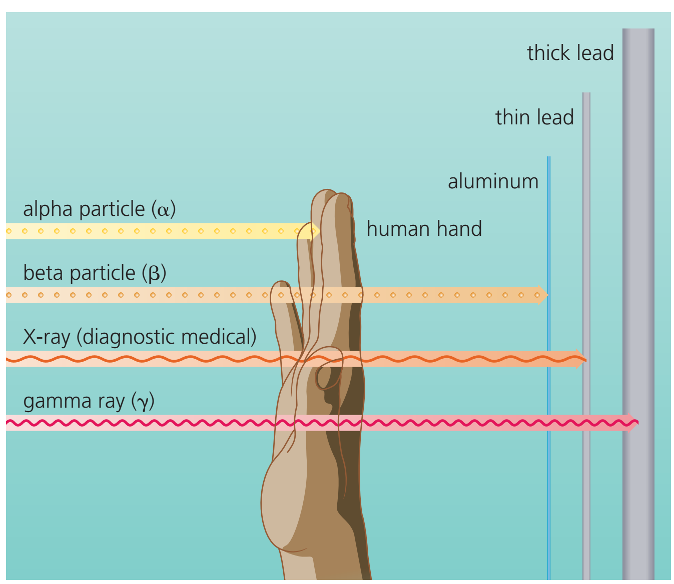

Figure 1 The penetrating ability of radiation. This is a measure of how much material is required to stop most, but not all, of the radiation going through the material.

In alpha and beta decays, the nucleus emits a particle and changes its identity. In other words, the atom has changed from one element to another. This is called transmutation. Transmutation changes a **parent nucleus** into a **daughter nucleus**. In gamma decay, the charge of the nucleus does not change, it just loses some energy. GO

To learn more about radioactive decay, go to www.science.nelson.com GO

Alpha Decay

Alpha decay occurs when a radioactive atom emits an **alpha particle**, α, which consists of two protons and two neutrons bound together into a particle identical to a helium nucleus, ${}^4_2He$. For example, the isotope polonium-210, the radioactive element discovered by Marie Curie, undergoes radioactive decay by emitting a helium nucleus. During the decay, the polonium-210 is changed into lead-206 (Figure 2). In this case, polonium-210 is the parent nucleus and lead-206 is the daughter nucleus. The process can be written as a nuclear reaction equation:

$$ {}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He $$

LEARNING TIP

Active readers adjust their reading to fit the difficulty of the text. If you find the text difficult to understand, go back and forth between the text and the diagram. Read more slowly, and reread.

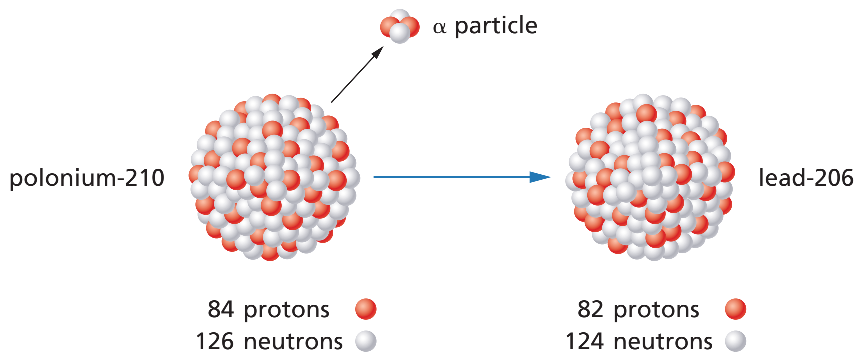

Figure 2 The alpha decay of polonium-210

After the alpha particle (remember, this is really a helium nucleus) has been emitted, it will slow down by crashing into surrounding atoms and eventually acquire two electrons to become a helium atom. Until the alpha particle becomes a stable helium atom, it moves around and collides with other atoms.

There are basically two rules for writing balanced nuclear equations: conservation of electric charge (atomic number) and conservation of the total number of protons and neutrons (mass number). The conservation of electric charge means that the amount of charge on the left-hand side of the arrow—in this case, +84—must equal the total charge on the right-hand side of the arrow—in this case, $82 + 2 = 84$. The mass number on the left side of the arrow, which is 210, must also equal the sum of the mass numbers on the right side of the arrow: $206 + 4 = 210$. Therefore, the mass number is conserved.

All alpha decays follow this pattern because the charge of all alpha particles is 2. We can write the general equation for alpha decay as:

$$ {}^{A}_{Z}N_{parent} \rightarrow {}^{A-4}_{Z-2}N_{daughter} + {}^{4}_{2}He $$

where N_{parent} is the parent nucleus and $N_{daughter}$ is the daughter nucleus. The letter Z represents the atomic number (number of protons) of the parent element, and A represents the mass number of the parent isotope (the number of protons plus neutrons).

Did You KNOW?

Polonium and the Spy

Former Russian spy Alexander Litvinenko was murdered using a radioactive isotope. He died three weeks after ingesting polonium-210, which had been dissolved most likely in a pot of tea. Polonium-210 is a strong emitter of alpha particles. Although alpha particles cannot travel very far, they can do tremendous damage to cells if they get inside the body through swallowing or inhaling. Doctors suspected that Mr. Litvinenko ingested less than a microgram of polonium-210.

SAMPLE PROBLEM 1

Determine the Nuclear Equation for Alpha Decay

Write the nuclear equation for the alpha decay of americium-241. What element has americium been transmuted into?

Solution

The atomic number of americium is 95 from the Periodic Table. Since the element undergoes alpha decay, the products will be a daughter nucleus and an alpha particle, ${}^{4}_{2}\text{He}$.

$$ {}^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\text{He} $$

Americium has been transmuted into neptunium.

Practice

Write the nuclear equation for the alpha decay of radium-226.

Beta Decay

In beta decay, the nucleus emits a **beta particle**, β, which is actually an electron, ${}^{0}_{-1}\text{e}$. Since the nucleus contains only protons and neutrons, how is it possible for the nucleus to emit an electron? Protons and electrons are very stable, but a neutron is not stable. A neutron in an unstable nucleus can decay into a proton, an electron, and a neutrino. Therefore, the electron comes from the decay of a neutron. Note that a neutrino is a subatomic particle that has energy, but has no mass or electric charge.

An example of beta decay is when carbon-14 undergoes radioactive decay to transmute into nitrogen-14 (Figure 3). The nuclear equation is:

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

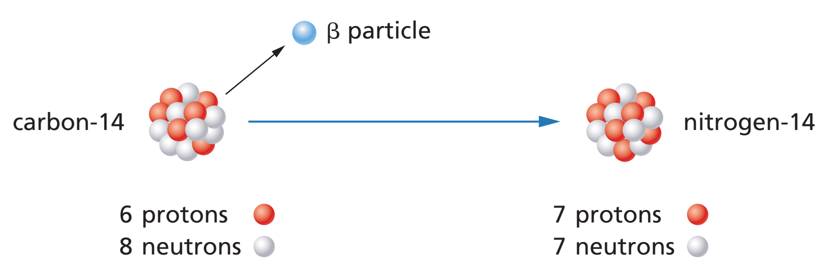

Figure 3 The beta decay of carbon-14

Note that in beta decay, the mass number of the daughter nucleus is the same as the parent nucleus. However, the atomic number of the daughter nucleus increases by one. For example, in the beta decay of carbon-14, when −1 is added to +7, the result is +6, which is the initial amount of electric charge. The neutrino often is omitted from beta decay equations.

Because the charge of all beta particles is −1 and the mass is close to 0, all beta decays follow this pattern. We can write the general equation as:

$$ {}^{A}_{Z}N_{\text{parent}} \rightarrow {}_{Z+1}^{A}N_{\text{daughter}} + {}^{0}_{-1}\text{e} $$

where N_{parent} is the parent nucleus, N_{daughter} is the daughter nucleus, Z represents the atomic number, and A represents the mass number.

SAMPLE PROBLEM 2

Determine the Nuclear Equation for Beta Decay

Write the nuclear equation for the beta decay of the isotope cesium-137. What element has cesium been transmuted into?

Solution

The atomic number of cesium is 55 from the Periodic Table. Since the element undergoes beta decay, the products will be a daughter nucleus and a beta particle.

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

Cesium has been transmuted into barium.

Practice

Write the nuclear equation for the beta decay of xenon-133.

STUDY TIP

Summarizing (condensing main points in your own words) is a helpful study tool. After reading Section 10.3, write a brief summary for each type of radioactive decay. Compare your summaries with a friend. Is there anything important that should be added?

Gamma Decay

In gamma decay, the nucleus emits a **gamma ray**, γ, which is very high-energy electromagnetic radiation. When the nucleus of an atom is in an excited state following the emission of an alpha or beta particle, the nucleus has a surplus of energy. The nucleus lowers its amount of energy by emitting a gamma ray. Since a gamma ray has no electric charge or mass, gamma decay does not change the type of isotope—it only changes the isotope's energy.

The following example shows the production of an excited nucleus followed by gamma decay. When americium-241 undergoes alpha decay, the daughter nucleus produced is neptunium-237.

$$^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np}^{*} + {}^{4}_{2}\text{He}$$

The asterisk beside the symbol for neptunium indicates that the nucleus is in an excited state. The excited nucleus then undergoes gamma decay and changes to a normal, or ground, state.

$$^{237}_{93}\text{Np}^{*} \rightarrow {}^{237}_{93}\text{Np} + {}^{0}_{0}\gamma$$

Because the gamma ray has no charge and no mass, all gamma decays follow this pattern and we can write the general equation for gamma decay as:

$$^{A}_{Z}N^{*} \rightarrow {}^{A}_{Z}N + {}^{0}_{0}\gamma$$

Remember that gamma decay adjusts the energy levels in a nucleus, but does not otherwise change the nucleus.

Did You KNOW?

Harold Johns and Cobalt-60

Harold Johns (1915–1998) is regarded as the Father of Medical Physics. Johns was born in China, but moved to Canada in the mid-1920s. He developed the first cobalt-60 cancer treatment unit in Saskatchewan. Cobalt-60 units are still built in Canada and distributed around the world. In 1977, Johns was elected as an Officer of the Order of Canada. He was inducted into the Canadian Medical Hall of Fame in 1998.

SAMPLE PROBLEM 3

Determine the Nuclear Equation for Gamma Decay

Boron-12 undergoes beta decay to produce an excited daughter nucleus. Write the nuclear equation for this decay, and then write the nuclear equation for the gamma decay of the excited daughter nucleus. What element has boron been transmuted into?

Solution

$$^{12}_{5}B \rightarrow {}^{12}_{6}C^{*} + {}^{0}_{-1}e$$

$$^{12}_{6}C^{*} \rightarrow {}^{12}_{6}C + {}^{0}_{0}\gamma$$

Boron has been transmuted into carbon.

Practice

The isotope cobalt-60 undergoes beta decay to produce a daughter nucleus in an excited state. Write the nuclear equation of the beta decay, and then write the nuclear equation that shows how the nucleus lowers its internal energy level.

Figure 4 In a cloud chamber, the alpha particles produce a thick, short track. Beta particles make a thin irregular track. Gamma rays have no charge and, thus, no track.

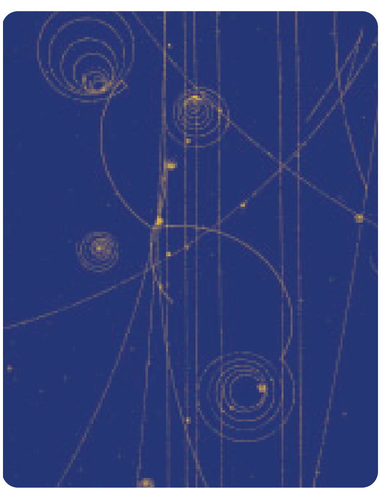

Figure 5 Tracks made by alpha and beta particles in a bubble chamber

To view an animation of a Geiger counter in action and to test your knowledge, go to **www.science.nelson.com**

Detection of Radioactive Emissions

How can scientists detect radioactive decay when alpha particles, beta particles, and gamma rays are invisible to the human eye? One device used to detect radioactivity is a cloud chamber. A diffusion cloud chamber is a small, clear plastic, sealed cylinder inside of which is a sponge saturated with alcohol. When the bottom of the cylinder is placed on dry ice, the air becomes supersaturated with alcohol. When a radioactive source is placed inside, it emits charged particles that remove some electrons from the atoms in the air as they travel, converting the atoms to positive ions. These ions cause the vapour to condense and create a visible track (Figure 4).

A bubble chamber is similar to a cloud chamber. The chamber contains a superheated liquid, such as propane or liquid hydrogen. When a charged particle passes through the liquid, bubbles form around the tracks of the particles. An electromagnet causes the charged particles to be deflected. Alpha and beta particles are deflected in opposite directions (Figure 5).

Another device that can detect radiation is a Geiger counter. Geiger counters also are based on the fact that some radiations produce trails of charged atoms (ions) as they pass through a gas. It consists of a cylinder containing a gas and a wire inside. There is a high voltage between the cylinder case and the wire. Charged particles enter through a window at one end of the cylinder and ionize the gases inside the cylinder. The positive ions are attracted to the negatively charged wire, which produces a current that can be detected and read as a count. Each burst of current represents the detection of one particle. The Geiger counter is connected to a counting device that keeps count of radiation entering the tube. Geiger counters can detect beta particles and gamma rays. Alpha particles are not able to penetrate the window of most counters.

10.3

CHECK YOUR Understanding

1. What happens when a radioactive atom undergoes radioactive decay?
2. How many beta particles would it take to have the same mass as a single alpha particle?
3. Why are alpha and beta radiation referred to as particles, while gamma radiation is referred to as rays?
4. Write a definition of transmutation in your own words.
5. What happens to the atomic number (Z) and mass number (A) of a parent nucleus during alpha decay?
6. List two differences between an alpha particle and a helium atom.
7. The following parent isotopes undergo alpha decay. Write the nuclear equation for these transmutations.
   (a) tungsten-180
   (b) samarium-147
   (c) sodium-20
8. Write a brief description of beta decay in your own words.
9. The mass number of an atom undergoing beta decay does not change. However, the daughter nucleus is a different element than the parent. Explain how this is possible.
10. The following parent isotopes undergo beta decay. Write the nuclear equation for this transmutation.
    (a) nickel-64
    (b) tritium
    (c) iron-59
11. How do the atomic number and the mass number of an atom change as a result of gamma decay? Why does an atom emit gamma radiation?
12. Iron-60 undergoes beta decay. The daughter produced is in an excited state and undergoes gamma decay. Write nuclear equations to show these two processes.
13. State whether the following descriptions apply to alpha, beta, or gamma radiation:
    (a) has a negative charge
    (b) is a helium nucleus
    (c) its path is deflected by a magnet
    (d) is similar to X-rays
    (e) is stopped by a few sheets of paper
    (f) an electric charge does not affect its path
    (g) has the most mass
    (h) easily penetrates skin and tissue
14. Complete the following nuclear equations:
    (a) $^{239}_{93}\text{Np} \rightarrow \textbf{?} + {}^{0}_{-1}\text{e}$
    (b) $^{232}_{90}\text{Th} \rightarrow \textbf{?} + {}^{4}_{2}\text{He}$
    (c) $^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + \textbf{?}$
    (d) $^{152}_{66}\text{Dy}^{*} \rightarrow {}^{152}_{66}\text{Dy} + \textbf{?}$
    (e) $^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + \textbf{?}$
    (f) $\textbf{?} \rightarrow {}^{209}_{81}\text{Tl} + {}^{4}_{2}\text{He}$
    (g) $^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + \textbf{?}$
    (h) $\textbf{?} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$
    (i) $\textbf{?} \rightarrow {}^{99}_{43}\text{Tc} + {}^{0}_{0}\gamma$
15. Name and describe three devices that are used to detect radioactivity.
16. Alpha and beta radiation leave visible tracks in a cloud chamber. However, gamma rays do not. Why?
17. Why do alpha particles leave short thick tracks in a cloud chamber, while beta particles leave long thin tracks?
18. How is a Geiger counter similar to a cloud chamber?
19. Why are some Geiger counters unable to detect alpha radiation?