Nuclear Reactions

18

Pedro Saura via Science/AAAS

Hand stencils on the walls of the El Castillo caves are estimated to be done by Neanderthals at least 40,800 years ago. They are now the oldest known cave art in the world, 5,000 to 10,000 years older than those in the Chauvet Caves in France. These stencils are dated by measuring the uranium decay, since there is no organic matter in them.

The changing of Bodies into Light, and Light into Bodies, is very conformable to the Course of Nature, which seems delighted with Transmutations.

—SIR ISAAC NEWTON
Opticks, 2nd edition (1718)
Book 3, Query 30, 349

Chapter Outline

The "ordinary chemical reactions" discussed to this point involve changes in the outer electronic structures of atoms or molecules. In contrast, nuclear reactions result from changes taking place within atomic nuclei. You will recall (Chapter 2) that atomic nuclei are represented by symbols such as

$$^{12}_{6}C \qquad ^{14}_{6}C$$

The atomic number Z (number of protons in the nucleus) is shown as a left subscript. The mass number A (number of protons + number of neutrons in the nucleus) appears as a left superscript.

The reactions that we discuss in this chapter will be represented by **nuclear equations**. An equation of this type uses nuclear symbols such as those above; in other respects it resembles an ordinary chemical equation. A nuclear equation must be balanced with respect to nuclear charge (atomic number) and nuclear mass (mass number). To see what that means, consider an equation that we will have a lot more to say about later in this chapter:

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

The reactants are an N-14 nucleus and a neutron; the products are a C-14 nucleus and an H-1 nucleus. The atomic numbers add to 7 on both sides:

Nuclear reactions usually involve the transmutation of elements.

$$\text{reactants: } 7 + 0 = 7 \qquad \text{products: } 6 + 1 = 7$$

whereas the mass numbers add to 15:

$$\text{reactants: } 14 + 1 = 15 \qquad \text{products: } 14 + 1 = 15$$

18-1 Nuclear Stability

As we have learned from Chapter 2, atomic nuclei consist of protons, which are positively charged, and neutrons, which have zero charge. According to classical electrostatics, we should expect the protons to repel one another and the nucleus to fly apart. It turns out, however, that at the very short distances of separation characteristic of atomic nuclei (about 10^{-15} m), there are strong attractive forces between nuclear particles. The stability of a nucleus depends upon the balance between these forces and electrostatic repulsion.

Despite extensive research, we still do not have a clear understanding of the way in which those forces lead to nuclear stability. All we have is a series of empirical rules for predicting which nuclei will be most stable. The most important of these rules are listed below.

- The neutron-to-proton ratio (n/p^+) required for stability varies with atomic number. The 264 known stable nuclei, shown as red dots in Figure 18.1, fall within a relatively narrow *belt of stability*. For light elements ($Z < 20$), this ratio is close to one. For example, the isotopes $^{12}_{6}C$, $^{14}_{7}N$, and $^{16}_{8}O$ are stable. As atomic number increases, the ratio increases; the belt of stability shifts to higher numbers of neutrons. With very heavy isotopes such as $^{206}_{82}Pb$, the stable neutron-to-proton ratio is about 1.5.

$$(206 - 82)/82 = 1.51$$

- Nuclei containing more than 83 protons are unstable. Putting it another way, no element beyond bismuth ($Z = 83$) has a stable isotope. All the isotopes of such elements are radioactive.
- Nuclei with an even number of **nucleons**, either protons or neutrons, tend to be more stable than those with an odd number of nuclear particles.
- Certain numbers of protons and neutrons appear to be particularly stable: 2, 8, 20, 28, 50, 82, and 126. These *magic numbers* were first suggested by Maria Mayer (1906–1972), who developed a nuclear shell model similar to, but much less regular than, the electron shell model discussed in Chapter 6. For her work,

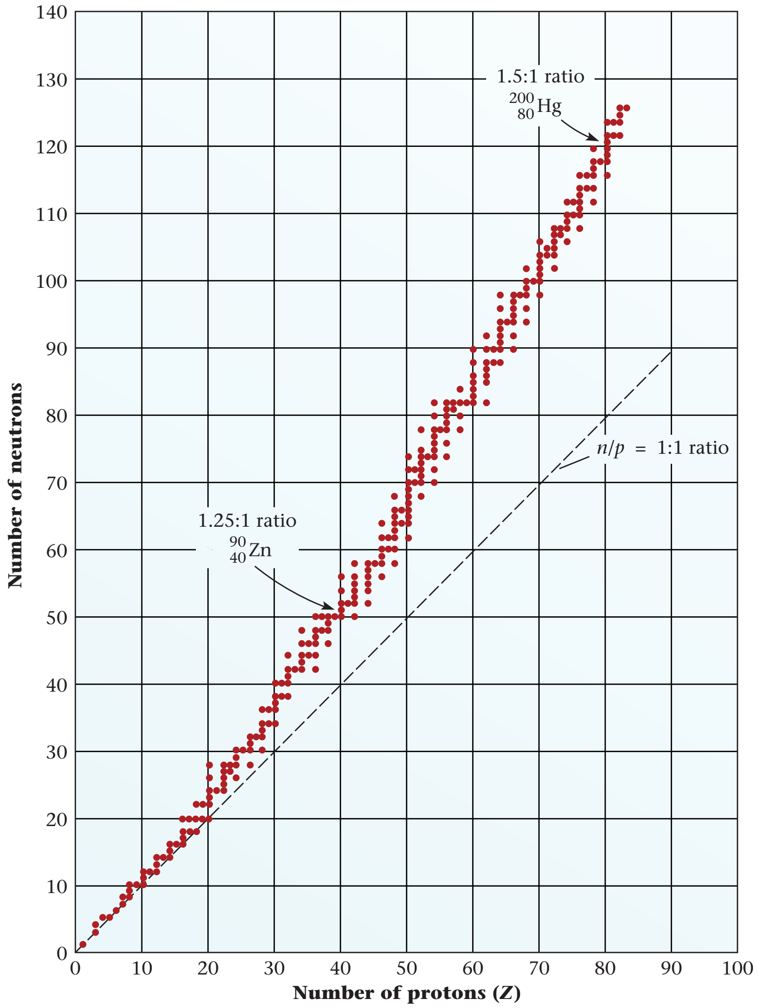


Figure 18.1 Neutron-to-proton ratios of stable isotopes. The ratios of stable isotopes (red dots) fall within a narrow range, referred to as the *belt of stability*. For light isotopes of small atomic number the stable ratio is 1:1. For heavier isotopes the ratio gradually increases to about 1.5:1. Isotopes outside the belt of stability are unstable and radioactive. There are no stable isotopes for elements of atomic number greater than 83 (Bi).

Maria Mayer won the Nobel Prize in Physics in 1963. The Nobel Prize in Physics has been awarded yearly (except between 1940 and 1942) for 106 years, and the only women to have won this prize so far are Maria Mayer and Marie Curie.

EXAMPLE 18.1

For each pair of nuclei, list which one is more stable.

a $^{6}_{3}Li$ or $^{9}_{3}Li$

STRATEGY

1. Determine the neutron-to-proton ratio.
2. Check the belt of stability.

SOLUTION

1. n/p^+	$^{6}_{3}Li$: $n/p^+ = 3/3 = 1$; $^{9}_{3}Li$: $n/p^+ = 6/3 = 2$
2. Stability	$^{9}_{3}Li$: is unstable. A $n/p^+ = 2$ lies well below the belt of stability.

b $^{204}_{82}Pb$ or $^{209}_{85}At$

STRATEGY AND SOLUTION

For Pb, $Z = 82$, whereas Z for At is 85. Pb is the more stable element.

18-2 Radioactivity

Unstable isotopes decompose (*decay*) by a process referred to as **radioactivity**. A few such nuclei occur in nature, accounting for *natural radioactivity*. Many more can be made ("induced") artificially by bombarding stable nuclei with high-energy particles. The radiation given off (Figure 18.2) may be in the form of

beta (β) particles identical in their properties to electrons

alpha (α) particles, which are $^{4}_{2}He$ nuclei, carrying a +2 charge because the two extranuclear electrons of the helium atom are missing

gamma (γ) rays, which consist of high-energy radiation

Mode of Decay

Naturally occurring radioactive nuclei commonly decompose by

- *alpha particle emission,* in which an ordinary helium nucleus, $^{4}_{2}He$, is given off. Uranium-238 behaves this way:

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

Notice that when alpha emission occurs, the atomic number decreases by two units; the mass number decreases by four units. Here, as in all nuclear equations, there is a balance of both atomic number ($90 + 2 = 92$) and mass number ($234 + 4 = 238$) on both sides of the arrow.

The **alpha particle** is by far the most massive particle emitted by radioactive nuclei. It has the highest *ionizing power*, i.e., the ability to ionize other molecules or ions. Because of their size, alpha particles have difficulty penetrating cells. Thus they can be stopped by clothing, skin, or even a sheet of paper. Alpha-emitting nuclei kept outside the body are relatively safe. Inhaling or ingesting these particles is much more dangerous, because cell membranes cannot stop them.

- *beta particle emission,* which produces an electron, given the symbol $^{0}_{-1}e$. An example of beta emission is

$$^{234}_{90}Th \longrightarrow {}^{0}_{-1}e + {}^{234}_{91}Pa$$

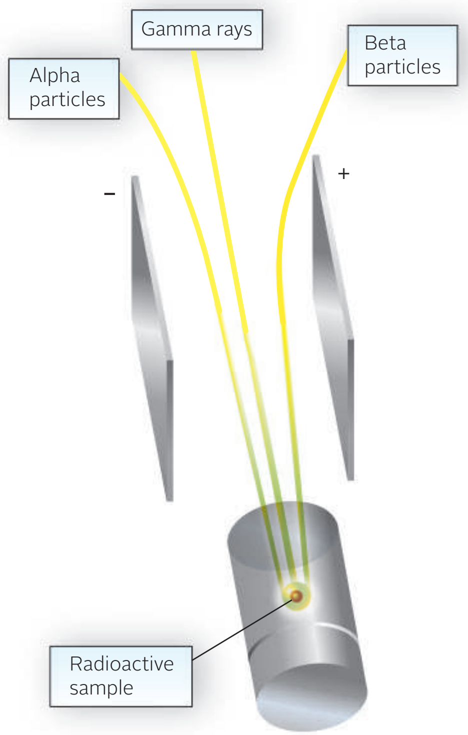


Figure 18.2 Nuclear radiation. In the presence of an electric field, alpha particles are deflected toward the negative pole, showing that they are positively charged, and beta particles are deflected toward the positive pole, showing that they are negatively charged. Because they are lighter, beta particles are deflected more than alpha particles. Gamma rays pass straight through the field and so must have no charge.

Notice that the product nucleus, $^{234}_{91}Pa$, has the same mass number as the reactant, $^{234}_{90}Th$, but its atomic number is one unit larger. Putting it another way, beta emission converts a neutron to a proton. It occurs with nuclei that contain "too many neutrons" for stability.

Beta particles are smaller and lighter than alpha particles. Thus although they can penetrate the cell more easily, they have a lower ionizing power. A sheet of metal can stop their entry into cells, and even when ingested or inhaled, they are less destructive than alpha particles.

- **gamma radiation,** which consists of high-energy photons. Because gamma emission changes neither the mass number nor the atomic number, it is ordinarily omitted in writing nuclear equations.

  Gamma rays, because of their size, have the lowest ionizing power. However, several inches of lead or a thick cement block is necessary to stop gamma ray penetration.

  Radioactive nuclei produced "artificially" in the laboratory can show α-, β-, or γ-emission. They can also decompose by

- *positron emission*. A **positron** is identical to an electron except that it has a charge of +1 rather than −1. A positron has the symbol $^{0}_{1}e$.

$$^{40}_{19}K \longrightarrow {}^{0}_{1}e + {}^{40}_{18}Ar$$

Here, a proton in K-40 (19 p^+, 21 n) is converted to a neutron in Ar-40 (18 p^+, 22 n). Positron emission is characteristic of nuclei that have too many protons for stability.

- **K-electron capture,** in which an electron in the innermost energy level ($n = 1$) "falls" into the nucleus.

$$^{82}_{37}Rb + {}^{0}_{-1}e \longrightarrow {}^{82}_{36}Kr$$

Notice that the result of K-electron capture is the same as positron emission; mass number remains unchanged, whereas atomic number decreases by one unit. Electron capture is more common with heavy nuclei, presumably because the $n = 1$ level is closer to the nucleus.

Table 18.1 is a summary of the different modes of radioactive decay described here.

Table 18.1 Modes of Radioactive Decay

Mode	Emission	Example	Change in A	Change in Z	Penetrating Power
α-decay	${}^{4}_{2}\text{He}$	${}^{238}_{92}\text{U} \longrightarrow {}^{4}_{2}\text{He} + {}^{234}_{90}\text{Th}$	−4	−2	≈0.03 mm
β-decay	${}^{0}_{-1}e^{-}$	${}^{234}_{90}\text{Th} \longrightarrow e + {}^{234}_{91}\text{Pa}$	0	+1	≈2 mm
γ-decay	photons		0	0	≈10 cm
positron emission	${}^{0}_{1}e$	${}^{40}_{19}\text{K} \longrightarrow {}^{0}_{1}e + {}^{40}_{18}\text{Ar}$	0	−1	
K-electron capture	none	${}^{82}_{37}\text{Rb} + {}^{0}_{-1}e^{-} \longrightarrow {}^{82}_{36}\text{Kr}$	0	−1	

EXAMPLE 18.2

Promethium ($Z = 61$) is essentially nonexistent in nature; all of its isotopes are radioactive. Write balanced nuclear equations for the decomposition of various isotopes of promethium:

Pm-142 by positron emission, Pm-147 by beta emission, and Pm-150 by alpha emission.

STRATEGY

1. Recall the symbol of the particle emitted for the specified decay mode.
2. Balance mass number and atomic number.
3. Find the symbol of the product isotope in the periodic table by using its atomic number.

SOLUTION

Pm-142 decomposition by positron emission.	
1. particle emitted	positron: ${}^{0}_{1}e$
2. mass and atomic number balance	${}^{142}_{61}\text{Pm} \longrightarrow {}^{0}_{1}e + {}^{142}_{60}$
3. reaction	${}^{142}_{61}\text{Pm} \longrightarrow {}^{0}_{1}e + {}^{142}_{60}\text{Nd}$
Pm-147 decomposition by beta emission.	
1. particle emitted	β-particle: ${}^{0}_{-1}e$
2. mass and atomic number balance	${}^{147}_{61}\text{Pm} \longrightarrow {}^{0}_{-1}e + {}^{147}_{62}$
3. reaction	${}^{147}_{61}\text{Pm} \longrightarrow {}^{0}_{-1}e + {}^{147}_{62}\text{Sm}$
Pm-150 decomposition by alpha emission.	
1. particle emitted	α-particle: ${}^{4}_{2}\text{He}$
2. mass and atomic number balance	${}^{150}_{61}\text{Pm} \longrightarrow {}^{4}_{2}\text{He} + {}^{146}_{59}$
3. reaction	${}^{150}_{61}\text{Pm} \longrightarrow {}^{4}_{2}\text{He} + {}^{146}_{59}\text{Pr}$

Bombardment Reactions

More than 1500 radioactive isotopes have been prepared in the laboratory. The number of such isotopes per element ranges from 1 (hydrogen and boron) to 34 (indium). They are all prepared by bombardment reactions in which a stable nucleus is converted to one that is radioactive, which in turn decays to stable products. The bombarding particle may be

- a *neutron,* usually of rather low energy, produced in a fission reactor (Section 18-5). A typical reaction of this type is

$$ {}^{27}_{13}\text{Al} + {}^{1}_{0}n \longrightarrow {}^{28}_{13}\text{Al} $$

The product nucleus, Al-28, is radioactive, decaying by beta emission:

$$ {}^{28}_{13}\text{Al} \longrightarrow {}^{28}_{14}\text{Si} + {}^{0}_{-1}e $$

Promethium is by far the rarest of the "rare earths" (Example 18.2).

- a *charged particle* (electron, positron, α-particle, . . .), which can be accelerated to very high velocities in electric and/or magnetic fields. In this way, the charged particle acquires enough energy to bring about a nuclear reaction, despite electrostatic repulsion with the components of the atom.

The first radioactive isotopes to be made in the laboratory were prepared in 1934 by Irene Curie and her husband, Frederic Joliot. They achieved this by bombarding certain stable isotopes with high-energy alpha particles. One reaction was

$$^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \longrightarrow {}^{30}_{15}\text{P} + {}^{1}_{0}n$$

The product, phosphorus-30, is radioactive, decaying by positron emission:

$$^{30}_{15}\text{P} \longrightarrow {}^{30}_{14}\text{Si} + {}^{0}_{1}e$$

An interesting application of bombardment reactions is the preparation of the so-called transuranium elements. Beginning with neptunium (Np, $Z = 93$) in 1940, a series of elements with atomic numbers greater than that of uranium have been synthesized. Much of this work was done by a group at the University of California, Berkeley, under the direction of Glenn Seaborg (1912–1999) and later Albert Ghiorso (1915–2010). A Russian group at Dubna near Moscow, led by G. N. Flerov (1913–1999), made significant contributions. The heavy elements (197 through 212) were prepared in the late twentieth century by a German group at Darmstadt under the direction of Peter Armbruster (1931–). Most of the nuclei produced have half-lives of a few microseconds. Experiments reporting the formation of elements 113, 115, and 117 have been reported in peer-reviewed journals, but their identification is yet to be confirmed by IUPAC (International Union of Pure and Applied Chemists).

In October 2006, a research team of scientists from the Lawrence Livermore National Laboratory in California, USA, and the Joint Institute of Nuclear Research in Dubna, Russia, reported the indirect detection of Uuo-294 (Element 118). It is reported to be produced by the following collisions.

$$^{249}_{98}\text{Cf} + {}^{48}_{20}\text{Ca} \longrightarrow {}^{294}_{118}\text{Uuo} + 3\,{}^{1}_{0}n$$

The decay products of Uuo-294, not the atoms themselves, were observed.

Some of the reactions used to prepare transuranium elements are listed in Table 18.2. Neutron bombardment is effective for the lower members of the series (elements 93 through 95), but the yield of product decreases sharply with increasing atomic number. To form the heavier transuranium elements, it is necessary to bombard appropriate targets with high-energy positive ions. By using relatively

The names of these elements reflect the names of their discoverers and other nuclear scientists.

Table 18.2 Synthesis of Transuranium Elements

	Neutron Bombardment
Neptunium, plutonium	$^{238}_{92}\text{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}e$ $^{239}_{93}\text{Np} \longrightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}e$
Americium	$^{239}_{94}\text{Pu} + 2\,{}^{1}_{0}n \longrightarrow {}^{241}_{95}\text{Am} + {}^{0}_{-1}e$
	Positive Ion Bombardment
Curium	$^{239}_{94}\text{Pu} + {}^{4}_{2}\text{He} \longrightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}n$
Californium	$^{242}_{96}\text{Cm} + {}^{4}_{2}\text{He} \longrightarrow {}^{245}_{98}\text{Cf} + {}^{1}_{0}n$
Rutherfordium	$^{249}_{98}\text{Cf} + {}^{12}_{6}\text{C} \longrightarrow {}^{257}_{104}\text{Rf} + 4\,{}^{1}_{0}n$
Dubnium	$^{249}_{98}\text{Cf} + {}^{15}_{7}\text{N} \longrightarrow {}^{260}_{105}\text{Db} + 4\,{}^{1}_{0}n$
Seaborgium	$^{249}_{98}\text{Cf} + {}^{18}_{8}\text{O} \longrightarrow {}^{263}_{106}\text{Sg} + 4\,{}^{1}_{0}n$

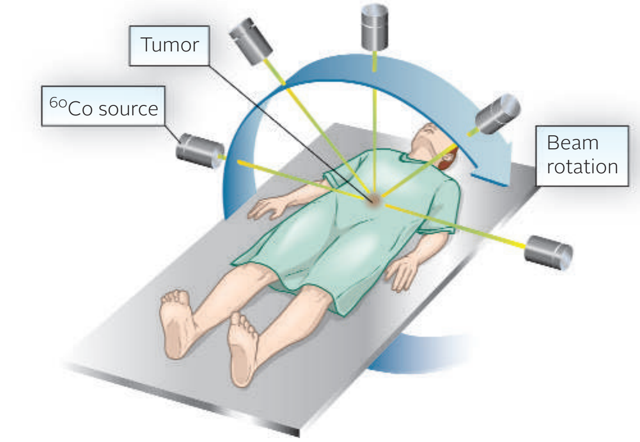


Figure 18.3 Cobalt-60 cancer therapy. Gamma rays from the rotating radiation source are concentrated at the location of the diseased tissue.

heavy bombarding particles such as carbon-12, one can achieve a considerable increase in atomic number.

Applications

A large number of radioactive nuclei have been used both in industry and in many areas of basic and applied research. A few of these are discussed below.

Medicine

Radioactive isotopes are commonly used in cancer therapy, usually to eliminate any malignant cells left after surgery. Cobalt-60 is most often used; γ-rays from this source are focused at small areas where cancer is suspected (Figure 18.3). Certain types of cancer can be treated internally with radioactive isotopes. If a patient suffering from cancer of the thyroid drinks a solution of NaI containing radioactive iodide ions (^{131}I or ^{123}I), the iodine moves preferentially to the thyroid gland. There the radiation destroys malignant cells without affecting the rest of the body.

More commonly, radioactive nuclei are used for diagnosis (Table 18.3). Positron emission tomography (PET) is a technique used to study brain disorders. The patient is given a dose of glucose ($C_6H_{12}O_6$) which has a radioactive isotope of fluorine attached to it. The fluorine isotope is a positron emitter. The brain is then scanned to detect positron emission from the radioactive "labeled" glucose. In this way, differences in glucose uptake and metabolism in patients with normal and abnormal brains are established. For example, PET scans have determined that the brain of a schizophrenic metabolizes only about 20% as much glucose as that of most people.

SPECT scans (single proton emission computer tomography) also use radioactive tracers and a scanner to give two- or three-dimensional images. The scans give information about blood flow to tissues and chemical reactions (metabolism) in the body.

Table 18.3 Diagnostic Uses of Radioactive Isotopes

Isotope	Use
$^{18}_{9}$F	Brain scan (PET); see text
$^{24}_{11}$Na	Circulatory disorders
$^{32}_{15}$P	Detection of eye tumors
$^{59}_{26}$Fe	Anemia
$^{67}_{31}$Ga	Scan for lung tumors, abscesses
$^{75}_{34}$Se	Pancreas scan
$^{99}_{43}$Tc	Imaging of brain, liver, kidneys, bone marrow
$^{133}_{54}$Xe	Lung imaging
$^{201}_{81}$Tl	Heart disorders

Chemistry

Radioactive nuclei are used extensively in chemical analysis. One technique of particular importance is *neutron activation analysis*. This procedure depends on the phenomenon of induced radioactivity. A sample is bombarded by neutrons, bringing about such reactions as

$$^{84}_{38}\text{Sr} + ^{1}_{0}n \longrightarrow ^{85}_{38}\text{Sr}$$

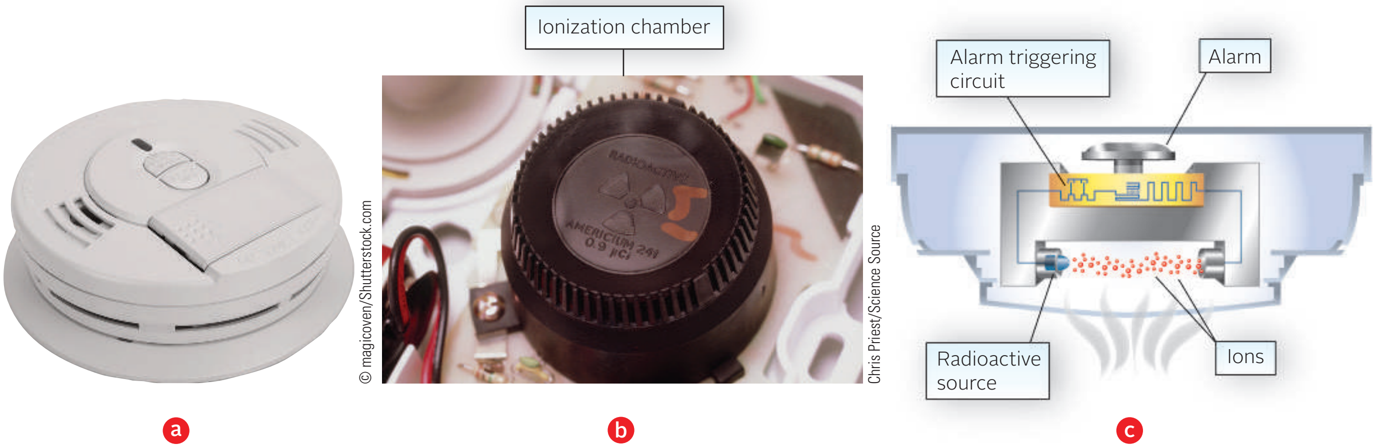


Figure 18.4 Smoke detector. Most smoke detectors use a tiny amount of a radioactive isotope to produce a current flow that drops off sharply in the presence of smoke particles, emitting an alarm in the process.

Ordinarily the element retains its chemical identity, but the isotope formed is radioactive, decaying by gamma emission. The magnitude of the energy change and hence the wavelength of the gamma ray vary from one element to another and so can serve for the qualitative analysis of the sample. The intensity of the radiation depends on the amount of the element present in the sample; this permits quantitative analysis of the sample. Neutron activation analysis can be used to analyze for 50 different elements in amounts as small as one picogram (10^{-12} g).

One application of neutron activation analysis is in the field of archaeology. By measuring the amount of strontium in the bones of prehistoric humans, it is possible to get some idea of their diet. Plants contain considerably more strontium than animals do, so a high strontium content suggests a largely vegetarian diet. Strontium analyses of bones taken from ancient farming communities consistently show a difference by sex; women have higher strontium levels than men. Apparently, in those days, women did most of the farming; men spent a lot of time away from home hunting and eating their kill.

Commercial Applications

Most smoke alarms (Figure 18.4) use a radioactive species, typically americium-241. A tiny amount of this isotope is placed in a small ionization chamber; decay of Am-241 ionizes air molecules within the chamber. Under the influence of a potential applied by a battery, these ions move across the chamber, producing an electric current. If smoke particles get into the chamber, the flow of ions is impeded and the current drops. This is detected by electronic circuitry, and an alarm sounds. The alarm also goes off if the battery voltage drops, indicating that it needs to be replaced.

Figure 18.5 Food preservation. Strawberries irradiated with gamma rays from radioactive isotopes to keep them fresh.

Another potential application of radioactive species is in food preservation (Figure 18.5). It is well known that gamma rays can kill insects, larvae, and parasites such as trichina that cause trichinosis in pork. Radiation can also inhibit the sprouting of onions and potatoes. Perhaps most important from a commercial standpoint, it can extend the shelf lives of many foods for weeks or even months. Many chemicals used to preserve foods have later been shown to have adverse health effects, so irradiation is an attractive alternative. Finally, irradiation can destroy microorganisms such as *E. coli* (which explains its use in treating beef) and anthrax (which explains its use in "sterilizing" suspected mail).

CHEMISTRY THE HUMAN SIDE

The history of radiochemistry is in no small measure the story of two remarkable women, Marie and Irene Curie, and their husbands, Pierre Curie and Frederic Joliot. Marie Curie (1867–1934) was born Maria Sklodowska in Warsaw, Poland, then a part of the Russian empire. In 1891, she emigrated to Paris to study at the Sorbonne, where she met and married a French physicist, Pierre Curie (1859–1906). The Curies were associates of Henri Becquerel (1852–1928), the man who discovered that uranium salts are radioactive. They showed that thorium, like uranium, is radioactive and that the amount of radiation emitted is directly proportional to the amount of uranium or thorium in the sample.

In 1898, Marie and Pierre Curie isolated two new radioactive elements, which they named radium and polonium. To obtain a few milligrams of these elements, they started with several tons of pitchblende ore and carried out a long series of tedious separations. Their work was done in a poorly equipped, unheated shed where the temperature reached 6°C (43°F) in winter. Four years later, in 1902, Marie determined the atomic mass of radium to within 0.5%, working with a tiny sample.

In 1903, the Curies received the Nobel Prize in Physics (with Becquerel) for the discovery of radioactivity. Three years later, Pierre Curie died at the age of 46, the victim of a tragic accident. He stepped from behind a carriage in a busy Paris street and was run down by a horse-driven truck. That same year, Marie became the first woman instructor at the Sorbonne. In 1911, she won the Nobel Prize in Chemistry for the discovery of radium and polonium, thereby becoming the first person to win two Nobel Prizes.

When Europe exploded into war in 1914, scientists largely abandoned their studies to go to the front. Marie Curie, with her daughter Irene, then 17 years old, organized medical units equipped with x-ray machinery. These were used to locate foreign metallic objects in wounded soldiers. Many of the wounds were to the head; French soldiers came out of the trenches without head protection because their government had decided that helmets looked too German. In November of 1918, the Curies celebrated the end of World War I; France was victorious, and Marie's beloved Poland was free again.

Humanities and Social Sciences Library/New York Public Library/Science Source

Marie and Pierre Curie with daughter Irene, at their home near Paris

In 1921, Irene Curie (1897–1956) began research at the Radium Institute. Five years later she married Frederic Joliot (1900–1958), a brilliant young physicist who was also an assistant at the Institute. In 1931, they began a research program in nuclear chemistry that led to several important discoveries and at least one near miss. The Joliot-Curies were the first to demonstrate induced radioactivity. They also discovered the positron, a particle that scientists had been seeking for many years. They narrowly missed finding another, more fundamental particle, the neutron. That honor went to James Chadwick in England (Chadwick, a student of Rutherford, discovered the neutron in 1932). In 1935, Irene Curie and Frederic Joliot received the Nobel Prize in Physics. The award came too late for Irene's mother, who had died of leukemia in 1934. Twenty-two years later, Irene Curie-Joliot died of the same disease. Both women acquired leukemia through prolonged exposure to radiation.

18-3 Rate of Radioactive Decay

As pointed out in Chapter 11, radioactive decay is a first-order process. This means that the following equations, discussed on pages 285–287, apply:

$$\text{rate} = kX$$

$$\ln \frac{X_o}{X} = kt$$

$$k = \frac{0.693}{t_{1/2}}$$

where k is the first-order rate constant, $t_{1/2}$ is the half-life, X is the amount of radioactive species present at time t, and X_o is the amount at $t = 0$.

k = rate constant = fraction of atoms decaying in unit time.

Because of the way in which rate of decay is measured (Figure 18.6), it is often described by the **activity** (A) of the sample, which expresses the number of atoms decaying in unit time. The first equation above can be written

$$A = kN \qquad \textbf{(18.1)}$$

where A is the activity, k the first-order rate constant, and N the number of radioactive nuclei present.

Courtesy of Beckman Coulter, Inc.

Figure 18.6 A liquid scintillation counter. This instrument is used to detect radiation and measure disintegrations per minute quickly and accurately.

Activity can be expressed in terms of the number of atoms decaying per second, or becquerels (Bq).

$$1\ \text{Bq} = 1\ \text{atoms/s}$$

Alternatively, activity may be cited in disintegrations per minute or, perhaps most commonly, in **curies** (Ci).

$$1\ \text{Ci} = 3.700 \times 10^{10}\ \text{atoms/s}$$

EXAMPLE 18.3 GRADED

The half-life of radium-226 is 1.60×10^3 y $= 5.05 \times 10^{10}$ s.

a Calculate k in s^{-1}.

ANALYSIS

Information given:	$t_{1/2}$ for Ra-226 (5.05×10^{10} s)
Asked for:	k in s^{-1}

STRATEGY

Substitute into the formula relating half-life and rate constant in a first-order reaction.

$$k = \frac{0.693}{t_{1/2}}$$

SOLUTION

k	$k = \dfrac{0.693}{5.05 \times 10^{10}\ \text{s}} = 1.37 \times 10^{-11}\ \text{s}^{-1}$

b What is the activity in curies of a 1.00-g sample of Ra-226?

ANALYSIS

Information given:	mass of sample (1.00 g) from part (a): $k(1.37 \times 10^{-11}\ \text{s}^{-1})$
Information implied:	atoms/s to Ci conversion factor Avogadro's number
Asked for:	activity (A) in Ci

STRATEGY

1. Find the number of nuclei N in 1.00 g of Ra-226 using Avogadro's number and 226 g/mol as the molar mass of Ra-226.
2. Substitute into Equation 18.1 to find activity in atoms/s.

   $$A = kN$$

3. Use the conversion factor

   $$1\ \text{Ci} = 3.700 \times 10^{10}\ \text{atoms/s}$$

   to find the activity in Ci.

SOLUTION

1. N	$1.00\ \text{g} \times \dfrac{6.022 \times 10^{23}\ \text{atoms}}{226\ \text{g}} = 2.66 \times 10^{21}\ \text{atoms}$
2. A (atoms/s)	$A = (1.37 \times 10^{-11}\ \text{s}^{-1})(2.66 \times 10^{21}\ \text{atom}) = 3.64 \times 10^{10}\ \text{atoms/s}$
3. A (Ci)	$3.64 \times 10^{10}\ \text{atoms/s} \times \dfrac{1\ \text{Ci}}{3.700 \times 10^{10}\ \text{atoms/s}} = 0.985\ \text{Ci}$

continued

c What is the mass in grams of a sample of Ra-226 that has an activity of 1.00×10^9 atoms/min?

ANALYSIS

Information given:	activity ($A = 1.00 \times 10^9$ atoms/min) from part (a): $k(1.37 \times 10^{-11}\ s^{-1})$
Information implied:	Avogadro's number
Asked for:	mass of Ra-226 with the given activity

STRATEGY

1. Since k is in s^{-1}, convert the given activity in atoms/min to atoms/s.
2. Find N by substituting into Equation 18.1.
3. Determine the mass of Ra-226 by using Avogadro's number as the conversion factor.

SOLUTION

1. A in atoms/s	$\left(1.00 \times 10^9 \frac{\text{atoms}}{\text{min}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right) = 1.67 \times 10^7$ atoms/s
2. N	$N = \frac{1.67 \times 10^7\text{ atoms/s}}{1.37 \times 10^{-11}\text{ s}^{-1}} = 1.22 \times 10^{18}$ atoms
3. Mass	$1.22 \times 10^{18}\text{ atoms} \times \frac{226\text{ g}}{6.022 \times 10^{23}\text{ atoms}} = 4.58 \times 10^{-4}$ g

END POINT

The curie (Ci) was supposed to be the activity of a one-gram sample of radium, the element discovered by the Curies. Part (b) shows it isn't quite.

Age of Organic Material

During the 1950s, Professor W. F. Libby (1908–1980) of the University of Chicago and others worked out a method for determining the age of organic material. It is based on the decay rate of carbon-14. The method can be applied to objects from a few hundred up to 50,000 years old. It has been used to determine the authenticity of canvases of Renaissance painters and to check the ages of relics left by prehistoric cave dwellers.

Carbon-14 is produced in the atmosphere by the interaction of neutrons from cosmic radiation with ordinary nitrogen atoms:

$$^{14}_{7}\text{N} + ^{1}_{0}n \longrightarrow ^{14}_{6}\text{C} + ^{1}_{1}\text{H}$$

The carbon-14 formed by this nuclear reaction is eventually incorporated into the carbon dioxide of the air. A steady-state concentration, amounting to about one atom of carbon-14 for every 10^{12} atoms of carbon-12, is established in atmospheric CO_2. More specifically, the concentration of C-14 is such that a sample containing one gram of carbon has an activity of 15.3 atoms/min. A living plant, taking in carbon dioxide, has this same activity, as do plant-eating animals or human beings.

When a plant or animal dies, the intake of radioactive carbon stops. Consequently, the radioactive decay of carbon-14

$$^{14}_{6}\text{C} \longrightarrow ^{14}_{7}\text{N} + ^{0}_{-1}e \qquad t_{1/2} = 5730\text{ y}$$

takes over, and the C-14 activity drops. The activity of a sample is directly proportional to the amount of C-14, so we can write:

$$\ln \frac{A_o}{A} = kt \qquad (18.2)$$

where A_o is the original activity, assumed to be 15.3 atoms/min, and A is the measured activity today; t is the age of the sample.

Since activity is directly proportional to amount, $X_o/X = A_o/A$.

EXAMPLE 18.4

A tiny piece of paper taken from the Dead Sea Scrolls, believed to date back to the first century A.D., was found to have an activity per gram of carbon of 12.1 atoms/min. Taking A_o to be 15.3 atoms/min, estimate the age of the scrolls.

ANALYSIS

Information given:	A (12.1 atoms/min); A_o (15.3 atoms/min)
Information implied:	$t_{1/2}$ for C-14 (5730 y)
Asked for:	Age of the scrolls

STRATEGY

1. Find k by substituting into the equation relating half-life and rate constant for a first-order reaction.

$$k = \frac{0.693}{t_{1/2}}$$

2. Substitute into Equation 18.2 to find t.

$$\ln \frac{A_o}{A} = kt$$

SOLUTION

1. k

$$k = \frac{0.693}{5730 \text{ y}} = 1.21 \times 10^{-4} \text{ y}^{-1}$$

2. t

$$\ln \frac{15.3 \text{ atoms/min}}{12.1 \text{ atoms/min}} = (1.21 \times 10^{-4} \text{ y}^{-1})(t) \longrightarrow 0.235 = (1.21 \times 10^{-4} \text{ y}^{-1})(t)$$

$$t = 1.94 \times 10^{3} \text{ y}$$

The scrolls do date back to the first century A.D.

Mary Evans Picture Library/Alamy

Figure 18.7 The Shroud of Turin. This piece of linen first appeared in about 1350 A.D. It bears a faint image (enhanced here) of a man who appears to have been crucified.

As you can imagine, it is not easy to determine accurately activities of the order of 10 atoms decaying per minute, about one "event" every six seconds. Elaborate precautions have to be taken to exclude background radiation. Moreover, relatively large samples must be used to increase the counting rate. Recently a technique has been developed whereby C-14 atoms can be counted very accurately in a specially designed mass spectrometer. This method was used to date the Shroud of Turin (Figure 18.7), using six samples with a total mass of about 0.1 g. Analysis by an international team of scientists in 1988 showed that the flax used to make the linen of which the Shroud is composed grew in the fourteenth century A.D. That means this remarkable burial garment could not have been used for the body of Christ.

18-4 Mass-Energy Relations

The energy change accompanying a nuclear reaction can be calculated from the relation

$$\Delta E = c^2 \, \Delta m$$

where

$$\Delta m = \text{change in mass} = \text{mass products} - \text{mass reactants}$$
$$\Delta E = \text{energy products} - \text{energy reactants}$$
$$c = \text{speed of light}$$

In a spontaneous nuclear reaction, the products weigh less than the reactants (Δm negative). In this case, the energy of the products is less than that of the reactants (ΔE negative) and energy is evolved to the surroundings.

Such a reaction is exothermic; ΔH, like ΔE, is negative.

In an "ordinary chemical reaction," Δm is immeasurably small. In a nuclear reaction, on the other hand, Δm is appreciable, amounting to 0.002% or more of the mass of reactants. The change in mass can readily be calculated from a table of nuclear masses (Table 18.4).

Table 18.4 Nuclear Masses on the ^{12}C Scale*

	At. No.	Mass No.	Mass (amu)		At. No.	Mass No.	Mass (amu)
e	0	0	0.00055	Br	35	79	78.8992
n	0	1	1.00867		35	81	80.8971
H	1	1	1.00728		35	87	86.9028
	1	2	2.01355	Rb	37	89	88.8913
	1	3	3.01550	Sr	38	90	89.8869
He	2	3	3.01493	Mo	42	99	98.8846
	2	4	4.00150	Ru	44	106	105.8832
Li	3	6	6.01348	Ag	47	109	108.8790
	3	7	7.01436	Cd	48	109	108.8786
Be	4	9	9.00999		48	115	114.8791
	4	10	10.01134	Sn	50	120	119.8748
B	5	10	10.01019	Ce	58	144	143.8817
	5	11	11.00656		58	146	145.8868
C	6	11	11.00814	Pr	59	144	143.8809
	6	12	11.99671	Sm	62	152	151.8857
	6	13	13.00006	Eu	63	157	156.8908
	6	14	13.99995	Er	68	168	167.8951
O	8	16	15.99052	Hf	72	179	178.9065
	8	17	16.99474	W	74	186	185.9138
	8	18	17.99477	Os	76	192	191.9197
F	9	18	17.99601	Au	79	196	195.9231
	9	19	18.99346	Hg	80	196	195.9219
Na	11	23	22.98373	Pb	82	206	205.9295
Mg	12	24	23.97845		82	207	206.9309
	12	25	24.97925		82	208	207.9316
	12	26	25.97600	Po	84	210	209.9368
Al	13	26	25.97977		84	218	217.9628
	13	27	26.97439	Rn	86	222	221.9703
	13	28	27.97477	Ra	88	226	225.9771
Si	14	28	27.96924	Th	90	230	229.9837
S	16	32	31.96329	Pa	91	234	233.9934
Cl	17	35	34.95952	U	92	233	232.9890
	17	37	36.95657		92	235	234.9934
Ar	18	40	39.95250		92	238	238.0003
K	19	39	38.95328		92	239	239.0038
	19	40	39.95358	Np	93	239	239.0019
Ca	20	40	39.95162	Pu	94	239	239.0006
Ti	22	48	47.93588		94	241	241.0051
Cr	24	52	51.92734	Am	95	241	241.0045
Fe	26	56	55.92066	Cm	96	242	242.0061
Co	27	59	58.91837	Bk	97	245	245.0129
Ni	28	59	58.91897	Cf	98	248	248.0186
Zn	30	64	63.91268	Es	99	251	251.0255
	30	72	71.91128	Fm	100	252	252.0278
Ge	32	76	75.90380		100	254	254.0331
As	33	79	78.90288				

*Note that these are *nuclear masses*. The masses of the corresponding atoms can be calculated by adding the masses of each extranuclear electron (0.000549). For example, for an *atom* of $^{4}_{2}He$ we have 4.00150 + 2(0.000549) = 4.00260. Similarly, for an atom of $^{12}_{6}C$, 11.99671 + 6(0.000549) = 12.00000.

To obtain a more useful form of the equation $\Delta E = c^2 \Delta m$, we substitute for c its value in meters per second.

$$c = 3.00 \times 10^8 \text{ m/s}$$

Thus $$\Delta E = 9.00 \times 10^{16} \frac{\text{m}^2}{\text{s}^2} \times \Delta m$$

But $$1 \text{ J} = 1 \text{ kg} \cdot \frac{\text{m}^2}{\text{s}^2}; \quad 1 \frac{\text{m}^2}{\text{s}^2} = 1 \frac{\text{J}}{\text{kg}}$$

So $$\Delta E = 9.00 \times 10^{16} \frac{\text{J}}{\text{kg}} \times \Delta m$$

This equation can be used to calculate the energy change in *joules*, if you know Δm in *kilograms*. Ordinarily, Δm is expressed in *grams;* ΔE is calculated in *kilojoules*. The relationship between ΔE and Δm in these units can be found by using conversion factors:

$$\Delta E = 9.00 \times 10^{16} \frac{\text{J}}{\text{kg}} \times \frac{1 \text{ kg}}{10^3 \text{ g}} \times \frac{1 \text{ kJ}}{10^3 \text{ J}} \times \Delta m$$

$$\Delta E = 9.00 \times 10^{10} \frac{\text{kJ}}{\text{g}} \times \Delta m \quad (18.3)$$

This is the most useful form of the mass-energy relation.

EXAMPLE 18.5

For the radioactive decay of radium, $^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$, calculate ΔE in kilojoules when 10.2 g of radium decays.

ANALYSIS

Information given:	nuclear reaction ($^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$) mass of Ra-226 (10.2 g)
Information implied:	nuclear masses (Table 18.4)
Asked for:	ΔE

STRATEGY

1. Use Table 18.4 to find nuclear masses and Δm for the decay of one mole of Ra-226. Do not round off.

   Δm = nuclear masses of products − nuclear masses of reactants.
2. Find Δm for the decay of 10.2 g of Ra-226.
3. Determine ΔE by substituting into Equation 18.3.

SOLUTION

1. Δm for one mole	Δm = (mass of 1 mol He-4 + mass of 1 mol Rn-222) − (mass of 1 mol Ra-226) $= 4.0015 \text{ g} + 221.9703 \text{ g} - 225.9771 \text{ g} = -0.0053$ g/mol Ra-226
2. Δm for 10.2 g	$\Delta m = 10.2 \text{ g Ra} \times \frac{1 \text{ mol Ra}}{226.0 \text{ g Ra}} \times \frac{-0.0053 \text{ g}}{1 \text{ mol Ra}} = -2.4 \times 10^{-4} \text{ g}$
3. ΔE	$\Delta E = \left(9.00 \times 10^{10} \frac{\text{kJ}}{\text{g}}\right)(\Delta m) = \left(9.00 \times 10^{10} \frac{\text{kJ}}{\text{g}}\right)(-2.4 \times 10^{-4} \text{ kJ}) = -2.2 \times 10^{7} \text{ kJ}$

END POINT

In ordinary chemical reactions, the energy change is of the order of 50 kJ/g or less. In this nuclear reaction, the energy change is much, much greater.

Nuclear Binding Energy

It is always true that ***a nucleus weighs less than the individual protons and neutrons of which it is composed.*** Consider, for example, the $^{6}_{3}\text{Li}$ nucleus, which contains three protons and three neutrons. According to Table 18.4, one mole of

Li-6 nuclei weighs 6.01348 g. In contrast, the total mass of three moles of neutrons and three moles of protons is

$$3(1.00867\text{ g}) + 3(1.00728\text{ g}) = 6.04785\text{ g}$$

Clearly, one mole of Li-6 weighs *less* than the corresponding protons and neutrons. For the process

$${}^{6}_{3}\text{Li} \longrightarrow 3\,{}^{1}_{1}\text{H} + 3\,{}^{1}_{0}n$$

$\Delta m = 6.04785\text{ g} - 6.01348\text{ g} = 0.03437\text{ g/mol Li}$.

The quantity just calculated is referred to as the **mass defect**. The corresponding energy difference is

$$\Delta E = 9.00 \times 10^{10}\,\frac{\text{kJ}}{\text{g}} \times 0.03437\,\frac{\text{g}}{\text{mol Li}} = 3.09 \times 10^{9}\,\frac{\text{kJ}}{\text{mol Li}}$$

This energy is referred to as the **binding energy.** It follows that 3.09×10^9 kJ of energy would have to be absorbed to decompose one mole of Li-6 nuclei into protons and neutrons.

$${}^{6}_{3}\text{Li} \longrightarrow 3\,{}^{1}_{0}n + 3\,{}^{1}_{1}\text{H} \qquad \Delta E = 3.09 \times 10^{9}\,\frac{\text{kJ}}{\text{mol Li}}$$

By the same token, 3.09×10^9 kJ of energy would be evolved when one mole of Li-6 is formed from protons and neutrons.

It takes a lot of energy to blow a nucleus apart.

EXAMPLE 18.6

Calculate the binding energy of C-14, in kilojoules per mole.

STRATEGY

1. Recall that the C-14 nucleus is made up of 6 protons (${}^{1}_{1}\text{H}$) and 8 neutrons (${}^{1}_{0}n$). Thus

   ${}^{14}_{6}\text{C} \longrightarrow 6\,{}^{1}_{1}\text{H} + 8\,{}^{1}_{0}n$
2. Use Table 18.4 to find Δm.
3. Substitute into Equation 18.3 to find ΔE in kJ/mol.

SOLUTION

1. Δm	$\Delta m = 6(1.00728\text{ g}) + 8(1.00867\text{ g}) - 13.99995\text{ g} = 0.11309\text{ g/mol C-14}$
2. ΔE	$\Delta E = 9.00 \times 10^{10}\,\frac{\text{kJ}}{\text{g}} \times 0.11309\,\frac{\text{g}}{\text{mol}} = 1.02 \times 10^{10}\text{ kJ/mol}$

The binding energy of a nucleus is, in a sense, a measure of its stability. The greater the binding energy, the more difficult it would be to decompose the nucleus into protons and neutrons. As you might expect, the binding energy as calculated above increases steadily as the nucleus gets heavier, containing more protons and neutrons. A better measure of the relative stabilities of different nuclei is the ***binding energy per mole of nuclear particles (nucleons)***. This quantity is calculated by dividing the binding energy per mole of nuclei by the number of particles per nucleus. Thus

$$\text{Li-6:} \quad 3.09 \times 10^{9}\,\frac{\text{kJ}}{\text{mol Li-6}} \times \frac{1\text{ mol Li-6}}{6\text{ mol nucleons}} = 5.15 \times 10^{8}\,\frac{\text{kJ}}{\text{mol}}$$

$$\text{C-14:} \quad 1.02 \times 10^{10}\,\frac{\text{kJ}}{\text{mol}} \times \frac{1\text{ mol C-14}}{14\text{ mol nucleons}} = 7.29 \times 10^{8}\,\frac{\text{kJ}}{\text{mol}}$$

Figure 18.8 shows a plot of this quantity, binding energy/mole of nucleons, versus mass number. Notice that the curve has a broad maximum in the vicinity of mass numbers 50 to 80. Consider what would happen if a heavy nucleus such as ${}^{235}_{92}\text{U}$

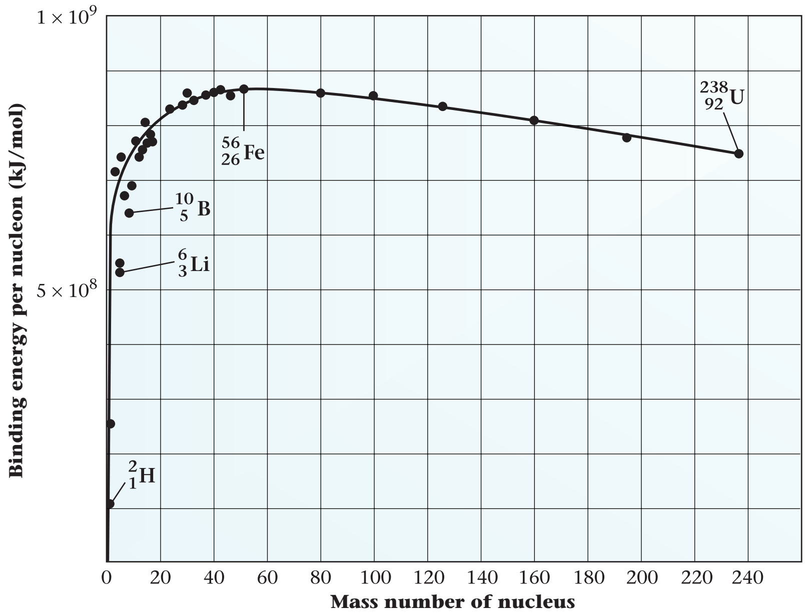


Figure 18.8 Binding energy per nucleon, a measure of nuclear stability. The binding energy has its maximum value for nuclei of intermediate mass, falling off for very heavy or very light nuclei. The form of this curve accounts for the fact that both fission and fusion give off large amounts of energy.

were to split into smaller nuclei with mass numbers near the maximum. This process, referred to as nuclear **fission**, should result in an evolution of energy. The same result is obtained if very light nuclei such as ^2_1H combine with one another to form a heavier nucleus. Indeed, this process, called nuclear **fusion,** should evolve even more energy, because the binding energy per nucleon increases very sharply at the beginning of the curve.

Both very heavy and very light nuclei are relatively unstable; they decompose with the evolution of energy.

18-5 Nuclear Fission

Library of Congress Prints and Photographs Division[LC-USZ62-39852]

Figure 18.9 A nuclear fission explosion. Such a dramatic and destructive release of energy had never been seen before the development of the "atomic bomb" during World War II.

The process of nuclear fission was discovered in Germany more than half a century ago in 1938 by Lise Meitner (1878–1968) and Otto Hahn (1879–1968). With the outbreak of World War II a year later, interest focused on the enormous amount of energy released in the process (Figure 18.9). At Los Alamos, in the mountains of New Mexico, a group of scientists led by J. Robert Oppenheimer (1904–1967) worked feverishly to produce the fission, or "atomic," bomb. Many of the members of this group were exiles from Nazi Germany. They were spurred on by the fear that Hitler would obtain the bomb first. Their work led to the explosion of the first atomic bomb in the New Mexico desert at 5:30 A.M. on July 16, 1945. Less than a month later (August 6, 1945), the world learned of this new weapon when another bomb was exploded over Hiroshima. This bomb killed 70,000 people and completely devastated an area of 10 square kilometers. Three days later, Nagasaki and its inhabitants met a similar fate. On August 14, Japan surrendered, and World War II was over.

The Hiroshima bomb was equivalent to 20,000 tons of TNT.

The Fission Process ($^{235}_{92}U$)

Several isotopes of the heavy elements undergo fission if bombarded by neutrons of high enough energy. In practice, attention has centered on two particular isotopes, $^{235}_{92}U$ and $^{239}_{94}Pu$. Both of these can be split into fragments by relatively low-energy neutrons.

Our discussion concentrates on the uranium-235 isotope. It makes up only about 0.7% of naturally occurring uranium. The more abundant isotope, uranium-238, does not undergo fission. The first process used to separate these isotopes, and until recently the only one available, was that of gaseous effusion (Chapter 5). The volatile compound uranium hexafluoride, UF_6, which sublimes at 56°C, is used for this purpose.

When a uranium-235 atom undergoes fission, it splits into two unequal fragments and a number of neutrons and beta particles. The fission process is complicated by the fact that different uranium-235 atoms split up in many different ways. For example, while one atom of $^{235}_{92}U$ is splitting to give isotopes of rubidium ($Z = 37$) and cesium ($Z = 55$), another may break up to give isotopes of bromine ($Z = 35$) and lanthanum ($Z = 57$), while still another atom yields isotopes of zinc ($Z = 30$) and samarium ($Z = 62$):

$$^{1}_{0}n + ^{235}_{92}U \longrightarrow \begin{cases} ^{90}_{37}Rb + ^{144}_{55}Cs + 2\,^{1}_{0}n \\ ^{87}_{35}Br + ^{146}_{57}La + 3\,^{1}_{0}n \\ ^{72}_{30}Zn + ^{160}_{62}Sm + 4\,^{1}_{0}n \end{cases}$$

More than 200 isotopes of 35 different elements have been identified among the fission products of uranium-235.

The stable neutron-to-proton ratio near the middle of the periodic table, where the fission products are located, is considerably smaller (~1.2) than that of uranium-235 (1.6). Hence the immediate products of the fission process contain too many neutrons for stability; they decompose by beta emission. In the case of rubidium-90, three steps are required to reach a stable nucleus:

$$^{90}_{37}Rb \longrightarrow ^{90}_{38}Sr + ^{0}_{-1}e \qquad t_{1/2} = 2.8 \text{ min}$$
$$^{90}_{38}Sr \longrightarrow ^{90}_{39}Y + ^{0}_{-1}e \qquad t_{1/2} = 29 \text{ y}$$
$$^{90}_{39}Y \longrightarrow ^{90}_{40}Zr + ^{0}_{-1}e \qquad t_{1/2} = 64 \text{ h}$$

The radiation hazard associated with fallout from nuclear weapons testing arises from radioactive isotopes such as these. One of the most dangerous is strontium-90. In the form of strontium carbonate, $SrCO_3$, it is incorporated into the bones of animals and human beings, where it remains for a lifetime.

Notice from the fission equations above that two to four neutrons are produced by fission for every one consumed. Once a few atoms of uranium-235 split, the neutrons produced can bring about the fission of many more uranium-235 atoms. This creates the possibility of a *chain reaction*, whose rate increases exponentially with time. This is precisely what happens in the atomic bomb. The energy evolved in successive fissions escalates to give a tremendous explosion within a few seconds.

For nuclear fission to result in a chain reaction, the sample must be large enough so that most of the neutrons are captured internally. If the sample is too small, most of the neutrons escape, breaking the chain. The *critical mass* of uranium-235 required to maintain a chain reaction in a bomb appears to be about 1 to 10 kg. In the bomb dropped on Hiroshima, the critical mass was achieved by using a conventional explosive to fire one piece of uranium-235 into another.

The evolution of energy in nuclear fission is directly related to the decrease in mass that takes place. About 80,000,000 kJ of energy is given off for every gram of $^{235}_{92}U$ that reacts. This is about 40 times as great as the energy change for simple nuclear reactions such as radioactive decay. The heat of combustion of coal is only about 30 kJ/g; the energy given off when TNT explodes is still smaller, about 2.8 kJ/g. Putting it another way, the fission of one gram of $^{235}_{92}U$ produces as much energy as the combustion of 2700 kg of coal or the explosion of 30 metric tons (3×10^4 kg) of TNT.

Nuclear Reactors

About 20% of the electricity generated in the United States come from nuclear reactors, which use the fission of U-235 to generate heat. That heat boils water and turns a turbine. A light-water reactor is shown schematically in Figure 18.10. The *fuel rods* contain cylindrical pellets of uranium dioxide (UO_2) in zirconium alloy tubes. The uranium in these reactors is "enriched" so that it contains about 3% U-235, the fissionable isotope. Natural uranium is less than 1% U-235. The

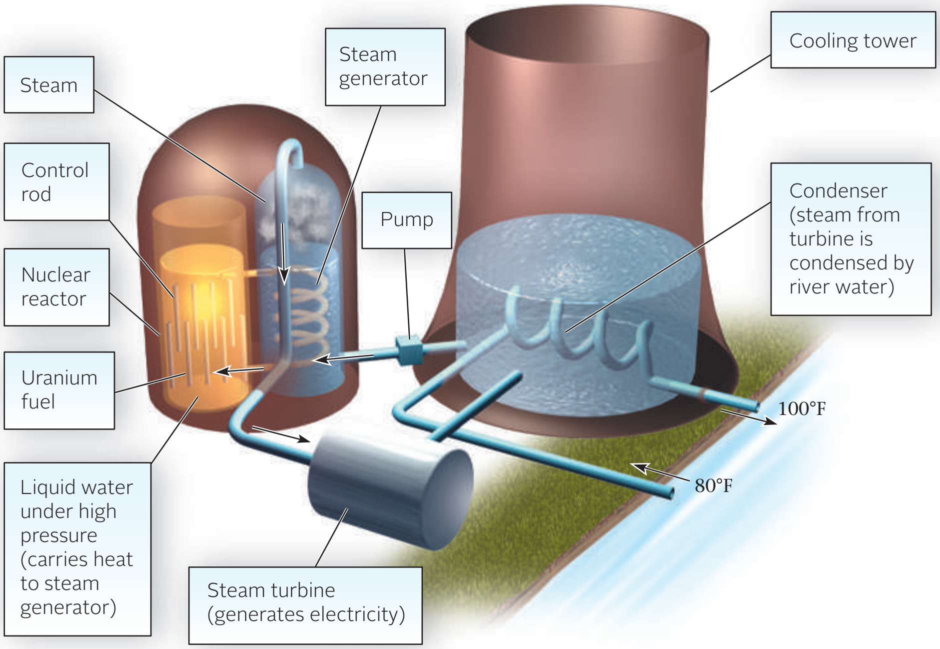


Figure 18.10 A pressurized water nuclear reactor. The control rods are made of a material such as cadmium or boron, which absorbs neutrons effectively. The fuel rods contain uranium oxide enriched in U-235.

control rods are cylinders that contain substances such as boron and cadmium, which absorb neutrons. By varying the depth to which these are inserted into the reactor core, the speed of the chain reactions can be controlled. In a pressurized water reactor, water at 140 atm absorbs the heat released by the chain reaction and is heated to about 320°C. This heated water passes through the steam generators, which also contain water under pressure. The water turns to steam at 270°C and drives a turbogenerator that produces electricity.

In a light water reactor, the circulating water in the core serves a purpose beyond cooling. It slows down, or moderates, the neutrons produced in the fission reactions. This is necessary if the chain reaction is to continue. Fast neutrons, unmoderated, are not readily absorbed by the U-235 nuclei. Reactors designed in Canada use heavy water, D_2O, which has had an important advantage over ordinary water. Its moderating properties are such that naturally occurring uranium can be used as a fuel. Energy-intensive enrichment has not been necessary. The next generation of Canadian reactors, called Advanced CANDU, include the use of lightly enriched uranium, just as light water reactors do.

By the 1970s it was generally supposed that nuclear fission would replace fossil fuels (oil, natural gas, coal) as an energy source. That hasn't happened. The most evident reasons are

- ***Nuclear accidents*** at Three Mile Island, Pennsylvania, in 1979 and Chernobyl, Ukraine, in 1986 had a devastating effect on public opinion in the United States and, to a smaller degree, elsewhere in the world. At Three Mile Island only about 50 curies of radiation were released to the environment and there were no casualties. The explosion at Chernobyl was a very different story. About 100 million curies were released, leading to at least 31 fatalities. Moreover, 135,000 people were permanently evacuated from the region surrounding the reactor. Since then, all the other reactors at Chernobyl—three, in addition to the one that exploded—have been permanently shut down.
- ***Disposal of radioactive wastes*** from nuclear reactors has proved to be a serious political issue. The NIMBY (not in my backyard) attitude applies here. The U.S. government has spent billions of dollars to develop a permanent nuclear waste storage repository at Yucca Mountain, Nevada, as the site for burying some 70,000 metric tons of nuclear waste. Current plans (mostly as a result of

political pressure), however, include closing the Yucca Mountain repository permanently, precluding waste storage there. The problem of radioactive waste disposal is not a uniquely American problem. Other nations have struggled with the disposal of wastes as well.

Currently, nuclear energy is being reevaluated in light of its carbon neutrality. That is, nuclear reactors do not directly contribute the gases, believed by many scientists to contribute to global warming, that the combustion of carbon-based fuels do. Furthermore, reactor designs now under construction or on the drawing boards (called Generation III+ reactors) are addressing some of the safety and cost issues that have plagued past designs. Generation III+ reactors are now under construction in China, Finland, Korea, and Japan, and one U.S. utility has made a firm commitment to construct one such reactor (the Westinghouse AP1000), adding two additional units to a pair of currently operating reactors in the state of Georgia. These will be the first new reactors constructed since the 1970s. Older designs are also being revived. The last reactor to go online in the United States, at Watts Bar in Tennessee, opened in 1996. Construction of what was to be a two-unit plant began in 1973. The second unit was never completed. Now, the Tennessee Valley Authority is actively working to restart construction on the unfinished reactor, expecting to have it online by December of 2015.

18-6 Nuclear Fusion

Recall (Figure 18.8) that very light nuclei, such as those of hydrogen, are unstable with respect to fusion into heavier isotopes. Indeed, the energy available from nuclear fusion is considerably greater than that given off in the fission of an equal mass of a heavy element (Example 18.7).

EXAMPLE 18.7

Calculate ΔE, in kilojoules per gram of reactants, in a fusion reaction,

$${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He},$$

and in a fission reaction,

$${}^{235}_{92}\text{U} \longrightarrow {}^{90}_{38}\text{Sr} + {}^{144}_{58}\text{Ce} + {}^{1}_{0}n + 4\,{}^{0}_{-1}e.$$

STRATEGY

1. Find Δm for the reaction as written by using the nuclear masses in Table 18.4.
2. Find Δm for one gram of reactant.
3. Substitute into Equation 18.3 to determine ΔE.

SOLUTION

fusion reaction

1. Δm/2 mol H-2

$$\Delta m = (\text{mass He-4}) - 2(\text{mass H-2})$$
$$= 4.00150\text{ g} - 2(2.01355\text{ g}) = -0.02560\text{ g}$$

2. Δm/g H-2

$$\Delta m = \frac{-0.02560\text{ g}}{2\text{ mol H-2}} \times \frac{2\text{ mol H-2}}{2(2.01355\text{ g})} = -0.006357\text{ g/g H-2}$$

3. ΔE

$$\Delta E = 9.00 \times 10^{10}\frac{\text{kJ}}{\text{g}} \times \frac{-6.357 \times 10^{-3}\text{ g}}{1\text{ g H-2}} = -5.72 \times 10^{8}\text{ kJ/g H-2}$$

fission reaction

1. Δm/mol U-235

$$\Delta m = \text{mass(Sr-90)} + \text{mass(Ce-144)} + \text{mass}({}^{1}_{0}n) + 4[\text{mass }({}^{0}_{-1}e)] - \text{mass(U-235)}$$
$$= [89.8869 + 143.8817 + 1.00867 + 4(0.00055)]\text{ g} - 234.9934\text{ g} = -0.21393\text{ g}$$

continued

2. Δm/g U-235	$\Delta m = \dfrac{-0.2139\text{ g}}{\text{mol U-235}} \times \dfrac{1\text{ mol U-235}}{235.0\text{ g}} = -9.102 \times 10^{-4}\text{ g/g U-235}$
3. ΔE	$\Delta E = 9.00 \times 10^{10}\,\dfrac{\text{kJ}}{\text{g}} \times \dfrac{-9.102 \times 10^{-4}\text{ g}}{1\text{ g U-235}} = -8.19 \times 10^{7}\text{ kJ/g U-235}$

END POINT

Comparing the answers to (a) and (b), it appears that the fusion reaction produces about seven times as much energy per gram of reactant (57.2×10^7 versus 8.19×10^7 kJ) as does the fission reaction. This factor varies from about 3 to 10, depending on the particular reaction chosen to represent the fission and fusion processes.

As an energy source, nuclear fusion possesses several additional advantages over nuclear fission. In particular, light isotopes suitable for fusion are far more abundant than the heavy isotopes required for fission. You can calculate, for example (Problem 79), that the fusion of only 2×10^{-9}% of the deuterium ($^2_1$H) in seawater would meet the total annual energy requirements of the world.

Unfortunately, fusion processes, unlike neutron-induced fission, have very high activation energies. To overcome the electrostatic repulsion between two deuterium nuclei and cause them to react, they have to be accelerated to velocities of about 10^6 m/s, about 10,000 times greater than ordinary molecular velocities at room temperature. The corresponding temperature for fusion, as calculated from kinetic theory, is of the order of 10^9°C. In the hydrogen bomb, temperatures of this magnitude were achieved by using a fission reaction to trigger nuclear fusion. If fusion reactions are to be used to generate electricity, it will be necessary to develop equipment in which very high temperatures can be maintained long enough to allow fusion to occur and give off energy. In any conventional container, the reactant nuclei would quickly lose their high kinetic energies by collisions with the walls.

In April 1997, the Tokamak fusion reactor at Princeton shut down when government funding was withdrawn.

One fusion reaction currently under study is a two-step process involving deuterium and lithium as the basic starting materials:

$$^2_1\text{H} + {}^3_1\text{H} \longrightarrow {}^4_2\text{He} + {}^1_0n$$
$$^6_3\text{Li} + {}^1_0n \longrightarrow {}^4_2\text{He} + {}^3_1\text{H}$$
$$^2_1\text{H} + {}^6_3\text{Li} \longrightarrow 2\,{}^4_2\text{He}$$

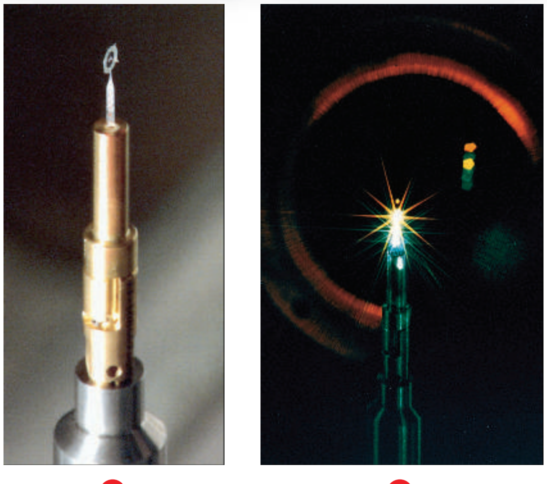
This process is attractive because it has a lower activation energy than other fusion reactions.

One possible way to achieve nuclear fusion is to use magnetic fields to confine the reactant nuclei and prevent them from touching the walls of the container, where they would quickly slow down below the velocity required for fusion. Using 400-ton magnets, it is possible to sustain the reaction for a fraction of a second. To achieve a net evolution of energy, this time must be extended to about one second. A practical fusion reactor would have to produce 20 times as much energy as it consumes. Optimists predict that this goal may be reached in 50 years.

Another approach to nuclear fusion is shown in Figure 18.11. Tiny glass pellets (about 0.1 mm in diameter) filled with frozen deuterium and tritium serve as a target. The pellets are illuminated by a powerful laser beam, which delivers 10^{12} kilowatts of power in one nanosecond (10^{-9} s). The reaction is the same as with magnetic confinement; unfortunately, at this point energy breakeven seems many years away.

A mixture of deuterium and tritium is sealed inside the tiny capsule (1 mm in diameter) at the tip of the laser target.

Exposure of the capsule to the energy of a powerful laser beam produces a 0.5-picosecond burst of energy from the fusion of the deuterium and tritium.



Courtesy of the University of California, Lawrence Livermore National Laboratory, and the U.S. Department of Energy

Lawrence Livermore National Laboratory

a b

Figure 18.11 Laser fusion.

CHEMISTRY **BEYOND** THE CLASSROOM

Biological Effects of Radiation

The harmful effects of radiation result from its high energy, sufficient to form unstable free radicals (species containing unpaired electrons) such as

These free radicals can react with and in that sense destroy organic molecules essential to life.

The extent of damage from radiation depends mainly on two factors. These are the amount of radiation absorbed and the type of radiation. The former is commonly expressed in *rads* (*r*adiation *a*bsorbed *d*ose). A rad corresponds to the absorption of 10^{-2} J of energy per kilogram of tissue:

$$1 \text{ rad} = 10^{-2} \text{ J/kg}$$

The biological effect of radiation is expressed in *rems* (*r*adiation *e*quivalent for *m*an). The number of rems is found by multiplying the number of rads by a "damage" factor, *n*:

$$\text{no. of rems} = n(\text{no. of rads})$$

where *n* is 1 for gamma and beta emission, 5 for low-energy neutrons, and 10 to 20 for high-energy neutrons and alpha particles. Table A lists some of the effects to be expected when a person is exposed to a single dose of radiation at various levels.

The average exposure to radiation of people living in the United States is about 360 mrem (0.36 rem) per year. Notice (Figure A) that 82% of the radiation comes from natural sources; the greatest single source by far is radon (55%). The level of exposure to radon depends on location. In 1985 a man named Stanley Watras, who happened to work at a nuclear power plant, found that he was setting off the radiation monitors when he went to work in the morning. It turned out that the house he lived in had a radon level 2000 times the national average.

Table A Effect of Exposure to a Single Dose of Radiation

Dose (rems)	Probable Effect
0 to 25	No observable effect
25 to 50	Small decrease in white blood cell count
50 to 100	Lesions, marked decrease in white blood cells
100 to 200	Nausea, vomiting, loss of hair
200 to 500	Hemorrhaging, ulcers, possible death
500+	Fatal

$^{222}_{86}$Rn, a radioactive isotope of radon, is a decay product of naturally occurring uranium-238. Because it is gaseous and chemically inert, radon seeps through cracks in concrete and masonry from the ground into houses. There its concentration builds up, particularly if the house is tightly insulated. Inhalation of radon-222 can cause health problems because its decay products, including Po-218 and Po-214, are intensely radioactive and readily absorbed in lung tissue. The Environmental Protection Agency (EPA) estimates that radon inhalation causes between 5000 and 20,000 of the 130,000 deaths from lung cancer annually in the United States. The EPA recommends that special ventilation devices be used to remove radon from basements if tests show (Figure B) that the radiation level exceeds 4×10^{-12} Ci/L.

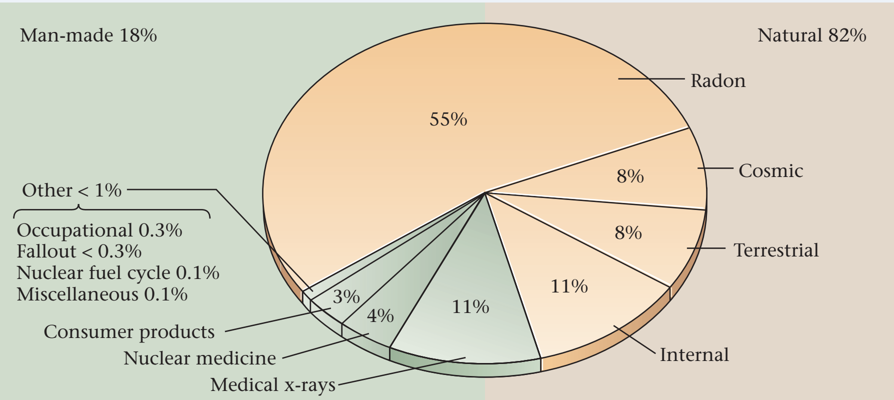


Figure A Sources of average radiation exposure of the U.S. population.

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Figure B A commercially available home-test kit for radon.

Key Concepts

1. Determine the more stable isotope or atom. **(Example 18.1; Problems 1–4)**
2. Write balanced nuclear equations. **(Example 18.2; Problems 5–20)**
3. Relate activity to rate constant and number of atoms. **(Example 18.3; Problems 21–34)**
4. Relate activity to age of objects. **(Example 18.4; Problems 35–42)**

5. Relate Δm to ΔE in a nuclear reaction. (**Examples 18.5; Problems 43, 44, 49–52**)

6. Calculate binding energies. (**Example 18.6; Problems 45–48**)

Key Equations

Rate of decay $\ln \frac{X_o}{X} = kt$ $k = 0.693/t_{1/2}$ $A = kN$

Mass-energy $\Delta E = 9.00 \times 10^{10} \frac{\text{kJ}}{\text{g}} \times \Delta m$

Key Terms

activity
alpha particle
beta particles
binding energy
curies
fission
fusion
gamma radiation
K-electron capture
nuclear equations
positron

Summary Problem

Consider the isotopes of gallium (Ga), a silvery metal that melts at 30°C. It is used primarily in different circuits: microwave, infrared, and high-speed switching.

(a) Write the nuclear symbol for Ga-67, which is used medically to scan for various tumors. How many protons are there in its nucleus? How many neutrons?

(b) Write the equation for the decomposition of Ga-67 by K-capture.

(c) Write nuclear equations to represent the bombardment of Ga-64 by a neutron, and the decay of the product nucleus by β-emission.

(d) Calculate ΔE in kJ when 1.00 g of Ga-71 (nuclear mass = 70.9476 amu) is bombarded by an α-particle producing As-72 (nuclear mass = 71.9493 amu) and neutrons.

(e) What are the mass defect and binding energy of Ga-71?

(f) The half-life of Ga-67 is 77.9 hours. What is the rate constant for Ga-67? What is the activity (in curies) of a 5.00×10^2-mg sample of Ga-67?

(g) How long will it take Ga-67 to decay and lose 95% of its radioactivity?

Answers

(a) $^{67}_{31}$Ga; **31 protons, 36 neutrons**

(b) $^{67}_{31}\text{Ga} + ^{0}_{-1}e \longrightarrow ^{67}_{30}\text{Zn}$

(c) $^{64}_{31}\text{Ga} + ^{1}_{0}n \longrightarrow ^{65}_{31}\text{Ga} \longrightarrow ^{0}_{-1}e + ^{65}_{32}\text{Ge}$

(d) **3.32×10^7 kJ**

(e) **mass defect = 0.6249 g; binding energy = 5.62×10^{10} kJ**

(f) **$k = 8.90 \times 10^{-3}\ \text{h}^{-1}$; $A = 3.00 \times 10^5$ Ci**

(g) **337 h ≈ 14 days**

Questions and Problems

Even-numbered questions and Challenge Problems have answers in Appendix 5 and fully worked solutions in the *Student Solutions Manual*.

18-1 Nuclear Stability

1. Which isotope in each of the following pairs should be stable?
(a) $^{10}_{5}$B or $^{9}_{5}$B (b) $^{18}_{8}$O or $^{16}_{8}$O (c) $^{24}_{12}$Mg or $^{23}_{12}$Mg

2. Which isotope in each of the following pairs should be more stable?
(a) $^{28}_{14}$Si or $^{29}_{14}$Si (b) $^{6}_{3}$Li or $^{8}_{3}$Li (c) $^{23}_{11}$Na or $^{20}_{11}$Na

3. For each pair of elements listed, predict which one has more stable isotopes:
(a) I or Sn (b) Ga or Ni (c) Si or Cl

4. For each pair of elements listed, predict which one has more stable isotopes.
(a) Ni or Cu (b) Se or Sb (c) Cd or Au

18-2 Radioactivity

Nuclear Equations

5. Smoke detectors contain a small amount of americium-241. Its decay product is neptunium-237. Identify the emission from americium-241.

6. Chromium-51, a positron emitter, is used in research to study red cell survival. It is delivered as a solution of sodium chromate. Write the nuclear equation for the decay of Cr-51.

7. Thorium-231 is the product of alpha emission. It is radioactive and emits beta radiation. Determine

(a) the parent nucleus of Th-231.

(b) the daughter product of Th-231 decay.

8. Uranium decays by alpha emission. Its daughter product emits β-radiation. Determine

(a) the daughter product of U-235 decay.

(b) the product obtained by β-emission of the daughter product in (a).

9. Write balanced nuclear reactions for the following:

(a) Formation of Am-241 through β-emissions.

(b) Formation of Kr-81 by K-electron capture.

(c) Formation of Ra-223 by α-emission.

10. Write balanced nuclear equations for the following:

(a) Formation of Mn-52 by positron emission.

(b) Formation of Ac-228 by β-emission.

(c) Formation of Np-232 by α-decay.

11. Write balanced nuclear equations for

(a) the alpha emission resulting in the formation of Pa-233.

(b) the loss of a positron by Y-85.

(c) the fusion of two C-12 nuclei to give Na-23 and another particle.

(d) the fission of Pu-239 to give Sn-130, another nucleus, and an excess of two neutrons.

12. Write balanced nuclear equations for

(a) the loss of an alpha particle by Th-230.

(b) the loss of a beta particle by Pb-210.

(c) the fission of U-235 to give Ba-140, another nucleus, and an excess of two neutrons.

(d) the K-capture of Ar-37.

13. When californium-249 is bombarded by a small isotope, rutherfordium, ${}^{257}_{104}\text{Rf}$, is formed together with 4 neutrons. The isotope formed quickly decays to Nobelium-253, ${}^{253}_{102}\text{No}$.

(a) What small isotope is used in the bombardment?

(b) What particle is emitted in the decay of Rf-257?

14. When Bi-209 is bombarded with Ni-64, one neutron and a new isotope, X, are formed. The isotope then goes through a series of alpha particle emissions.

(a) Write the nuclear symbol for the isotope formed.

(b) Write the nuclear symbol for the isotope formed after the third alpha particle emission.

15. Consider the "new" isotope ${}^{285}_{120}\text{Z}$. Compare the product nuclides (call them X and Q, respectively) after β and positron emission.

16. Follow the directions for Question 15 but compare the product nuclides after K-capture and positron emission.

17. Write balanced nuclear equations for the bombardment of

(a) U-238 with a nucleus to produce Fm-249 and five neutrons.

(b) Al-26 with an alpha particle to produce P-30.

(c) Cu-63 with a nucleus producing Zn-63 and a neutron.

(d) Al-27 with deuterium (${}^{2}_{1}\text{H}$) to produce an alpha particle and another nucleus.

18. Write balanced nuclear equations for the bombardment of

(a) Fe-54 with an alpha particle to produce another nucleus and two protons.

(b) Mo-96 with deuterium (${}^{2}_{1}\text{H}$) to produce a neutron and another nucleus.

(c) Ar-40 with an unknown particle to produce K-43 and a proton.

(d) a nucleus with a neutron to produce a proton and P-31.

19. Balance the following equations by filling in the blanks.

(a) ${}^{235}_{92}\text{U} + {}^{1}_{0}n \longrightarrow {}^{137}_{54}\_\_\_\_ + 2\,{}^{1}_{0}n + \_\_\_\_$

(b) ${}^{232}_{90}\text{Th} + {}^{12}_{6}\_\_\_\_ \longrightarrow \_\_\_\_\,{}^{1}_{0}n + {}^{240}_{96}\text{Cm}$

(c) ${}^{4}_{2}\text{He} + {}^{96}_{42}\text{Mo} \longrightarrow {}^{100}_{43}\_\_\_\_ + \_\_\_\_$

(d) $\_\_\_\_ + {}^{2}_{1}\text{H} \longrightarrow {}^{210}_{84}\_\_\_\_ + {}^{1}_{0}n$

20. Balance the following nuclear equations by filling in the blanks:

(a) Es-240 + neutron $\longrightarrow$ 2 neutrons + ____ + Gd-161

(b) ____ $\longrightarrow$ β-particle + Co-59

(c) $4\,{}^{1}_{1}\text{H} \longrightarrow$ ____ + 2 positrons

(d) Mg-24 + neutron $\longrightarrow$ proton + ____

18-3 Rate of Radioactive Decay

21. How long (in hours) would it take to disintegrate 3.17×10^{17} atoms from a 12.0-mCi (millicurie) source?

22. A 15.0-mCi (millicurie) radioactive source runs for 2.63 hours. How many atoms have disintegrated?

23. A scintillation counter registers emitted radiation caused by the disintegration of nuclides. If each atom of a nuclide emits one count, what is the activity of a sample that registers 3.00×10^4 disintegrations in five minutes?

24. A Geiger counter counts 0.070% of all the particles emitted by a sample. What is the activity that registers 19.4×10^3 counts in one minute?

25. Yttrium-87 has a rate constant of $2.6 \times 10^{-6}\ \text{s}^{-1}$. What is the activity of a 5.00-mg sample?

26. Krypton-87 has a rate constant of $1.5 \times 10^{-4}\ \text{s}^{-1}$. What is the activity of a 2.00-mg sample?

27. Iodine-131 is used to treat thyroid cancer. It decays by beta emission and has a half-life of 8.1 days.

(a) Write a balanced nuclear reaction for the decay of iodine-131.

(b) What is the activity (in Ci) of a 2.50-mg sample of the isotope?

28. Copper-64 is used to study tumors of the brain. It has a half-life of 12.8 hours. What is the activity (in Ci) of 1.50 mg Cu-64?

29. Lead-210 has a half-life of 20.4 years. This isotope decays by beta particle emission. A counter registers 1.3×10^4 disintegrations in five minutes. How many grams of Pb-210 are there?

30. Bromine-82 has a half-life of 36 hours. A sample containing Br-82 was found to have an activity of 1.2×10^5 disintegrations/min. How many grams of Br-82 were present in the sample? Assume that there were no other radioactive nuclides in the sample.

31. Fluorine-18 has a decay constant of $6.31 \times 10^{-3}\ \text{min}^{-1}$. How many counts will one get on a Geiger counter in one minute from 1.00 mg of F-18? Assume the sensitivity of the counter is such that it intercepts 0.50% of the emitted radiation.

32. Chlorine-36 decays by β-emission. It has a decay constant of $2.3 \times 10^{-6}\ \text{y}^{-1}$. How many β-particles are emitted in one minute from a 1.000-mg sample of Cl-36? How many curies does this represent?

33. Co-60 is used extensively in radiotherapy as a source of γ-rays. Its half-life is 5.27 years.

(a) How many years will it take to decrease to 30.0% of its original activity?

(b) If a cobalt source is ten years old, what percent of its original activity remains?

34. Phosphorus-32 is used in biochemical studies to follow the pathway taken by metabolites. Its half-life is 14.3 days. A vial containing 10.0 μg ($1\ \mu g = 1 \times 10^{-6}$ g) of P-32 is accidentally spilled into a sink.

(a) How long will it take P-32 in the drain to exhibit 68% of its original activity?

(b) How many atoms of P-32 remain in the sink after 755 days?

35. Carbon from a cypress beam obtained from the tomb of an ancient Egyptian king gave 9.2 disintegrations/minute of C-14 per gram of carbon. Carbon from living material gives 15.3 disintegrations/min of C-14 per gram of carbon. Carbon-14 has a half-life of 5730 years. How old is the cypress beam?

36. A "new" painting supposedly painted by Michelangelo (1475–1564) is authenticated by C-14 dating. The C-14 content ($t_{1/2} = 5730$ y) of the canvas is 0.972 times that of a living plant. Could the painting have been done by Michelangelo, or at least while Michelangelo was alive?

37. Planks from an old boat were found in a cave near the shore. Analysis of the boat's wood gave 13.6 disintegrations/min/g of carbon. The half-life of C-14 is 5730 years. Analysis of a tree cut down when the cave was found showed 15.3 disintegrations/min/g of C-14. In what century was the boat built?

38. A sample of a wooden artifact gives 5.0 disintegrations/min/g carbon. The half-life of C-14 is 5730 years, and the activity of C-14 in wood just cut down from a tree is 15.3 disintegrations/min/g carbon. How old is the wooden artifact?

39. The radioactive isotope tritium, ${}^{3}_{1}H$, is produced in nature in much the same way as ${}^{14}_{6}C$. Its half-life is 12.3 years. Estimate the ${}^{3}_{1}H$ ratio of the tritium of water in the area to the tritium in a bottle of wine claimed to be 25 years old.

40. Consider the information given about tritium in Problem 39. Estimate the age of a sample of Scotch whiskey that has a tritium content 62% that of the water in the area where the whiskey was produced.

41. A rock from an archaeological dig was found to contain 0.255 g of Pb-206 per gram of U-238. Assume that the rock did not contain any Pb-206 at the time of its formation and that U-238 decayed only to Pb-206. How old is the rock? (For U-238, $t_{1/2} = 4.5 \times 10^{9}$ y.)

42. A meteor has a Pb-206 : U-238 mass ratio of 0.813 : 1.00. Use the assumptions of Question 41 to estimate the age of the meteor.

18-4 Mass-Energy Relations

43. Plutonium-239 is used as the energy source for heart pacemakers and space probes. It decays by alpha emission.

(a) Calculate Δm in grams when one mole of Pu-239 decays.

(b) How much energy (in kilojoules) is given off by the decay of 2.00 mg of Pu-239?

44. Strontium-90 is a dangerous by-product of atomic testing because it mimics the action of calcium in the body. It decays in two β-emissions to give zirconium-90 (nuclear mass = 89.8824 g).

(a) Write a balanced nuclear equation for the overall decay of Sr-90.

(b) Calculate Δm in grams when one mole of Sr-90 decays to Zr-90.

(c) How much energy (in kJ) is given off by the decay of 6.50 mg of Sr-90?

45. For Be-10, calculate

(a) the mass defect.

(b) the binding energy.

46. For Al-28, calculate

(a) the mass defect.

(b) the binding energy in kJ/mol.

47. Which has the larger binding energy, F-19 or O-17?

48. Which has the larger binding energy, K-40 or Ca-40? Show by calculation.

18-5 Nuclear Fission

18-6 Nuclear Fusion

49. Consider the fusion of B-10 with an alpha particle. The products of the fusion are C-13 and a proton.

(a) Write a nuclear reaction for this process.

(b) How much energy is released when 1.00 g of B-10 is fused with an α-particle?

50. Show by calculation which process produces more energy per gram of material reacting.

fission of U-235: ${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{94}_{40}Zr + {}^{140}_{58}Ce + 6\,{}^{0}_{-1}e + 2\,{}^{1}_{0}n$

fusion of deuterium: ${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{1}H + {}^{1}_{1}H$

Nuclear masses for Ce-140 and Zr-94 are 139.8734 and 93.8841, respectively.

51. Consider the fission reaction in which U-235 is bombarded by neutrons. The products of the bombardment are Rb-89, Ce-144, beta particles, and more neutrons.

(a) Write a balanced nuclear equation for the bombardment.

(b) Calculate ΔE when one gram of U-235 undergoes fission.

(c) The detonation of TNT, an explosive, evolves 2.76 kJ/g. How many kilograms of TNT are required to produce the same amount of energy as one milligram of U-235?

52. Pentaerythritol tetranitrate ($C_5H_8N_4O_{12}$ [PETN]) was the explosive meant to be used by the "underwear bomber." Its combustion produces 6.47 kJ/g of energy. Use the reaction in Problem 51 to calculate the mass of PETN (in kg) required to produce the same amount of energy as that produced when one microgram (1×10^{-6} g) of U-235 undergoes fission.

Unclassified

53. How many disintegrations per second occur in a basement that is $40 \times 40 \times 10$ feet if the radiation level from radon is the allowed 4×10^{-12} Ci/L?

54. Iodine-131 is used in the treatment of tumors in the thyroid gland. Its half-life is 8.1 days. Suppose that, due to a shipment delay, the I-131 in a hospital's pharmacy is 2.0 days old.

(a) What percentage of the I-131 has disintegrated?
(b) A patient is scheduled to receive 15.0 mg of I-131. What dosage (in milligrams) should the hospital pharmacist recommend for this patient if the 2-day-old bottle of I-131 is used?

55. An explosion of ammonium nitrate releases 37.0 kJ/mol of energy.
(a) How many tons of ammonium nitrate (1 ton = 2000 lbs) are required to release 1 million kJ of energy?
(b) How many tons of TNT ($\Delta E = -2.76$ kJ/g) are needed to release the same amount of energy?
(c) How many tons of U-235 are needed to obtain the same amount of energy?

56. Smoke detectors contain small amounts of americium-241. Am-241 decays by emitting α-particles and has a decay constant of $1.51 \times 10^{-3}\ y^{-1}$. If a smoke detector gives off ten disintegrations per second, how many grams of Am-241 are present in the detector?

57. The amount of oxygen dissolved in a sample of water can be determined by using thallium metal containing a small amount of the isotope Tl-204. When excess thallium is added to oxygen-containing water, the following reaction occurs.

$$2Tl(s) + \tfrac{1}{2}O_2(g) + H_2O \longrightarrow 2Tl^+(aq) + 2OH^-(aq)$$

After reaction, the activity of a 25.0-mL water sample is 745 counts per minute (cpm), caused by the presence of Tl^+-204 ions. The activity of Tl-204 is 5.53×10^5 cpm per gram of thallium metal. Assuming that O_2 is the limiting reactant in the above equation, calculate its concentration in moles per liter.

58. A 25-mL sample of 0.050 *M* $AgNO_3$ is mixed with 25 mL of 0.050 *M* NaI labeled with I-131. The NaI solution has an activity of 1.25×10^{10} counts/min·mL. The following reaction takes place:

$$Ag^+(aq) + I^-(aq) \longrightarrow AgI(s)$$

After the precipitate is removed by filtration, what is the activity of I^- in the filtrate? The K_{sp} for AgI is 1×10^{-16}.

59. A 100.0-g sample of water containing tritium, ${}^3_1H$, emits 2.89×10^3 beta particles per second. Tritium has a half-life of 12.3 years. What percentage of all the hydrogen atoms in the water sample is tritium?

60. Use the half-life of tritium given in Problem 59 to calculate the activity in curies of 1.00 mL of ${}^3_1H_2$ at STP.

61. One of the causes of the explosion at Chernobyl may have been the reaction between zirconium, which coated the fuel rods, and steam.

$$Zr(s) + 2H_2O(g) \longrightarrow ZrO_2(s) + 2H_2(g)$$

If half a metric ton of zirconium reacted, what pressure was exerted by the hydrogen gas produced at 55°C in the containment chamber, which had a volume of 2.0×10^4 L?

62. To measure the volume of the blood in an animal's circulatory system, the following experiment was performed. A 5.0-mL sample of an aqueous solution containing 1.7×10^5 counts per minute (cpm) of tritium was injected into the bloodstream. After an adequate period of time to allow for the complete circulation of the tritium, a 5.0-mL sample of blood was withdrawn and found to have 1.3×10^3 cpm on the scintillation counter. Assuming that only a negligible amount of tritium has decayed during the experiment, what is the volume of the animal's circulatory system?

63. Consider the fission reaction

$${}^1_0n + {}^{235}_{92}U \longrightarrow {}^{89}_{37}Rb + {}^{144}_{58}Ce + 3\,{}^{0}_{-1}e + 3\,{}^1_0n$$

How many liters of octane, C_8H_{18}, the primary component of gasoline, must be burned to $CO_2(g)$ and $H_2O(g)$ to produce as much energy as the fission of one gram of U-235 fuel? Octane has a density of 0.703 g/mL; its heat of formation is −249.9 kJ/mol.

64. A compound of Cr^{3+} and $C_2O_4{}^{2-}$ is made by a reaction that involves Na_2CrO_4 and oxalic acid, $H_2C_2O_4$, a reducing agent. The sodium chromate has an activity of 765 counts per minute per gram, from Cr-51. The oxalic acid has an activity of 512 counts per minute per gram. It is labeled with C-14. Because Cr-51 and C-14 emit different particles during decay, their activities can be counted independently. A sample of the compound was found to have a Cr-51 count of 314 cpm and a C-14 count of 235 cpm. How many oxalate ions are bound to one Cr^{3+} ion?

65. Radium-226 decays by alpha emission to radon-222. Suppose that 25.0% of the energy given off by one gram of radium is converted to electrical energy. What is the minimum mass of lithium that would be needed for the voltaic cell $Li \mid Li^+ \parallel Cu^{2+} \mid Cu$, at standard conditions, to produce the same amount of electrical work ($\Delta G°$)?

66. Polonium-210 decays to Pb-206 by alpha emission. Its half-life is 138 days. What volume of helium at 25°C and 1.20 atm would be obtained from a 25.00-g sample of Po-210 left to decay for 75 hours?

67. For how many years could all the energy needs of the world be supplied by the fission of U-235? Use the following assumptions:

- The world has about 1.0×10^7 metric tons of uranium ore, which are about 0.75% U-235.
- The energy consumption of the world is about 4.0×10^{15} kJ/y and does not change with time.
- The fission of U-235 releases about 8.0×10^7 kJ/g of U-235.

68. When a positron and an electron collide, they annihilate each other and produce two gamma photons, which carry the same amount of energy. What is the wavelength (in nanometers) of these photons?

Conceptual Questions

69. Classify the following statements as true or false. If false, correct the statement to make it true.
(a) The mass number increases in beta emission.
(b) A radioactive species with a large rate constant, *k*, decays very slowly.
(c) Fusion gives off less energy per gram of fuel than fission.

70. Explain how
(a) alpha and beta radiation are separated by an electric field.
(b) radioactive C-11 can be used as a tracer to study brain disorders.
(c) a self-sustaining chain reaction occurs in nuclear fission.

71. Suppose the ${}^{14}C/{}^{12}C$ ratio in plants a thousand years ago was 10% higher than it is today. What effect, if any, would this have on the calculated age of an artifact found by the C-14 method to be a thousand years old?

72. The following data are obtained for a radioactive isotope. Plot the data and determine the half-life of the isotope.

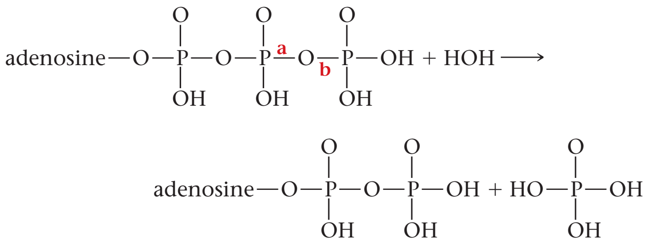
Time (h)	0.00	0.50	1.00	1.50	2.00	2.50
Activity (atoms/h)	14,472	13,095	11,731	10,615	9605	8504

73. Fill in the following table:

Event	Change in Atomic Number	Change in Mass Number
α-decay	______	______
β-emission	______	______
positron emission	______	______
K-electron capture	______	______
γ-decay	______	______

74. The principle behind the home smoke detector is described on page 472. Americium-241 is present in such detectors. It has a decay constant of $1.51 \times 10^{-3}\ y^{-1}$. You are urged to check the battery in the detector at least once a year. You are, however, never encouraged to check how much Am-241 remains undecayed. Explain why.

75. The cleavage of ATP (adenosine triphosphate) to ADP (adenosine diphosphate) and H_3PO_4 may be written as follows:



It is interesting to determine which bond (the P—O bond marked **a** or the O—P bond marked **b**) is cleaved by hydrolysis (reaction with water).

(**a**) Outline an experiment (using radioactivity) that can be used to determine where the cleavage results.

(**b**) Describe the results that would lead you to conclude that cleavage results at **a**.

(**c**) Describe the results that would lead you to conclude that cleavage results at **b**.

Results show that the cleavage occurs at **b**.

Challenge Problems

76. An activity of 20 picocuries (20×10^{-12} Ci) of radon-222 per liter of air in a house constitutes a health hazard to anyone living there. The half-life of radon-222 is 3.82 days. Calculate the concentration of radon in air (moles per liter) that corresponds to a 20-picocurie activity level.

77. Plutonium-239 decays by the reaction

$$^{239}_{94}Pu \longrightarrow ^{235}_{92}U + ^{4}_{2}He$$

Its rate constant is 5.5×10^{-11}/min. In a one-gram sample of Pu-239,

(**a**) how many grams decompose in 45 minutes?

(**b**) how much energy in kilojoules is given off in 45 minutes?

(**c**) what radiation dosage in rems (page 485) is received by a 75-kg man exposed to a gram of Pu-239 for 45 minutes?

78. It is possible to estimate the activation energy for fusion by calculating the energy required to bring two deuterons close enough to one another to form an alpha particle. This energy can be obtained by using Coulomb's law in the form $E = 8.99 \times 10^9\ q_1q_2/r$, where q_1 and q_2 are the charges of the deuterons (1.60×10^{-19} C), r is the radius of the He nucleus, about 2×10^{-15} m, and E is the energy in joules.

(**a**) Estimate E in joules per alpha particle.

(**b**) Using the equation $E = mv^2/2$, estimate the velocity (meters per second) each deuteron must have if a collision between the two of them is to supply the activation energy for fusion (m is the mass of the deuteron in kilograms).

79. Consider the reaction

$$2\,^{2}_{1}H \longrightarrow ^{4}_{2}He$$

(**a**) Calculate ΔE in kilojoules per gram of deuterium fused.

(**b**) How much energy is potentially available from the fusion of all the deuterium in seawater? The percentage of deuterium in water is about 0.0017%. The total mass of water in the oceans is 1.3×10^{24} g.

(**c**) What fraction of the deuterium in the oceans would have to be consumed to supply the annual energy requirements of the world (2.3×10^{17} kJ)?

80. Carbon-14 (C-14) with a half-life of 5730 years decays to nitrogen-14 (N-14). A sample of carbon dioxide containing carbon in the form of C-14 only is sealed in a vessel at 1.00-atmosphere pressure. Over time, the CO_2 becomes NO_2 through the radioactive decay process. The following equilibrium is established:

$$2NO_2(g) \rightleftharpoons N_2O_4(g)$$

If the equilibrium constant for the equation as written is 1×10^{-5}, what is the pressure of N_2O_4 after 20,000 years? Assume that the CO_2 does not participate in any chemical reactions.

81. Uranium in water decays to form Zn^{2+} and Sm by fission. Uranium has a half-life of 7×10^8 years. The zinc ions react with water and act as a weak acid according to the following equation:

$$Zn(H_2O)_4^{2+}(aq) \rightleftharpoons H^+(aq) + Zn(H_2O)_3(OH)^+(aq) \quad K_a = 3.3 \times 10^{-10}$$

Assuming that this is the only radioactive decay of any significance and that neither Sm nor U acts as a weak acid, how many years will it take a 1.00 M solution of U to achieve a pH of 6.0?

82. To determine the K_{sp} value of Hg_2I_2, a solid sample is used, in which some of the iodine is present as radioactive I-131. The count rate of the sample is 5.0×10^{11} counts per minute per mole of I. An excess amount of $Hg_2I_2(s)$ is placed in some water, and the solid is allowed to come to equilibrium with its respective ions. A 150.0-mL sample of the saturated solution is withdrawn and the radioactivity measured at 33 counts per minute. From this information, calculate the K_{sp} value for Hg_2I_2.