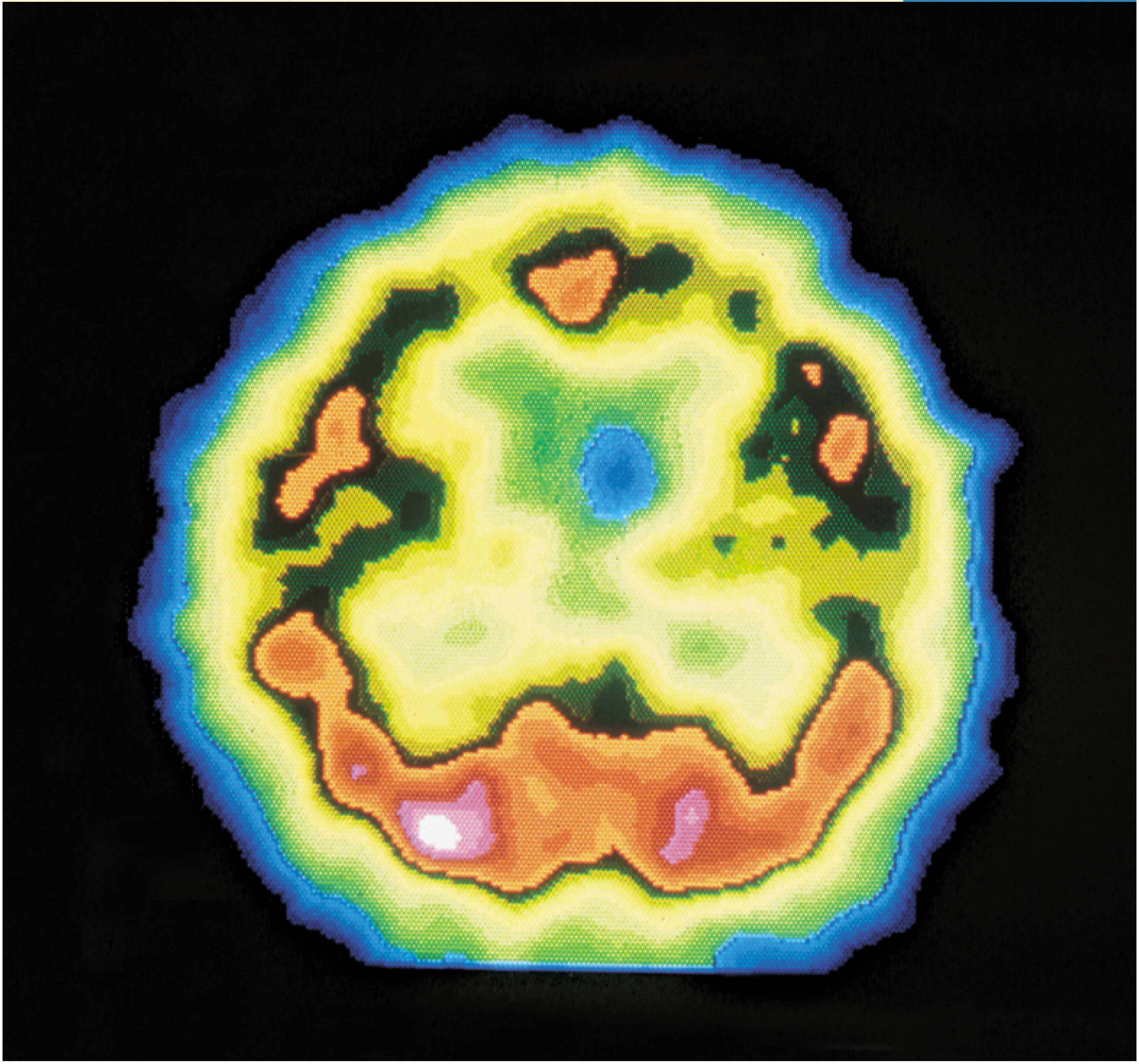
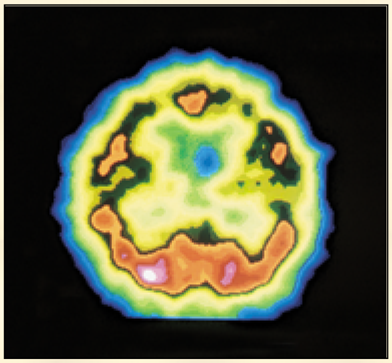
26

Nuclear Chemistry





Positron emission tomography (PET) allows mapping of tissues. This PET scan shows the distribution of radioactive glucose in a healthy human brain.

OUTLINE

OBJECTIVES

After you have studied this chapter, you should be able to

- *Describe the makeup of the nucleus*
- *Describe the relationships between neutron–proton ratio and nuclear stability*
- *Tell what is meant by the band of stability*
- *Calculate mass deficiency and nuclear binding energy*
- *Describe the common types of radiation emitted when nuclei undergo radioactive decay*
- *Write and balance equations that describe nuclear reactions*
- *Predict the different kinds of nuclear reactions undergone by nuclei, depending on their positions relative to the band of stability*
- *Describe methods for detecting radiation*
- *Understand half-lives of radioactive elements*
- *Carry out calculations associated with radioactive decay*
- *Interpret disintegration series*
- *Tell about some uses of radionuclides, including the use of radioactive elements for dating objects*
- *Describe some nuclear reactions that are induced by bombardment of nuclei with particles*
- *Tell about nuclear fission and some of its applications, including nuclear reactors*
- *Tell about nuclear fusion and some prospects for and barriers to its use for the production of energy*

Chemical properties are determined by electron distributions and are only indirectly influenced by atomic nuclei. Until now, we have discussed ordinary chemical reactions, so we have focused on electron configurations. Nuclear reactions involve changes in the composition of nuclei. These extraordinary processes are often accompanied by the release of tremendous amounts of energy and by transmutations of elements. Some differences between nuclear reactions and ordinary chemical reactions follow.

Nuclear Reaction	Ordinary Chemical Reaction
1. Elements may be converted from one to another.	**1.** No new elements can be produced.
2. Particles within the nucleus are involved.	**2.** Only the electrons participate.
3. Tremendous amounts of energy are released or absorbed.	**3.** Relatively small amounts of energy are released or absorbed.
4. Rate of reaction is not influenced by external factors.	**4.** Rate of reaction depends on factors such as concentration, temperature, catalyst, and pressure.

Marie Sklodowska Curie (1867–1934) is the only person to have been honored with Nobel Prizes in both physics and chemistry. In 1903, Pierre (1859–1906) and Marie Curie and Henri Becquerel (1852–1908) shared the prize in physics for the discovery of natural radioactivity. Marie Curie also received the 1911 Nobel Prize in chemistry for her discovery of radium and polonium and the compounds of radium. She named polonium for her native Poland. Marie's daughter, Irene Joliot-Curie (1897–1956), and Irene's husband, Frederick Joliot (1900–1958), received the 1935 Nobel Prize in chemistry for the first synthesis of a new radioactive element.

Medieval alchemists spent years trying to convert other metals into gold without success. Years of failure and the acceptance of Dalton's atomic theory early in the nineteenth century convinced scientists that one element could not be converted into another. Then, in 1896 Henri Becquerel discovered "radioactive rays" **(natural radioactivity)** coming from a uranium compound. Ernest Rutherford's study of these rays showed that atoms of one element may indeed be converted into atoms of other elements by spontaneous nuclear disintegrations. Many years later it was shown that nuclear reactions initiated by bombardment of nuclei with accelerated subatomic particles or other nuclei can also transform one element into another—accompanied by the release of radiation **(induced radioactivity).**

Becquerel's discovery led other researchers, including Marie and Pierre Curie, to discover and study new radioactive elements. Many radioactive isotopes, or **radioisotopes,** now have important medical, agricultural, and industrial uses.

Nuclear fission is the splitting of a heavy nucleus into lighter nuclei. **Nuclear fusion** is the combination of light nuclei to produce a heavier nucleus. Huge amounts of energy are released when these processes occur. These processes could satisfy a large portion of our future energy demands. Current research is aimed at surmounting the technological problems associated with safe and efficient use of nuclear fission reactors and with the development of controlled fusion reactors.

In Chapter 5, we represented an atom of a particular isotope by its *nuclide symbol.* Radioisotopes are often called **radionuclides.**

26-1 THE NUCLEUS

In Chapter 5 we described the principal subatomic particles (Table 26-1). Recall that the neutrons and protons together constitute the nucleus, with the electrons occupying essentially empty space around the nucleus. The nucleus is only a minute fraction of the total volume of an atom, yet nearly all the mass of an atom resides in the nucleus. Thus, nuclei are extremely dense. It has been shown experimentally that nuclei of all elements have approximately the same density, 2.4×10^{14} g/cm^3.

If enough nuclei could be gathered together to occupy one cubic centimeter, the total weight would be about 250 million tons!

TABLE 26-1 *Fundamental Particles of Matter*

Particle	Mass	Charge
Electron (e^-)	0.00054858 amu	1−
Proton (p or p^+)	1.0073 amu	1+
Neutron (n or n^0)	1.0087 amu	none

From an electrostatic point of view, it is amazing that positively charged protons can be packed so closely together. Yet many nuclei do not spontaneously decompose, so they must be stable. In the early twentieth century when Rutherford postulated the nuclear model of the atom, scientists were puzzled by such a situation. Physicists have since detected many very short-lived subatomic particles (in addition to protons, neutrons, and electrons) as products of nuclear reactions. Well over 100 have been identified. A discussion of these many particles is beyond the scope of a chemistry text. Furthermore their functions are not entirely understood, but it is now thought that they help to overcome the proton–proton repulsions and to bind nuclear particles **(nucleons)** together. The attractive forces among nucleons appear to be important over only extremely small distances, about 10^{-13} cm.

26-2 NEUTRON–PROTON RATIO AND NUCLEAR STABILITY

The term **"nuclide"** is used to refer to different atomic forms of all elements. The term "isotope" applies only to different forms of the same element. Most naturally occurring nuclides have even numbers of protons and even numbers of neutrons; 157 nuclides fall into this category. Nuclides with odd numbers of both protons and neutrons are least common (there are only four), and those with odd–even combinations are intermediate in abundance (Table 26-2). Furthermore, nuclides with certain "magic numbers" of protons and neutrons seem to be especially stable. Nuclides with a number of protons *or* a number of neutrons *or* a sum of the two equal to 2, 8, 20, 28, 50, 82, or 126 have unusual stability. Examples are $^{4}_{2}He$, $^{16}_{8}O$, $^{42}_{20}Ca$, $^{88}_{38}Sr$, and $^{208}_{82}Pb$. This suggests an energy level (shell) model for the nucleus similar to the shell model of electron configurations.

The nuclide symbol for an element (Section 5-7) is

$$^{A}_{Z}E$$

where E is the chemical symbol for the element, Z is its atomic number, and A is its mass number.

Figure 26-1 is a plot of the number of neutrons (N) versus number of protons (Z) for the stable nuclides (the **band of stability**). For low atomic numbers, the most stable nuclides have equal numbers of protons and neutrons ($N = Z$). Above atomic number 20, the most stable nuclides have more neutrons than protons. Careful examination reveals an approximately stepwise shape to the plot due to the stability of nuclides with even numbers of nucleons.

TABLE 26-2 *Abundance of Naturally Occurring Nuclides*

Number of protons	even	even	odd	odd
Number of neutrons	even	odd	even	odd
Number of such nuclides	157	52	50	4

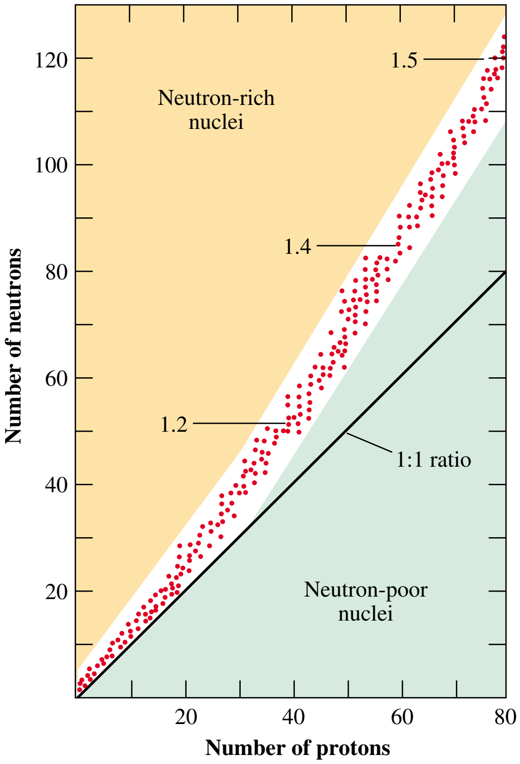


Figure 26-1 A plot of the number of neutrons versus the number of protons in stable nuclei. As atomic number increases, the *N*/*Z* ratio (the decimal fractions) of the stable nuclei increases. The stable nuclei are located in an area known as the band of stability. Most radioactive nuclei occur outside this band.

26-3 NUCLEAR STABILITY AND BINDING ENERGY

Experimentally, we observe that the masses of atoms other than ${}^{1}_{1}\text{H}$ are always *less* than the sum of the masses of their constituent particles. We now know why this *mass deficiency* occurs. We also know that the mass deficiency is in the nucleus of the atom and has nothing to do with the electrons; however, *because tables of masses of isotopes include the electrons, we shall also include them.*

The **mass deficiency, Δm,** for a nucleus is the difference between the sum of the masses of electrons, protons, and neutrons in the atom (calculated mass) and the actual measured mass of the atom.

Do you remember how to find the numbers of protons, neutrons, and electrons in a specified atom? Review Section 5-7.

$$\Delta m = (\text{sum of masses of all } e^-, p^+, \text{and } n^0) - (\text{actual mass of atom})$$

For most naturally occurring isotopes, the mass deficiency is only about 0.15% or less of the calculated mass of an atom.

EXAMPLE 26-1 *Mass Deficiency*

Calculate the mass deficiency for chlorine-35 atoms in amu/atom and in g/mol atoms. The actual mass of a chlorine-35 atom is 34.9689 amu.

Plan

We first find the numbers of protons, electrons, and neutrons in one atom. Then we determine the "calculated" mass as the sum of the masses of these particles. The mass deficiency is the actual mass subtracted from the calculated mass. This deficiency is commonly expressed either as mass per atom or as mass per mole of atoms.

Solution

Each atom of $^{35}_{17}Cl$ contains 17 protons, 17 electrons, and $(35 - 17) = 18$ neutrons. First we sum the masses of these particles.

$$\begin{array}{rll} \text{protons:} & 17 \times 1.0073 \text{ amu} = 17.124 \text{ amu} & \text{(masses from Table 26-1)} \\ \text{electrons:} & 17 \times 0.00054858 \text{ amu} = 0.0093 \text{ amu} & \\ \text{neutrons:} & 18 \times 1.0087 \text{ amu} = 18.157 \text{ amu} & \\ \hline & \text{sum} = 35.290 \text{ amu} & \longleftarrow \text{calculated mass} \end{array}$$

Then we subtract the actual mass from the "calculated" mass to obtain Δm.

$$\Delta m = 35.290 \text{ amu} - 34.9689 \text{ amu} = \boxed{0.321 \text{ amu}} \quad \text{mass deficiency (in one atom)}$$

We have calculated the mass deficiency in amu/atom. Recall (Section 5-9) that 1 gram is 6.022×10^{23} amu. We can show that a number expressed in amu/atom is equal to the same number in g/mol of atoms.

$$\frac{\underline{?}\text{ g}}{\text{mol}} = \frac{0.321 \text{ amu}}{\text{atom}} \times \frac{1 \text{ g}}{6.022 \times 10^{23} \text{ amu}} \times \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol } ^{35}\text{Cl atoms}}$$

$$= \boxed{0.321 \text{ g/mol of } ^{35}\text{Cl atoms}} \longleftarrow \text{(mass } \textit{deficiency} \text{ in a mole of Cl atoms)}$$

You should now work Exercises 14a and 16a, b.

What has happened to the mass represented by the mass deficiency? In 1905, Einstein set forth the Theory of Relativity. He stated that matter and energy are equivalent. An obvious corollary is that matter can be transformed into energy and energy into matter. The transformation of matter into energy occurs in the sun and other stars. It happened on earth when controlled nuclear fission was achieved in 1939 (Section 26-14). The reverse transformation, energy into matter, has not yet been accomplished on a large scale. Einstein's equation, which we encountered in Chapter 1, is $E = mc^2$. E represents the amount of energy released, m the mass of matter transformed into energy, and c the speed of light in a vacuum, 2.997925×10^8 m/s (usually rounded off to 3.00×10^8 m/s).

A mass deficiency represents the amount of matter that would be converted into energy and released if the nucleus were formed from initially separate protons and neutrons. This energy is the **nuclear binding energy, *BE*.** It provides the powerful short-range force that holds the nuclear particles (protons and neutrons) together in a very small volume.

We can rewrite the Einstein relationship as

$$BE = (\Delta m)c^2$$

Specifically, if 1 mole of ^{35}Cl nuclei were to be formed from 17 moles of protons and 18 moles of neutrons, the resulting mole of nuclei would weigh 0.321 gram less than the original collection of protons and neutrons (Example 26-1).

Nuclear binding energies may be expressed in many different units, including kilojoules/mole of atoms, kilojoules/gram of atoms, and megaelectron volts/nucleon. Some useful equivalences are

1 megaelectron volt (MeV) = 1.60×10^{-13} J and 1 joule (J) = 1 $\text{kg}\cdot\text{m}^2/\text{s}^2$

Let's use the value of Δm for ^{35}Cl atoms to calculate their nuclear binding energy.

EXAMPLE 26-2 *Nuclear Binding Energy*

Calculate the nuclear binding energy ^{35}Cl in (a) kilojoules per mole of Cl atoms, (b) kilojoules per gram of Cl atoms, and (c) megaelectron volts per nucleon.

Plan

The mass deficiency that we calculated in Example 26-1 is related to the binding energy by the Einstein equation.

Solution

The mass deficiency is 0.321 g/mol = 3.21×10^{-4} kg/mol.

$$\text{(a)}\ BE = (\Delta m)c^2 = \frac{3.21 \times 10^{-4}\ \text{kg}}{\text{mol}\ ^{35}\text{Cl atoms}} \times (3.00 \times 10^{8}\ \text{m/s})^2 = 2.89 \times 10^{13}\ \frac{\text{kg}\cdot\text{m}^2/\text{s}^2}{\text{mol}\ ^{35}\text{Cl atoms}}$$

$$= 2.89 \times 10^{13}\ \text{J/mol}\ ^{35}\text{Cl atoms} = \boxed{2.89 \times 10^{10}\ \text{kJ/mol of}\ ^{35}\text{Cl atoms}}$$

(b) From Example 26-1, the actual mass of ^{35}Cl is

$$\frac{34.9689\ \text{amu}}{^{35}\text{Cl atom}} \quad \text{or} \quad \frac{34.9689\ \text{g}}{\text{mol}\ ^{35}\text{Cl atoms}}$$

We use this mass to set up the needed conversion factor.

$$BE = \frac{2.89 \times 10^{10}\ \text{kJ}}{\text{mol of}\ ^{35}\text{Cl atoms}} \times \frac{1\ \text{mol}\ ^{35}\text{Cl atoms}}{34.9689\ \text{g}\ ^{35}\text{Cl atoms}} = \boxed{8.26 \times 10^{8}\ \text{kJ/g}\ ^{35}\text{Cl atoms}}$$

(c) The number of nucleons in *one* atom of ^{35}Cl is 17 protons + 18 neutrons = 35 nucleons.

The mass number, *Z*, is equal to the number of nucleons in one atom.

$$BE = \frac{2.89 \times 10^{10}\ \text{kJ}}{\text{mol of}\ ^{35}\text{Cl atoms}} \times \frac{1000\ \text{J}}{\text{kJ}} \times \frac{1\ \text{MeV}}{1.60 \times 10^{-13}\ \text{J}} \times \frac{1\ \text{mol}\ ^{35}\text{Cl atoms}}{6.022 \times 10^{23}\ ^{35}\text{Cl atoms}} \times \frac{1\ ^{35}\text{Cl atom}}{35\ \text{nucleons}}$$

$$= \boxed{8.57\ \text{MeV/nucleon}}$$

You should now work Exercises 14 and 16.

The nuclear binding energy of a mole of ^{35}Cl nuclei, 2.89×10^{13} J/mol, is an enormous amount of energy—enough to heat 6.9×10^{7} kg ($\approx$ 76,000 tons) of water from 0°C to 100°C! Stated differently, this is also the amount of energy that would be required to separate 1 mole of ^{35}Cl nuclei into 17 moles of protons and 18 moles of neutrons. This has never been done.

Figure 26-2 is a plot of average binding energy per gram of nuclei versus mass number. It shows that nuclear binding energies (per gram) increase rapidly with increasing mass number, reach a maximum around mass number 50, and then decrease slowly. The nuclei with the highest binding energies (mass numbers 40 to 150) are the most stable. Large amounts of energy would be required to separate these nuclei into their component

Some unstable radioactive nuclei do emit a single proton, a single neutron, or other subatomic particles as they decay in the direction of greater stability. None decomposes entirely into elementary particles.

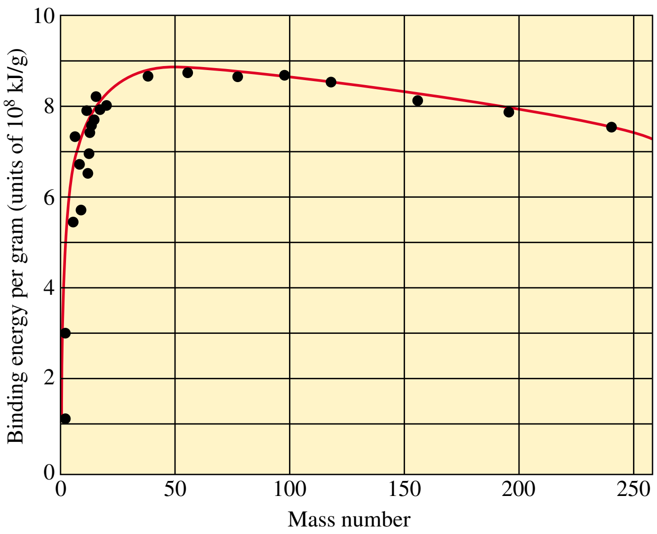


Figure 26-2 Plot of binding energy per gram versus mass number. Very light and very heavy nuclei are relatively unstable.

neutrons and protons. Even though these nuclei are the most stable ones, *all* nuclei are stable with respect to complete decomposition into protons and neutrons because all (except ^{1}H) nuclei have mass deficiencies. In other words, the energy equivalent of the loss of mass represents an associative force that is present in all nuclei except ^{1}H. It must be overcome to separate the nuclei completely into their subatomic particles.

26-4 RADIOACTIVE DECAY

Nuclei whose neutron-to-proton ratios lie outside the stable region undergo spontaneous radioactive decay by emitting one or more particles or electromagnetic rays or both. The type of decay that occurs usually depends on whether the nucleus is above, below, or to the right of the band of stability (Figure 26-1). Common types of radiation emitted in decay processes are summarized in Table 26-3.

The particles can be emitted at different kinetic energies. In addition, radioactive decay often leaves a nucleus in an excited (high-energy) state. Then the decay is followed by gamma ray emission.

$$\text{(excited nucleus)} \longrightarrow {}^{M}_{Z}E^{*} \longrightarrow {}^{M}_{Z}E + {}^{0}_{0}\gamma$$

Recall that the energy of electromagnetic radiation is $E = h\nu$, where h is Planck's constant and ν is the frequency.

The energy of the gamma ray ($h\nu$) is equal to the energy difference between the ground and excited nuclear states. This is like the emission of lower energy electromagnetic radiation that occurs as an atom in its excited electronic state returns to its ground state (Section 5-12). Studies of gamma ray energies strongly suggest that nuclear energy levels are quantized just as are electronic energy levels. This adds further support for a shell model for the nucleus.

The penetrating abilities of the particles and rays are proportional to their energies. Beta particles and positrons are about 100 times more penetrating than the heavier and slower-moving alpha particles. They can be stopped by a $\frac{1}{8}$-inch-thick (0.3 cm) aluminum

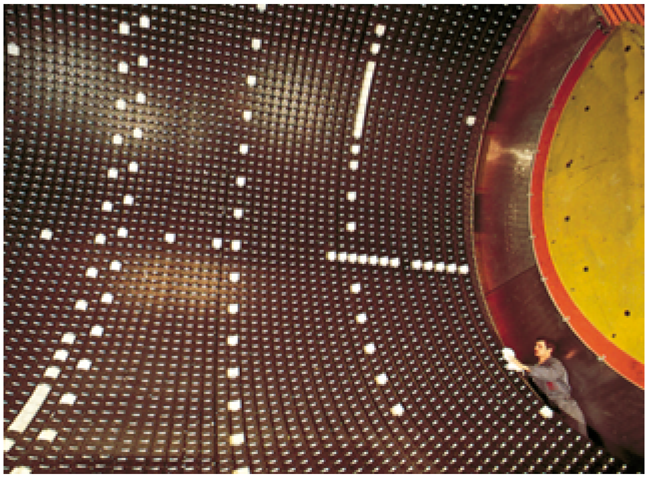
TABLE 26-3 *Common Types of Radioactive Emissions*

Type and Symbol[a]	Identity	Mass (amu)	Charge	Velocity	Penetration
beta (β^-, ${}_{-1}^{0}\beta$, ${}_{-1}^{0}e$)	electron	0.00055	1−	≤90% speed of light	low to moderate, depending on energy
positron[b] (${}_{+1}^{0}\beta$, ${}_{+1}^{0}e$)	positively charged electron	0.00055	1+	≤90% speed of light	low to moderate, depending on energy
alpha (α, ${}_{2}^{4}\alpha$, ${}_{2}^{4}\mathrm{He}$)	helium nucleus	4.0026	2+	≤10% speed of light	low
proton (${}_{1}^{1}p$, ${}_{1}^{1}\mathrm{H}$)	proton, hydrogen nucleus	1.0073	1+	≤10% speed of light	low to moderate, depending on energy
neutron (${}_{0}^{1}n$)	neutron	1.0087	0	≤10% speed of light	very high
gamma (${}_{0}^{0}\gamma$) ray	high-energy electromagnetic radiation such as X-rays	0	0	speed of light	high

[a] *The number at the upper left of the symbol is the number of nucleons, and the number at the lower left is the number of positive charges.*

[b] *On the average, a positron exists for only about a nanosecond (1×10^{-9} second) before colliding with an electron and being converted into the corresponding amount of energy.*

plate. They can burn skin severely but cannot reach internal organs. Alpha particles have low penetrating ability and cannot damage or penetrate skin. They can damage sensitive internal tissue if inhaled, however. The high-energy gamma rays have great penetrating power and severely damage both skin and internal organs. They travel at the speed of light and can be stopped by thick layers of concrete or lead.



A technician cleans lead glass blocks that form part of the giant OPAL particle detector at CERN, the European center for particle physics near Geneva, Switzerland.

Robotics technology is used to manipulate highly radioactive samples safely.

26-5 EQUATIONS FOR NUCLEAR REACTIONS

In *chemical* reactions, atoms in molecules and ions are rearranged, but matter is neither created nor destroyed, and atoms are not changed into other atoms. In earlier chapters, we learned to write balanced chemical equations to represent chemical reactions. Such equations must show the same total number of atoms of each kind on both sides of the equation and the same total charge on both sides of the equation. In a nuclear reaction, a different kind of transformation occurs, one in which a proton can change into a neutron, or a neutron can change into a proton, but the total number of nucleons remains the same. This leads to two requirements for the equation for a nuclear reaction:

1. The sum of the mass numbers (the left superscript in the nuclide symbol) of the reactants must equal the sum of the mass numbers of the products.
2. The sum of the atomic numbers (the left subscript in the nuclide symbol) of the reactants must equal the sum of the atomic numbers of the products; this maintains charge balance.

Because such equations are intended to describe only the changes in the nucleus, they do not ordinarily include ionic charges (which are due to changes in the arrangements of electrons). In the following sections, we will see many examples of such equations for nuclear reactions.

26-6 NEUTRON-RICH NUCLEI (ABOVE THE BAND OF STABILITY)

Nuclei in this region have too high a ratio of neutrons to protons. They undergo decays that *decrease* the ratio. The most common such decay is **beta emission.** A beta particle is an electron ejected *from the nucleus* when a neutron is converted into a proton.

$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta $$

Thus, beta emission results in an increase of one in the number of protons (the atomic number) and a decrease of one in the number of neutrons, with no change in mass number. Examples of beta particle emission are

$$ {}^{228}_{88}\text{Ra} \longrightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta \qquad \text{and} \qquad {}^{14}_{6}\text{C} \longrightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta $$

The sum of the mass numbers on each side of the first equation is 228, and the sum of the atomic numbers on each side is 88. The corresponding sums for the second equation are 14 and 6, respectively.

26-7 NEUTRON-POOR NUCLEI (BELOW THE BAND OF STABILITY)

Two types of decay for nuclei below the band of stability are **positron emission** or **electron capture** (*K* capture). Positron emission is most commonly encountered with artificially radioactive nuclei of the lighter elements. Electron capture occurs most often with heavier elements.

A positron has the mass of an electron but a positive charge. Positrons are emitted when protons are converted to neutrons.

$$^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta$$

Thus, positron emission results in a *decrease* by one in atomic number and an *increase* by one in the number of neutrons, with *no change* in mass number.

$$^{38}_{19}\text{K} \longrightarrow {}^{38}_{18}\text{Ar} + {}^{0}_{+1}\beta \qquad \text{and} \qquad {}^{15}_{8}\text{O} \longrightarrow {}^{15}_{7}\text{N} + {}^{0}_{+1}\beta$$

The same effect can be accomplished by electron capture (*K* capture), in which an electron from the *K* shell ($n = 1$) is captured by the nucleus.

Electron capture by the nucleus differs from an atom gaining an electron to form an ion.

$$^{106}_{47}\text{Ag} + {}^{0}_{-1}e \longrightarrow {}^{106}_{46}\text{Pd} \qquad \text{and} \qquad {}^{37}_{18}\text{Ar} + {}^{0}_{-1}e \longrightarrow {}^{37}_{17}\text{Cl}$$

Some nuclides, such as $^{22}_{11}\text{Na}$, undergo both electron capture and positron emission.

$$^{22}_{11}\text{Na} + {}^{0}_{-1}e \longrightarrow {}^{22}_{10}\text{Ne}\ (3\%) \qquad \text{and} \qquad {}^{22}_{11}\text{Na} \longrightarrow {}^{22}_{10}\text{Ne} + {}^{0}_{+1}\beta\ (97\%)$$

Some of the neutron-poor nuclei, especially the heavier ones, *increase* their neutron-to-proton ratios by undergoing **alpha emission.** Alpha particles are helium nuclei, $^{4}_{2}\text{He}$, consisting of two protons and two neutrons. Alpha emission also results in an increase of the neutron-to-proton ratio. An example is the alpha emission of lead-204.

α-particles carry a double positive charge, but charge is usually not shown in nuclear reactions.

$$^{204}_{82}\text{Pb} \longrightarrow {}^{200}_{80}\text{Hg} + {}^{4}_{2}\alpha$$

26-8 NUCLEI WITH ATOMIC NUMBER GREATER THAN 83

All nuclides with atomic number greater than 83 are beyond the band of stability and are radioactive. Many of these decay by alpha emission.

The only stable nuclide with atomic number 83 is $^{209}_{83}\text{Bi}$.

$$^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha \qquad \text{and} \qquad {}^{210}_{84}\text{Po} \longrightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\alpha$$

The decay of radium-226 was originally reported in 1902 by Rutherford and Soddy. It was the first transmutation of an element ever observed. A few heavy nuclides also decay by beta emission, positron emission, and electron capture.

Some isotopes of uranium ($Z = 92$) and elements of higher atomic number, the **transuranium elements,** also decay by spontaneous nuclear fission. In this process a heavy nuclide splits into nuclides of intermediate mass and neutrons.

$$^{252}_{98}\text{Cf} \longrightarrow {}^{142}_{56}\text{Ba} + {}^{106}_{42}\text{Mo} + 4\,{}^{1}_{0}n$$

26-9 DETECTION OF RADIATION

Photographic Detection

Emanations from radioactive substances affect photographic plates just as ordinary visible light does. Becquerel's discovery of radioactivity resulted from the unexpected exposure of such a plate, wrapped in black paper, by a nearby enclosed sample of a uranium-containing compound, potassium uranyl sulfate. After a photographic plate has been developed and fixed, the intensity of the exposed spot is related to the amount of radiation that struck the plate. Quantitative detection of radiation by this method is difficult and tedious.

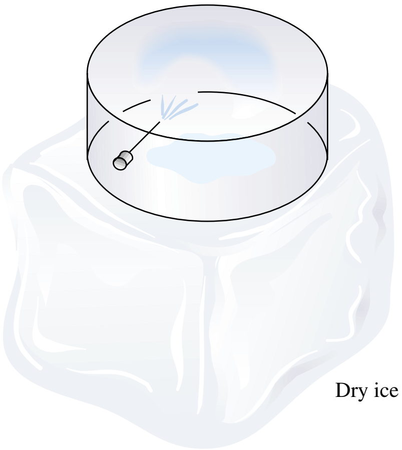


Figure 26-3 A cloud chamber. The emitter is glued onto a pin stuck into a stopper that is mounted on the chamber wall. The chamber has some volatile liquid in the bottom and rests on dry ice. The cool air near the bottom becomes supersaturated with vapor. When an emission speeds through this vapor, ions are produced. These ions serve as "seeds" about which the vapor condenses, forming tiny droplets, or fog.

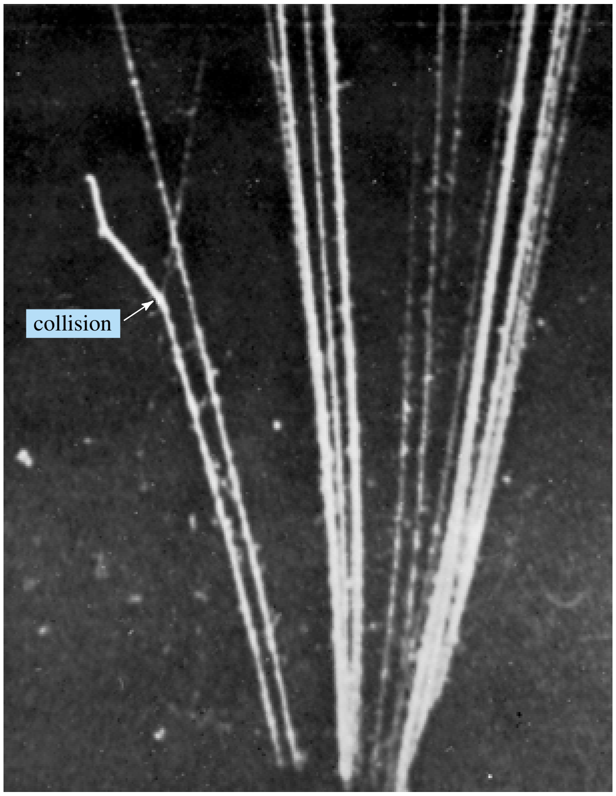


Figure 26-4 A historic cloud chamber photograph of alpha tracks in nitrogen gas. The forked track was shown to be due to a speeding proton (going off to the left) and an isotope of oxygen (going off to the right). It is assumed that the α-particle struck the nucleus of a nitrogen atom at the point where the track forks.

Detection by Fluorescence

Fluorescent substances can absorb high-energy radiation such as gamma rays and subsequently emit visible light. As the radiation is absorbed, the absorbing atoms jump to excited electronic states. The excited electrons return to their ground states through a series of transitions, some of which emit visible light. This method may be used for the quantitative detection of radiation, using an instrument called a **scintillation counter.**

Cloud Chambers

The original cloud chamber was devised by C. T. R. Wilson (1869–1959) in 1911. A chamber contains air saturated with vapor. Particles emitted from a radioactive substance ionize air molecules in the chamber. Cooling the chamber causes droplets of liquid to condense on these ions. The paths of the particles can be followed by observing the foglike tracks produced. The tracks may be photographed and studied in detail. Figures 26-3 and 26-4 show a cloud chamber and a cloud chamber photograph, respectively.

Gas Ionization Counters

The Geiger counter can detect only β and γ radiation. The α-particles cannot penetrate the walls or window of the tube.

A common gas ionization counter is the **Geiger–Müller counter** (Figure 26-5). Radiation enters the tube through a thin window. Windows of different stopping powers can be used to admit only radiation of certain penetrating powers.

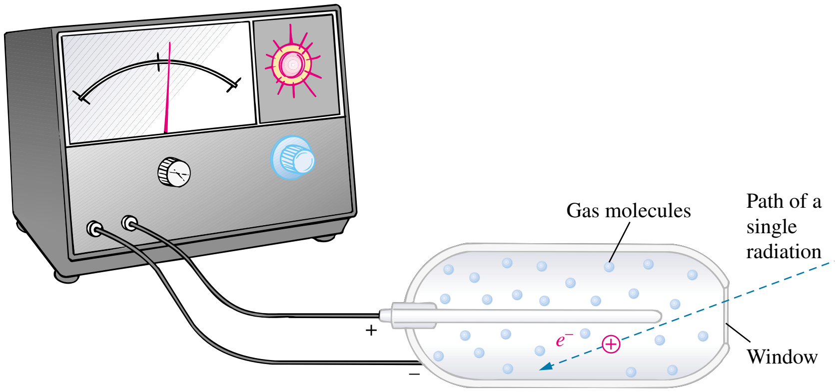


Figure 26-5 The principle of operation of a gas ionization counter. The center wire is positively charged, and the shell of the tube is negatively charged. When radiation enters through the window, it ionizes one or more gas atoms. The electrons are attracted to the central wire, and the positive ions are drawn to the shell. This constitutes a pulse of electric current, which is amplified and displayed on the meter or other readout.

A sample of carnotite, a uranium ore, shown with a Geiger–Müller counter.

26-10 RATES OF DECAY AND HALF-LIFE

Radionuclides have different stabilities and decay at different rates. Some decay nearly completely in a fraction of a second and others only after millions of years. The rates of all radioactive decays are independent of temperature and obey *first-order kinetics.* In Section 16-3 we saw that the rate of a first-order process is proportional only to the concentration of one substance. The rate law and the integrated rate equation for a first-order process (Section 16-4) are

$$\text{rate of decay} = k[\text{A}] \qquad \text{and} \qquad \ln\left(\frac{\text{A}_0}{\text{A}}\right) = akt$$

Here A represents the amount of decaying radionuclide of interest remaining after some time t, and A_0 is the amount present at the beginning of the observation. The k is the rate constant, which is different for each radionuclide. Each atom decays independently of the others, so the stoichiometric coefficient a is *always* 1 for radioactive decay. We can therefore drop it from the calculations in this chapter and write the integrated rate equation as

$$\ln\left(\frac{\text{A}_0}{\text{A}}\right) = kt$$

Because A_0/A is a ratio, A_0 and A can represent either molar concentrations of a reactant or masses of a reactant. The rate of radioactive disintegrations follows first-order kinetics, so it is proportional to the amount of A present; we can write the integrated rate equation in terms of N, the number of disintegrations per unit time:

$$\ln\left(\frac{N_0}{N}\right) = kt$$

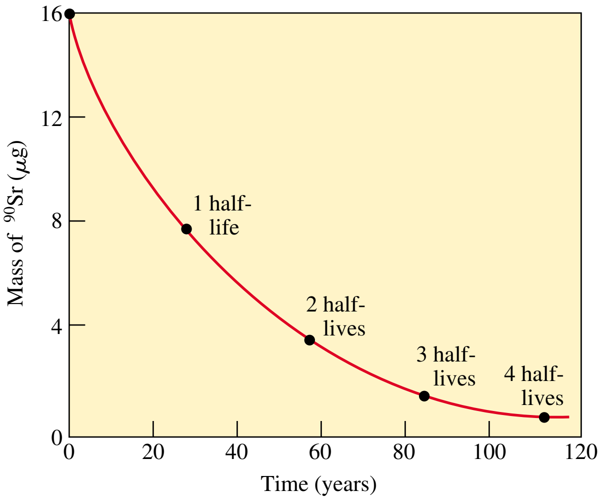


Figure 26-6 The decay of a 16-μg sample of $^{90}_{38}$Sr.

In nuclear chemistry, the decay rate is usually expressed in terms of the half-life, $t_{1/2}$, of the process. This is the amount of time required for half of the original sample to react. For a first-order process, $t_{1/2}$ is given by the equation

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

In 1963, a treaty was signed by the United States, the Soviet Union, and the United Kingdom prohibiting the further testing of nuclear weapons in the atmosphere. Since then, strontium-90 has been disappearing from the air, water, and soil according to the curve in Figure 26-6. So the treaty has largely accomplished its aim up to the present.

The isotope strontium-90 was introduced into the atmosphere by the atmospheric testing of nuclear weapons. Because of the chemical similarity of strontium to calcium, it now occurs with Ca in measurable quantities in milk, bones, and teeth as a result of its presence in food and water supplies. It is a radionuclide that undergoes beta emission with a half-life of 28 years. It may cause leukemia, bone cancer, and other related disorders. If we begin with a 16-μg sample of $^{90}_{38}$Sr, 8 μg will remain after one half-life of 28 years. After 56 years, 4 μg will remain; after 84 years, 2 μg; and so on (Figure 26-6).

Similar plots for other radionuclides all show the same shape of **exponential decay curve.** About ten half-lives (280 years for $^{90}_{38}$Sr) must pass for radionuclides to lose 99.9% of their radioactivity.

EXAMPLE 26-3 *Rate of Radioactive Decay*

Gamma rays destroy both cancerous and normal cells, so the beams of gamma rays must be directed as nearly as possible at only cancerous tissue.

The "cobalt treatments" used in medicine to arrest certain types of cancer rely on the ability of gamma rays to destroy cancerous tissues. Cobalt-60 decays with the emission of beta particles and gamma rays, with a half-life of 5.27 years.

$$^{60}_{27}\text{Co} \longrightarrow \, ^{60}_{28}\text{Ni} + \, ^{0}_{-1}\beta + \, ^{0}_{0}\gamma$$

How much of a 3.42-μg sample of cobalt-60 remains after 30.0 years?

▶ The γ-radiation from ^{60}Co is used to treat cancers near the surface of the body.

Plan

We determine the value of the specific rate constant, *k*, from the given half-life. This value is then used in the first-order integrated rate equation to calculate the amount of cobalt-60 remaining after the specified time.

Solution

We first determine the value of the specific rate constant.

$$t_{1/2} = \frac{0.693}{k} \qquad \text{so} \qquad k = \frac{0.693}{t_{1/2}} = \frac{0.693}{5.27\ \text{y}} = 0.131\ \text{y}^{-1}$$

This value can now be used to determine the ratio of A_0 to A after 30.0 years.

$$\ln\left(\frac{A_0}{A}\right) = kt = 0.131\ \text{y}^{-1}(30.0\ \text{y}) = 3.93$$

Taking the inverse ln of both sides, $\frac{A_0}{A} = 51$.

$$A_0 = 3.42\ \mu\text{g, so}$$

$$A = \frac{A_0}{51} = \frac{3.42\ \mu\text{g}}{51} = \boxed{0.067\ \mu\text{g}\ ^{60}_{27}\text{Co}}\ \text{remains after 30.0 years.}$$

You should now work Exercise 54.

26-11 DISINTEGRATION SERIES

Many radionuclides cannot attain nuclear stability by only one nuclear reaction. Instead, they decay in a series of disintegrations. A few such series are known to occur in nature. Two begin with isotopes of uranium, ^{238}U and ^{235}U, and one begins with ^{232}Th. All three of these end with a stable isotope of lead ($Z = 82$). Table 26-4 outlines in detail the ^{238}U, ^{235}U, and ^{232}Th disintegration series, showing half-lives. For any particular decay step, the decaying nuclide is called the **parent** nuclide, and the product nuclide is the **daughter.**

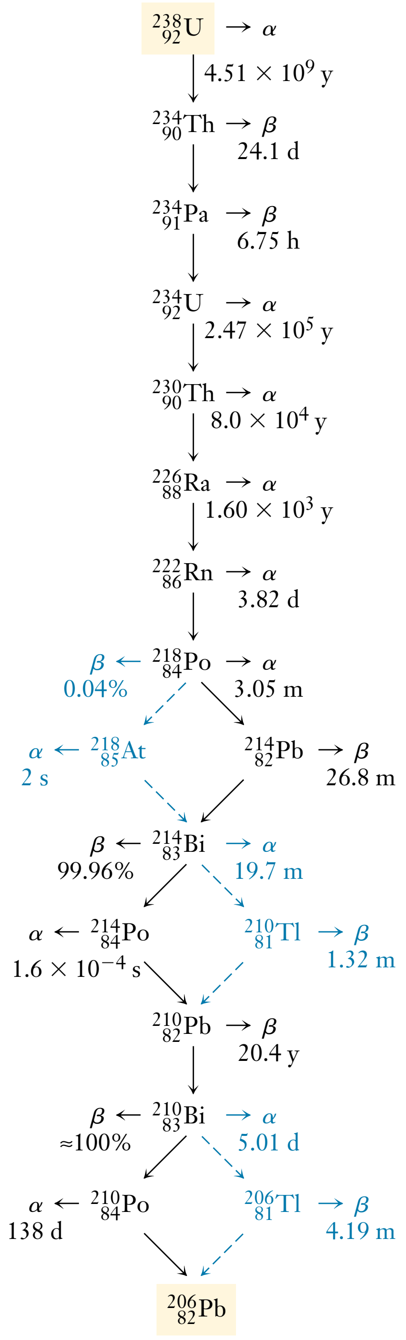
Uranium-238 decays by alpha emission to thorium-234 in the first step of one series. Thorium-234 subsequently emits a beta particle to produce protactinium-234 in the second step. The series can be summarized as shown in Table 26-4a. The *net* reaction for the ^{238}U series is

$$^{238}_{92}\text{U} \longrightarrow {}^{206}_{82}\text{Pb} + 8\ {}^{4}_{2}\text{He} + 6\ {}^{0}_{-1}\beta$$

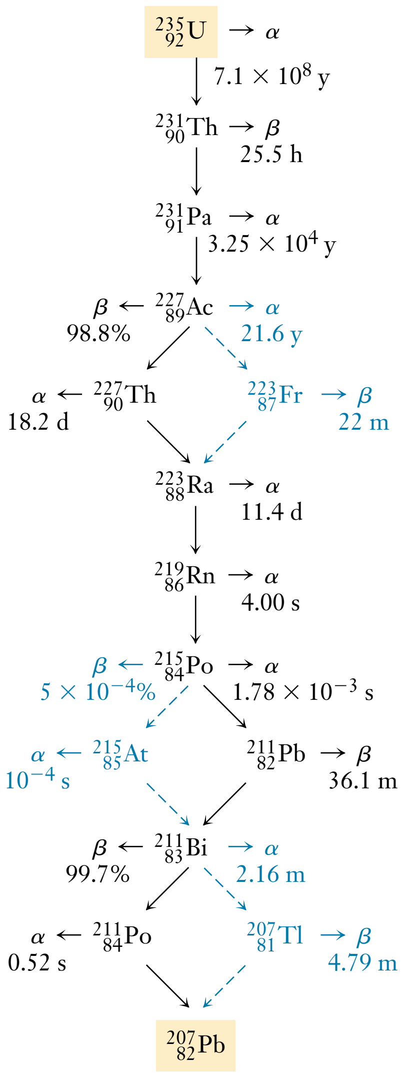
"Branchings" are possible at various points in the chain. That is, two successive decays may be replaced by alternative decays, but they always result in the same final product. There are also decay series of varying lengths starting with some of the artificially produced radionuclides (Section 26-13).

TABLE 26-4 *Emissions and Half-Lives of Members of Natural Radioactive Series*[*]

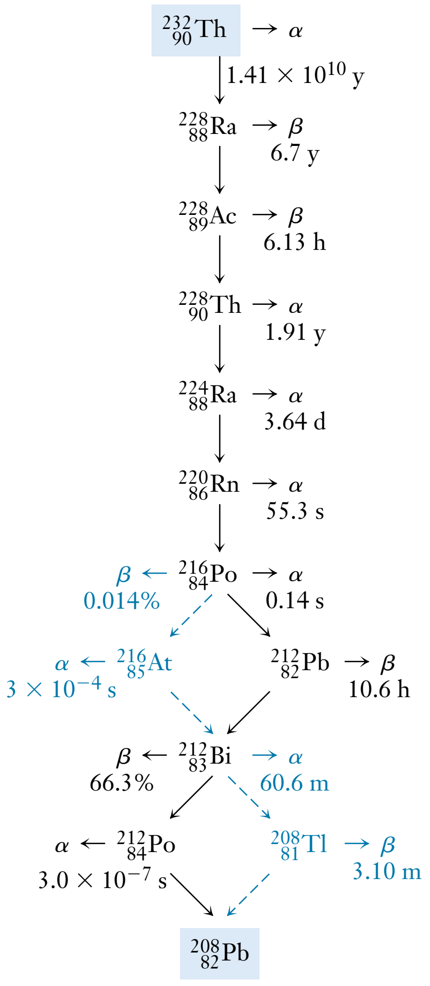
(a) ^{238}U Series



(b) ^{235}U Series



(c) ^{232}Th Series



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[*] *Abbreviations are y, year; d, day; m, minute; and s, second. Less prevalent decay branches are shown in blue.*

26-12 USES OF RADIONUCLIDES

Radionuclides have practical uses because they decay at known rates. Some applications make use of the radiation that is continuously emitted by radionuclides.

Radioactive Dating

The ages of articles of organic origin can be estimated by **radiocarbon dating.** The radioisotope carbon-14 is produced continuously in the upper atmosphere as nitrogen atoms capture cosmic-ray neutrons.

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

The carbon-14 atoms react with oxygen molecules to form $^{14}CO_2$. This process continually supplies the atmosphere with radioactive $^{14}CO_2$, which is removed from the atmosphere by photosynthesis. The intensity of cosmic rays is related to the sun's activity. As long as this remains constant, the amount of $^{14}CO_2$ in the atmosphere remains constant. $^{14}CO_2$ is incorporated into living organisms just as ordinary $^{12}CO_2$ is, so a certain fraction of all carbon atoms in living substances is carbon-14. This decays with a half-life of 5730 years.

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

After death, the plant no longer carries out photosynthesis, so it no longer takes up $^{14}CO_2$. Other organisms that consume plants for food stop doing so at death. The emissions from the ^{14}C in dead tissue then decrease with the passage of time. The activity per gram of carbon is a measure of the length of time elapsed since death. Comparison of ages of ancient trees calculated from ^{14}C activity with those determined by counting rings indicates that cosmic ray intensity has varied somewhat throughout history. The calculated ages can be corrected for these variations. The carbon-14 technique is useful only for dating objects less than 50,000 years old. Older objects have too little activity to be dated accurately.

The **potassium–argon** and **uranium–lead methods** are used for dating older objects. Potassium-40 decays to argon-40 with a half-life of 1.3 billion years.

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

Because of its long half-life, potassium-40 can be used to date objects up to 1 million years old by determination of the ratio of $^{40}_{19}K$ to $^{40}_{18}Ar$ in the sample. The uranium–lead method is based on the natural uranium-238 decay series, which ends with the production of stable lead-206. This method is used for dating uranium-containing minerals several billion years old because this series has an even longer half-life. All the ^{206}Pb in such minerals is assumed to have come from ^{238}U. Because of the very long half-life of $^{238}_{92}U$, 4.5 billion years, the amounts of intermediate nuclei can be neglected. A meteorite that was 4.6 billion years old fell in Mexico in 1969. Results of $^{238}U/^{206}Pb$ studies on such materials of extraterrestrial origin suggest that our solar system was formed several billion years ago.

In 1992, hikers in the Italian Alps found the remains of a man who had been frozen in a glacier for about 4000 years. This discovery is especially important because of the unusual preservation of tissues, garments, and personal belongings. Radiocarbon dating is used to estimate the ages of archaeological finds such as these.

In recent decades atmospheric testing of nuclear warheads has also caused fluctuations in the natural abundance of ^{14}C.

Gaseous argon is easily lost from minerals. Measurements based on the $^{40}K/^{40}Ar$ method may therefore not be as reliable as desired.

In Table 26-4(a) we see that the first step, the decay of ^{238}U, is the slowest step (longest half-life). We learned in Section 16-7 that the slowest step is the rate-determining step.

EXAMPLE 26-4 *Radiocarbon Dating*

A piece of wood taken from a cave dwelling in New Mexico is found to have a carbon-14 activity (per gram of carbon) only 0.636 times that of wood cut today. Estimate the age of the wood. The half-life of carbon-14 is 5730 years.

Plan

As we did in Example 26-3, we determine the specific rate constant k from the known half-life. The time required to reach the present fraction of the original activity is then calculated from the first-order decay equation.

Solution

First we find the first-order specific rate constant for ^{14}C.

$$t_{1/2} = \frac{0.693}{k} \qquad \text{or} \qquad k = \frac{0.693}{t_{1/2}} = \frac{0.693}{5730 \text{ y}} = 1.21 \times 10^{-4} \text{ y}^{-1}$$

The present ^{14}C activity, N (disintegrations per unit time), is 0.636 times the original activity, N_0.

$$N = 0.636 \, N_0$$

We substitute into the first-order decay equation

$$\ln\left(\frac{N_0}{N}\right) = kt$$

$$\ln\left(\frac{N_0}{0.636 \, N_0}\right) = (1.21 \times 10^{-4} \text{ y}^{-1})t$$

We cancel N_0 and solve for t.

$$\ln\left(\frac{1}{0.636}\right) = (1.21 \times 10^{-4} \text{ y}^{-1})t$$

$$0.452 = (1.21 \times 10^{-4} \text{ y}^{-1})t \qquad \text{or} \qquad t = 3.74 \times 10^3 \text{y (or 3740 y)}$$

You should now work Exercises 58 and 62.

EXAMPLE 26-5 *Uranium–Lead Dating*

A sample of uranium ore is found to contain 4.64 mg of ^{238}U and 1.22 mg of ^{206}Pb. Estimate the age of the ore. The half-life of ^{238}U is 4.51×10^9 years.

Plan

The original mass of ^{238}U is equal to the mass of ^{238}U remaining plus the mass of ^{238}U that decayed to produce the present mass of ^{206}Pb. We obtain the specific rate constant, k, from the known half-life. Then we use the ratio of original ^{238}U to remaining ^{238}U to calculate the time elapsed, with the aid of the first-order integrated rate equation.

Solution

First we calculate the amount of ^{238}U that must have decayed to produce 1.22 mg of ^{206}Pb, using the isotopic masses.

$$\underline{?} \text{ mg } ^{238}U = 1.22 \text{ mg } ^{206}Pb \times \frac{238 \text{ mg } ^{238}U}{206 \text{ mg } ^{206}Pb} = 1.41 \text{ mg } ^{238}U$$

Thus, the sample originally contained 4.64 mg + 1.41 mg = 6.05 mg of ^{238}U.

We next evaluate the specific rate (disintegration) constant, k.

$$t_{1/2} = \frac{0.693}{k} \qquad \text{so} \qquad k = \frac{0.693}{t_{1/2}} = \frac{0.693}{4.51 \times 10^9 \text{ y}} = 1.54 \times 10^{-10} \text{ y}^{-1}$$

Now we calculate the age of the sample, t.

$$\ln\left(\frac{A_0}{A}\right) = kt$$

$$\ln\left(\frac{6.05\text{ mg}}{4.64\text{ mg}}\right) = (1.54 \times 10^{-10}\text{ y}^{-1})t$$

$$\ln 1.30 = (1.54 \times 10^{-10}\text{ y}^{-1})t$$

$$\frac{0.262}{1.54 \times 10^{-10}\text{ y}^{-1}} = t \qquad \text{or} \qquad t = 1.70 \times 10^{9}\text{ years}$$

The ore is approximately 1.7 billion years old.

You should now work Exercise 76.

Medical Uses

The use of cobalt radiation treatments for cancerous tumors was described in Example 26-3. Several other nuclides are used as **radioactive tracers** in medicine. Radioisotopes of an element have the same chemical properties as stable isotopes of the same element, so they can be used to "label" the presence of an element in compounds. A radiation detector can be used to follow the path of the element throughout the body. Modern computer-based techniques allow construction of an image of the area of the body where the radioisotope is concentrated. Salt solutions containing ^{24}Na can be injected into the bloodstream to follow the flow of blood and locate obstructions in the circulatory system. Thallium-201 tends to concentrate in healthy heart tissue, whereas technetium-99 concentrates in abnormal heart tissue. The two can be used together to survey damage from heart disease.

Iodine-123 concentrates in the thyroid gland, liver, and certain parts of the brain. This radioisotope is used to monitor goiter and other thyroid problems, as well as liver and brain tumors. One of the most useful radioisotopes in medical applications in recent years is an isotope of technetium, an element that does not occur naturally on earth. This isotope, ^{99m}Tc, is produced by the decay of ^{99}Mo.

This isotope of iodine is also used in the treatment of thyroid cancer. Because of its preferential absorption in the thyroid gland, it delivers radiation where it is needed.

$$^{99}\text{Mo} \longrightarrow {}^{99m}\text{Tc} + {}^{\ 0}_{-1}\beta$$

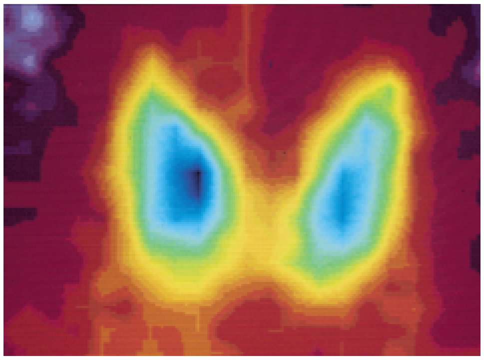
The "m" in the superscript of ^{99m}Tc stands for "metastable." This isotope is formed at a high energy, and then slowly decays with a half-life of 6.0 hours by emitting gamma radiation.

$$^{99m}\text{Tc} \longrightarrow {}^{99}\text{Tc} + \gamma$$

The "Chemistry in Use" feature on the textbook Web site describes some medical applications of ^{99m}Tc.

Another form of imaging that uses positron emitters (Section 26-6) is **positron emission tomography (PET).** Isotopes commonly used in this technique are short-lived positron emitters such as ^{11}C ($t_{1/2}$ = 20.4 min), ^{13}N ($t_{1/2}$ = 9.98 min), ^{15}O ($t_{1/2}$ = 2.05 min), and ^{18}F ($t_{1/2}$ = 110 min). The appropriate isotope is incorporated into a chemical that is normally taken up by the tissues that are being investigated, for instance carbon dioxide or glucose including ^{11}C or water including ^{15}O. This radioactive chemical can then be administered by inhalation or injection. The patient is then placed into a cylindrical gamma ray detector. When these radioisotopes decay, the emitted positron quickly encounters an electron and reacts in a matter–antimatter annihilation, to give off two gamma rays in opposite directions.

$${}^{\ 0}_{+1}\beta + {}^{\ 0}_{-1}\beta \longrightarrow 2\gamma$$



A scan of the radiation released by radioactive iodine concentrated in thyroid tissue gives an image of the thyroid gland.

The directions of emission of millions of such pairs of gamma rays detected over several minutes allow for a computer reconstruction of an image of the tissue containing the positron emitter.

The energy produced by the decay of plutonium-238 is converted into electrical energy in heart pacemakers. The relatively long half-life of the isotope allows the device to be used for 10 years before replacement.

Agricultural Uses

The procedure works because the female flies mate only once. In an area highly populated with sterile males, the probability of a "productive" mating is very small.

The pesticide DDT is toxic to humans and animals repeatedly exposed to it. DDT persists in the environment for a long time. It concentrates in fatty tissues. The DDT once used to control the screwworm fly was replaced by a radiological technique. Irradiating the male flies with gamma rays alters their reproductive cells, sterilizing them. When great numbers of sterilized males are released in an infested area, they mate with females, who, of course, produce no offspring. This results in the reduction and eventual disappearance of the population.

Labeled fertilizers can also be used to study nutrient uptake by plants and to study the growth of crops. Gamma irradiation of some foods allows them to be stored for longer periods without spoiling. For example, it retards the sprouting of potatoes and onions. In 1999, the FDA approved gamma irradiation of red meat as a way to curb food-borne illnesses. In addition to significantly reducing levels of *Listeria*, *Salmonella*, and other bacteria, such irradiation is currently the only known way to completely eliminate the dangerous strain of *Escherichia coli* bacteria in red meat. Absorption of gamma rays by matter produces no radioactive nuclides, so foods preserved in this way are *not* radioactive.

Industrial Uses

There are many applications of radiochemistry in industry and engineering. When great precision is required in the manufacture of strips or sheets of metal of definite thicknesses, the penetrating powers of various kinds of radioactive emissions are utilized. The thickness of the metal is correlated with the intensity of radiation passing through it. The flow

A weak radioactive source such as americium is used in some smoke detectors. Radiation from the source ionizes the air to produce a weak current. Smoke particles interrupt the current flow by attracting the ions. This decrease in current triggers the alarm.

Moderate irradiation with gamma rays from radioactive isotopes has kept the strawberries at the right fresh for 15 days, while those at the left are moldy. Such irradiation kills mold spores but does no damage to the food. The food does *not* become radioactive.

of a liquid or gas through a pipeline can be monitored by injecting a sample containing a radioactive substance. Leaks in pipelines can also be detected in this way.

In addition to the ^{238}Pu-based heart pacemaker already mentioned, lightweight, portable power packs that use radioactive isotopes as fuel have been developed for other uses. Polonium-210, californium-242, and californium-244 have been used in such generators to power instruments for space vehicles and in polar regions. These generators can operate for years with only a small loss of power.

Research Applications

The pathways of chemical reactions can be investigated using radioactive tracers. When radioactive $^{35}S^{2-}$ ions are added to a saturated solution of cobalt sulfide in equilibrium with solid cobalt sulfide, the solid becomes radioactive. This shows that sulfide ion exchange occurs between solid and solution in the solubility equilibrium.

$$CoS(s) \rightleftharpoons Co^{2+}(aq) + S^{2-}(aq) \qquad K_{sp} = 8.7 \times 10^{-23}$$

Photosynthesis is the process by which the carbon atoms in CO_2 are incorporated into glucose, $C_6H_{12}O_6$, in green plants.

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

The process is more complex than the net equation implies; it actually occurs in many steps and produces a number of intermediate products. By using labeled $^{14}CO_2$, we can identify the intermediate molecules. They contain the radioactive ^{14}C atoms.

26-13 ARTIFICIAL TRANSMUTATIONS OF ELEMENTS

The first artificially induced nuclear reaction was carried out by Rutherford in 1915. He bombarded nitrogen-14 with alpha particles to produce an isotope of oxygen and a proton.

$$^{14}_{7}N + ^{4}_{2}\alpha \longrightarrow ^{1}_{1}H + ^{17}_{8}O$$

Such reactions are often indicated in abbreviated form, with the bombarding particle and emitted subsidiary particles shown parenthetically between the parent and daughter nuclei.

$$^{14}_{7}N\ (^{4}_{2}\alpha,\ ^{1}_{1}p)\ ^{17}_{8}O$$

Several thousand different artificially induced reactions have been carried out with bombarding particles such as neutrons, protons, deuterons ($^{2}_{1}H$), alpha particles, and other small nuclei.

Bombardment with Positive Ions

A problem arises with the use of positively charged nuclei as projectiles. For a nuclear reaction to occur, the bombarding nuclei must actually collide with the target nuclei, which are also positively charged. Collisions cannot occur unless the projectiles have sufficient kinetic energy to overcome coulombic repulsion. The required kinetic energies increase with increasing atomic numbers of the target and of the bombarding particle.

Particle accelerators called **cyclotrons** (atom smashers) and **linear accelerators** have overcome the problem of repulsion. A cyclotron (Figure 26-7) consists of two hollow, D-shaped electrodes called "dees." Both dees are in an evacuated enclosure between the poles of an electromagnet. The particles to be accelerated are introduced at the center in the

The first cyclotron was constructed by E. O. Lawrence (1901–1958) and M. S. Livingston at the University of California in 1930.

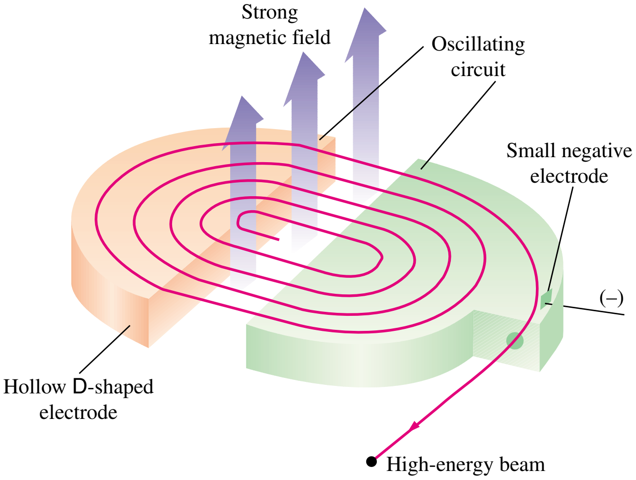


Figure 26-7 Schematic representation of a cyclotron.

The path of the particle is initially circular because of the interaction of the particle's charge with the electromagnet's field. As the particle gains energy, the radius of the path increases, and the particle spirals outward.

gap between the dees. The dees are connected to a source of high-frequency alternating current that keeps them oppositely charged. The positively charged particles are attracted toward the negative dee. The magnetic field causes the path of the charged particles to curve 180° to return to the space between the dees. Then the charges are reversed on the dees, so the particles are repelled by the first dee (now positive) and attracted to the second. This repeated process is synchronized with the motion of the particles. They accelerate along a spiral path and eventually emerge through an exit hole oriented so that the beam hits the target atoms (Figure 26-8).

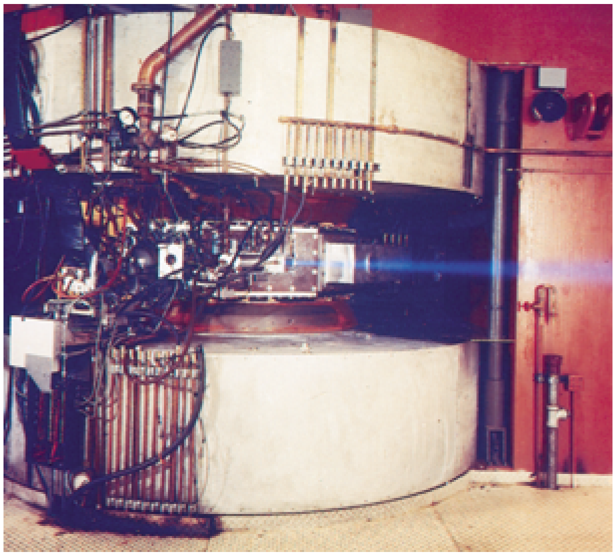


Figure 26-8 A beam of protons (bright blue stream) from a cyclotron at the Argonne National Laboratory. Nuclear reactions take place when protons and other atomic particles strike the nuclei of atoms.

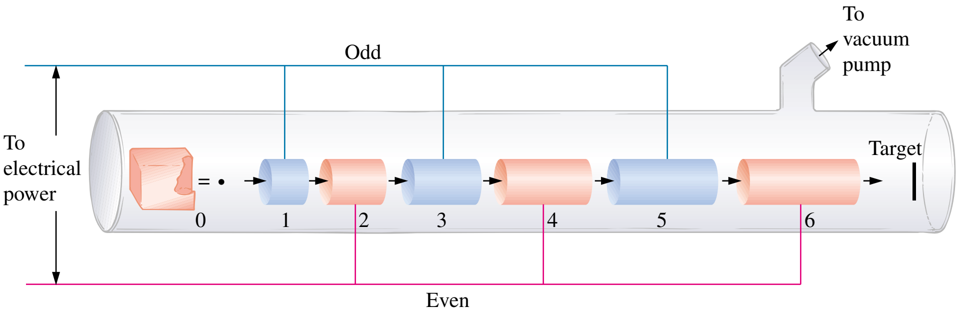


Figure 26-9 Diagram of an early type of linear accelerator. An alpha emitter is placed in the container at the left. Only those α-particles that happen to be emitted in line with the series of accelerating tubes can escape.

In a linear accelerator the particles are accelerated through a series of tubes within an evacuated chamber (Figure 26-9). The odd-numbered tubes are at first negatively charged and the even ones positively charged. A positively charged particle is attracted toward the first tube. As it passes through that tube, the charges on the tubes are reversed so that the particle is repelled out of the first tube (now positive) and toward the second (negative) tube. As the particle nears the end of the second tube, the charges are again reversed. As this process is repeated, the particle is accelerated to very high velocities. The polarity is changed at constant frequency, so subsequent tubes are longer to accommodate the increased distance traveled by the accelerating particle per unit time. The bombardment target is located outside the last tube. If the initial polarities are reversed, negatively charged particles can also be accelerated. The longest linear accelerator, completed in 1966 at Stanford University, is about 2 miles long. It is capable of accelerating electrons to energies of nearly 20 GeV.

The first linear accelerator was built in 1928 by a German physicist, Rolf Wideroe.

Many nuclear reactions have been induced by such bombardment techniques. At the time of development of particle accelerators, there were a few gaps among the first 92 elements in the periodic table. Particle accelerators were used between 1937 and 1941 to synthesize three of the four "missing" elements: numbers 43 (technetium), 85 (astatine), and 87 (francium).

One gigaelectron volt (GeV) = 1×10^9 eV = 1.60×10^{-10} J. This is sometimes called 1 billion electron volts (BeV) in the United States.

An aerial view of the particle accelerator dedicated in 1978 at the Fermi National Accelerator Laboratory (Fermilab), near Batavia, Illinois. This proton accelerator, 4 miles in circumference, accelerates protons to energies of 1 trillion electron volts. Construction of a vastly larger accelerator known as the superconducting supercollider, or SSC, was begun near Waxahachie, Texas. However, this project was abandoned in 1994 when the U.S. Congress voted to discontinue funding for it.

$$\begin{aligned} {}^{96}_{42}\mathrm{Mo} + {}^{2}_{1}\mathrm{H} &\longrightarrow {}^{97}_{43}\mathrm{Tc} + {}^{1}_{0}n \\ {}^{209}_{83}\mathrm{Bi} + {}^{4}_{2}\alpha &\longrightarrow {}^{210}_{85}\mathrm{At} + 3\,{}^{1}_{0}n \\ {}^{230}_{90}\mathrm{Th} + {}^{1}_{1}p &\longrightarrow {}^{223}_{87}\mathrm{Fr} + 2\,{}^{4}_{2}\alpha \end{aligned}$$

Many hitherto unknown, unstable, artificial isotopes of known elements have also been synthesized so that their nuclear structures and behavior could be studied.

Neutron Bombardment

Neutrons bear no charge, so they are not repelled by nuclei as positively charged projectiles are. They do not need to be accelerated to produce bombardment reactions. Neutron beams can be generated in several ways. A frequently used method involves bombardment of beryllium-9 with alpha particles.

$${}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\alpha \longrightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n$$

Nuclear reactors (Section 26-15) are also used as neutron sources. Neutrons ejected in nuclear reactions usually possess high kinetic energies and are called **fast neutrons.** When they are used as projectiles they cause reactions, such as (n, p) or (n, α) reactions, in which subsidiary particles are ejected. The fourth "missing" element, number 61 (promethium), was synthesized by fast neutron bombardment of neodymium-142.

Fast neutrons move so rapidly that they are likely to pass right through a target nucleus without reacting. Hence, the probability of a reaction is low, even though the neutrons may be very energetic.

$${}^{142}_{60}\mathrm{Nd} + {}^{1}_{0}n \longrightarrow {}^{143}_{61}\mathrm{Pm} + {}^{0}_{-1}\beta$$

Slow neutrons ("thermal" neutrons) are produced when fast neutrons collide with **moderators** such as hydrogen, deuterium, oxygen, or the carbon atoms in paraffin. These neutrons are more likely to be captured by target nuclei. Bombardments with slow neutrons can cause neutron-capture (n, γ) reactions.

$${}^{200}_{80}\mathrm{Hg} + {}^{1}_{0}n \longrightarrow {}^{201}_{80}\mathrm{Hg} + {}^{0}_{0}\gamma$$

Slow neutron bombardment also produces the $^{3}\mathrm{H}$ isotope (tritium).

$${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}n \longrightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha \qquad (n,\ \alpha)\ \text{reaction}$$

E. M. McMillan (1907–1991) discovered the first transuranium element, neptunium, in 1940 by bombarding uranium-238 with slow neutrons.

$${}^{238}_{92}\mathrm{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{92}\mathrm{U} + {}^{0}_{0}\gamma$$

$${}^{239}_{92}\mathrm{U} \longrightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\beta$$

Several additional elements have been prepared by neutron bombardment or by bombardment of the nuclei so produced with positively charged particles. Some examples are

$$\left.\begin{aligned} {}^{238}_{92}\mathrm{U} + {}^{1}_{0}n &\longrightarrow {}^{239}_{92}\mathrm{U} + {}^{0}_{0}\gamma \\ {}^{239}_{92}\mathrm{U} &\longrightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\beta \\ {}^{239}_{93}\mathrm{Np} &\longrightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\beta \end{aligned}\right\} \quad \text{plutonium}$$

$$\begin{aligned} {}^{239}_{94}\mathrm{Pu} + {}^{4}_{2}\alpha &\longrightarrow {}^{242}_{96}\mathrm{Cm} + {}^{1}_{0}n && \text{curium} \\ {}^{246}_{96}\mathrm{Cm} + {}^{12}_{6}\mathrm{C} &\longrightarrow {}^{254}_{102}\mathrm{No} + 4\,{}^{1}_{0}n && \text{nobelium} \\ {}^{252}_{98}\mathrm{Cf} + {}^{10}_{5}\mathrm{B} &\longrightarrow {}^{257}_{103}\mathrm{Lr} + 5\,{}^{1}_{0}n && \text{lawrencium} \end{aligned}$$

26-14 NUCLEAR FISSION

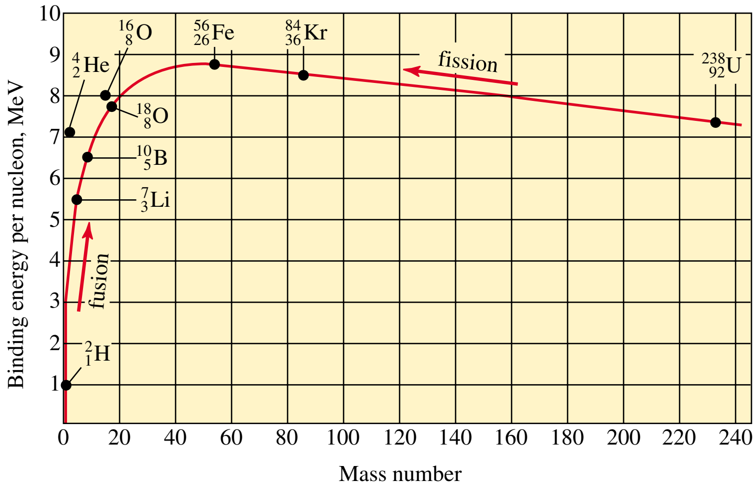
Isotopes of some elements with atomic numbers above 80 are capable of undergoing fission in which they split into nuclei of intermediate masses and emit one or more neutrons. Some fissions are spontaneous; others require that the activation energy be supplied by bombardment. A given nucleus can split in many different ways, liberating enormous amounts of energy. Some of the possible fissions that can result from bombardment of fissionable uranium-235 with fast neutrons follow. The uranium-236 is a short-lived intermediate.

$$
{}^{235}_{92}\mathrm{U} + {}^{1}_{0}n \longrightarrow {}^{236}_{92}\mathrm{U}
\begin{array}{l}
\nearrow {}^{160}_{62}\mathrm{Sm} + {}^{72}_{30}\mathrm{Zn} + 4\,{}^{1}_{0}n + \text{energy} \\
\nearrow {}^{146}_{57}\mathrm{La} + {}^{87}_{35}\mathrm{Br} + 3\,{}^{1}_{0}n + \text{energy} \\
\longrightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}n + \text{energy} \\
\searrow {}^{144}_{55}\mathrm{Cs} + {}^{90}_{37}\mathrm{Rb} + 2\,{}^{1}_{0}n + \text{energy} \\
\searrow {}^{144}_{54}\mathrm{Xe} + {}^{90}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}n + \text{energy}
\end{array}
$$

Recall that the binding energy is the amount of energy that must be supplied to the nucleus to break it apart into subatomic particles. Figure 26-10 is a plot of binding energy per nucleon versus mass number. It shows that atoms of intermediate mass number have the highest binding energies per nucleon; therefore, they are the most stable. Thus, fission is an energetically favorable process for heavy atoms, because atoms with intermediate masses and greater binding energies per nucleon are formed.

The term “nucleon” refers to a nuclear particle, either a neutron or a proton.

Which isotopes of which elements undergo fission? Experiments with particle accelerators have shown that every element with an atomic number of 80 or more has one or more isotopes capable of undergoing fission, provided they are bombarded at the right energy. Nuclei with atomic numbers between 89 and 98 fission spontaneously with long half-lives of 10^4 to 10^{17} years. Nuclei with atomic numbers of 98 or more fission spontaneously with shorter half-lives of a few milliseconds to 60.5 days. One of the *natural* decay modes of the transuranium elements is via spontaneous fission. In fact, all known nuclides



1 MeV = 1.60×10^{-13} J

Figure 26-10 Variation in nuclear binding energy with atomic mass. The most stable nucleus is ${}^{56}_{26}\mathrm{Fe}$, with a binding energy of 8.80 MeV per nucleon.

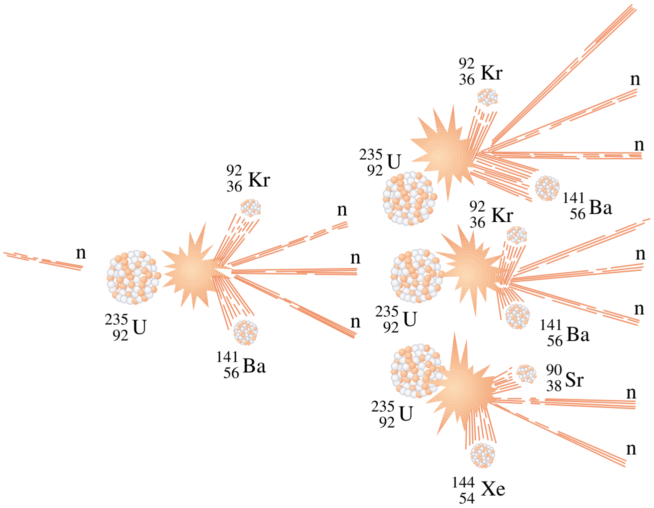


Figure 26-11 A self-propagating nuclear chain reaction. A stray neutron induces a single fission, liberating more neutrons. Each of them induces another fission, each of which is accompanied by release of two or three neutrons. The chain continues to branch in this way, very quickly resulting in an explosive rate of fission.

with *mass numbers* greater than 250 do this because they are too big to be stable. Most nuclides with mass numbers between 225 and 250 do not undergo fission spontaneously (except for a few with extremely long half-lives). They can be induced to undergo fission when bombarded with particles of relatively low kinetic energies. Particles that can supply the required activation energy include neutrons, protons, alpha particles, and fast electrons. For nuclei lighter than mass 225, the activation energy required to induce fission rises very rapidly.

In Section 26-2 we discussed the stability of nuclei with even numbers of protons and even numbers of neutrons. We should not be surprised to learn that both ^{233}U and ^{235}U can be excited to fissionable states by slow neutrons much more easily than ^{238}U, because they are less stable. It is so difficult to cause fission in ^{238}U that this isotope is said to be "nonfissionable."

Typically, two or three neutrons are produced per fission reaction. These neutrons can collide with other fissionable atoms to repeat the process. If sufficient fissionable material, the **critical mass,** is contained in a small enough volume, a sustained chain reaction can result. If too few fissionable atoms are present, most of the neutrons escape and no chain reaction occurs. Figure 26-11 depicts a fission chain reaction.

In an atomic bomb, two subcritical portions of fissionable material are brought together to form a critical mass. A nuclear fission explosion results. A tremendous amount of heat energy is released, as well as many radionuclides whose effects are devastating to life and the environment. The radioactive dust and debris are called **fallout.**

The launching of the nuclear submarine *Hyman G. Rickover* into the Thames River in Connecticut (August 27, 1983).

26-15 NUCLEAR FISSION REACTORS

In a nuclear fission reactor, the fission reaction is controlled by inserting materials to absorb some of the neutrons so that the mixture does not explode. The energy that is produced can be safely used as a heat source in a power plant.

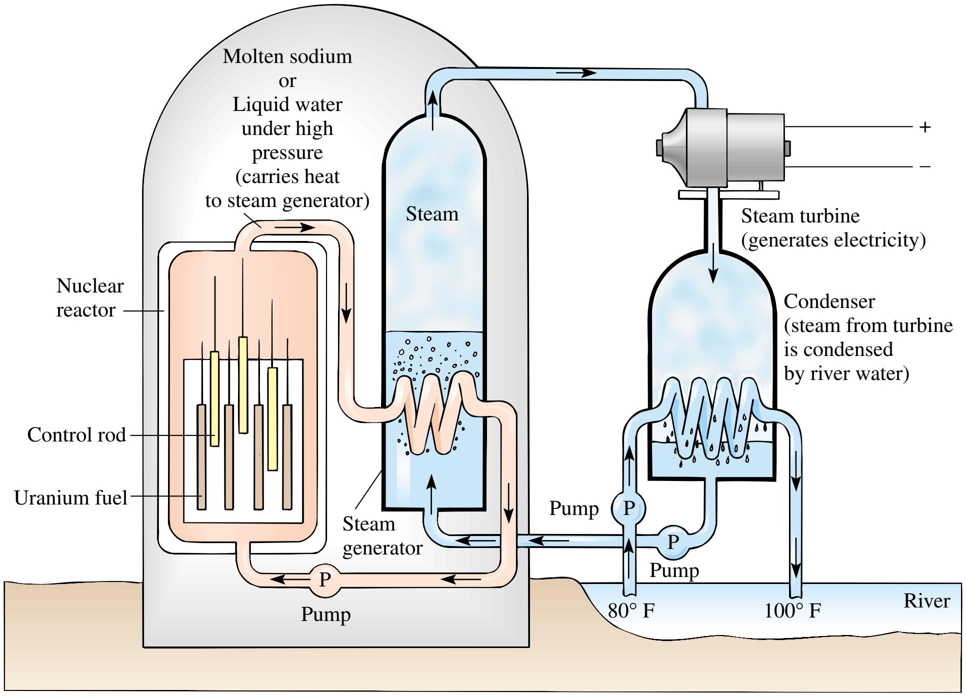


Figure 26-12 A schematic diagram of a light water reactor plant. This design includes two closed loops of water. The water that carries heat from the reactor to the steam generator is in a closed loop and is not released to the environment.

Light Water Reactors

Most commercial nuclear power plants in the United States are "light water" reactors, moderated and cooled by ordinary water. Figure 26-12 is a schematic diagram of a light water reactor plant. The reactor core at the left replaces the furnace in which coal, oil, or natural gas is burned in a fossil fuel plant. Such a fission reactor consists of five main components: (1) fuel, (2) moderator, (3) control rods, (4) cooling system, and (5) shielding.

Fuel

Rods of U_3O_8 enriched in uranium-235 serve as the fuel. Unfortunately, uranium ores contain only about 0.7% $^{235}_{92}\text{U}$. Most of the rest is nonfissionable $^{238}_{92}\text{U}$. The enrichment is done in processing and reprocessing plants by separating gaseous $^{235}\text{UF}_6$ from $^{238}\text{UF}_6$, prepared from the ore. Separation by diffusion is based on the slower rates of diffusion of heavier gas molecules (Section 12-14). Another separation procedure uses the ultracentrifuge.

A potentially more efficient method of enrichment would involve the use of sophisticated tunable lasers to ionize $^{235}_{92}\text{U}$ selectively and not $^{238}_{92}\text{U}$. The ionized $^{235}_{92}\text{U}$ could then be made to react with negative ions to form another compound, easily separated from the mixture. For this method to work, we must construct lasers capable of producing radiation monochromatic enough to excite one isotope and not the other—a difficult challenge.

Uranium is deposited on the negative electrode in the electrorefining phase of fuel reprocessing. The crystalline mass is about 97% LiCl and KCl. The remaining 3% uranium chloride is responsible for the amethyst color.

Moderator

The fast neutrons ejected during fission are too energetic to be absorbed efficiently by other nuclei. Thus, they must be slowed by collisions with atoms of comparable mass that do not absorb them, called **moderators.** The most commonly used moderator is ordinary water, although graphite is sometimes used. The most efficient moderator is helium, which slows neutrons but does not absorb them all. The next most efficient is "heavy water" (deuterium oxide, ${}^{2}_{1}H_2O$ or ${}^{2}_{1}D_2O$). This is so expensive that it has been used chiefly in research reactors. A Canadian-designed power reactor that uses heavy water is more neutron-efficient than light water reactors. This design is the basis of the many reactors in Canada.

Control Rods

Cadmium and boron are good neutron absorbers.

$$ {}^{10}_{5}\mathrm{B} + {}^{1}_{0}n \longrightarrow {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\alpha $$

The rate of a fission reaction is controlled by the use of movable control rods, usually made of cadmium or boron steel. They are automatically inserted in or removed from spaces between the fuel rods. The more neutrons absorbed by the control rods, the fewer fissions occur and the less heat is produced. Hence, the heat output is governed by the control system that operates the rods.

Cooling System

Two cooling systems are needed. First, the moderator itself serves as a coolant for the reactor. It transfers fission-generated heat to a steam generator. This converts water to steam. The steam then goes to turbines that drive generators to produce electricity. Another coolant (river water, sea water, or recirculated water) condenses the steam from the turbine, and the condensate is then recycled into the steam generator.

The danger of meltdown arises if a reactor is shut down quickly. The disintegration of radioactive fission products still goes on at a furious rate, fast enough to overheat the fuel elements and to melt them. So it is not enough to shut down the fission reaction. Efficient cooling must be continued until the short-lived isotopes are gone and the heat from their disintegration is dissipated. Only then can the circulation of cooling water be stopped.

The 1979 accident at Three Mile Island, near Harrisburg, Pennsylvania, was due to stopping the water pumps too soon *and* the inoperability of the emergency pumps. A combination of mechanical malfunctions, errors, and carelessness produced the overheating that damaged the fuel assembly. It did not and *could not explode*, although melting of the core material did occur. The 1986 accident at Chernobyl, in the USSR, involved a reactor of a very different design and was far more serious. The effects of that disaster will continue for decades.

The neutrons are the worst problem of radiation. The human body contains a high percentage of H_2O, which absorbs neutrons very efficiently. A new weapon, the neutron bomb, produces massive amounts of neutrons and so is effective against people, but it does not produce the long-lasting radiation of the fission atomic bomb.

Shielding

It is essential that people and the surrounding countryside be adequately shielded from possible exposure to radioactive nuclides. The entire reactor is enclosed in a steel containment vessel. This is housed in a thick-walled concrete building. The operating personnel are further protected by a so-called biological shield, a thick layer of organic material made of compressed wood fibers. This absorbs the neutrons and beta and gamma rays that would otherwise be absorbed in the human body.

Breeder Reactors

The possibility of shortages in the known supply of ${}^{235}_{92}U$ has led to the development of **breeder reactors,** which can manufacture more fuel than they use. A breeder reactor is designed not only to generate electrical power but also to maximize neutron capture in the core by ${}^{238}_{92}U$. The fuel of a typical breeder reactor consists of the abundant but nonfissionable isotope ${}^{238}_{92}U$ mixed with ${}^{235}_{92}U$ or ${}^{239}_{94}Pu$, which produce neutrons when they undergo fission. Some of these neutrons are absorbed by ${}^{238}_{92}U$ to form ${}^{239}_{92}U$. This unstable uranium isotope soon leads, after two steps of beta emission to ${}^{239}_{94}Pu$.

$${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \xrightarrow[t_{1/2} = 23.4 \text{ min}]{\beta \text{ decay}} {}^{239}_{93}Np \xrightarrow[t_{1/2} = 2.35 \text{ days}]{\beta \text{ decay}} {}^{239}_{94}Pu$$

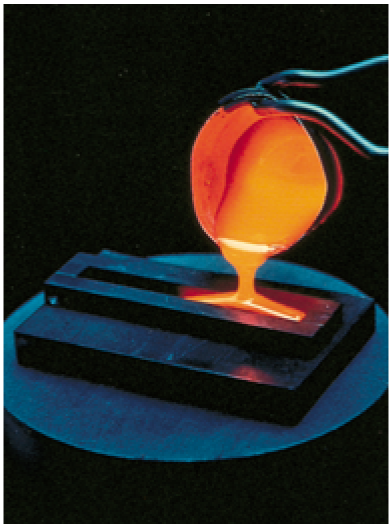
This fissionable ${}^{239}_{94}Pu$ can then be used as fuel in a reactor.

For every ${}^{235}_{92}U$ or ${}^{239}_{94}Pu$ nucleus that undergoes fission, more than one neutron is captured by ${}^{238}_{92}U$ to produce ${}^{239}_{94}Pu$. Thus, the breeder reactor can produce more fissionable material than it consumes. After about 7 years, enough ${}^{239}_{94}Pu$ can be collected to fuel a new reactor *and* to refuel the original one.

Nuclear Power: Hazards and Benefits

Controlled fission reactions in nuclear reactors are of great use and even greater potential. The fuel elements of a nuclear reactor have neither the composition nor the extremely compact arrangement of the critical mass of a bomb. Thus, no possibility of nuclear explosion exists. However, various dangers are associated with nuclear energy generation. The possibility of "meltdown" has been discussed with respect to cooling systems in light water reactors. Proper shielding precautions must be taken to ensure that the radionuclides produced are always contained within vessels from which neither they nor their radiations can escape. Long-lived radionuclides from spent fuel must be stored underground in heavy, shock-resistant containers until they have decayed to the point that they are no longer biologically harmful. As examples, strontium-90 ($t_{1/2}$ = 28 years) and plutonium-239 ($t_{1/2}$ = 24,000 years) must be stored for 280 years and 240,000 years, respectively, before they lose 99.9% of their activities. Critics of nuclear energy contend that the containers could corrode over such long periods, or burst as a result of earth tremors, and that transportation and reprocessing accidents could cause environmental contamination with radionuclides. They claim that river water used for cooling is returned to the rivers with too much heat (thermal pollution), thus disrupting marine life. (It should be noted, though, that fossil fuel electric power plants cause the same thermal pollution for the same amount of electricity generated.) The potential for theft also exists. Plutonium-239, a fissionable material, could be stolen from reprocessing plants and used to construct atomic weapons.

Proponents of the development of nuclear energy argue that the advantages far outweigh the risks. Nuclear energy plants do not pollute the air with oxides of sulfur, nitrogen, carbon, and particulate matter, as fossil fuel electric power plants do. The big advantage of nuclear fuels is the enormous amount of energy liberated per unit mass of fuel. At present, nuclear reactors provide about 22% of the electrical energy consumed in the United States. In some parts of Europe, where natural resources of fossil fuels are scarcer, the utilization of nuclear energy is higher. For instance, in France and Belgium, more than 80% of electrical energy is produced from nuclear reactors. With rapidly declining fossil fuel reserves, it appears likely that nuclear energy and solar energy will become increasingly important. Intensifying public concerns about nuclear power, however, may mean that further growth in energy production using nuclear power in the United States must await technological developments to overcome the remaining hazards.



Nuclear waste may take centuries to decompose, so we cannot afford to take risks in its disposal. Suggested approaches include casting it into ceramics, as shown here, to eliminate the possibility of the waste dissolving in ground water. The encapsulated waste could then be deposited in underground salt domes. Located in geologically stable areas, such salt domes have held petroleum and compressed natural gas trapped for millions of years. The political problems of nuclear waste disposal are at least as challenging as the technological ones. Refer to the Chemistry in Use box entitled "Managing Nuclear Wastes" in this chapter.

CHEMISTRY IN USE *The Environment*

Managing Nuclear Wastes

Some may consider a career in managing nuclear waste as being just about the worst job anyone would ever want, but hundreds of technically trained people have spent years working to solve the problems associated with nuclear power. The major part of the continuing challenge is political. Nuclear power plants generate about 23% of the electricity in the United States. Most of the high-level nuclear waste (HLW) that is generated from nuclear power plants—in the form of spent nuclear fuel (SNF)—is generated where many people live, in the eastern half of the United States. The safest place for a repository is away from people, in a dry, remote location, probably in the western United States, where there are fewer people (and fewer votes!).

SNF constitutes about half of the HLW in the United States. The other half comes from the construction and existence of nuclear weapons. All HLW is a federal responsibility. About 90% of the radioactivity in nuclear waste is from HLW. The largest volume of nuclear waste is low-level waste (LLW) and that is mostly the responsibility of the state (or group of states) in which it is generated. LLW is rather awkwardly defined, being everything that is neither HLW nor defense waste and consists of wastes from hospitals; pharmaceutical labs; research labs; and the moon suits, tools, and the like from nuclear power plants. In the eastern United States, most of the LLW is in the form of the plastic beads that make up the ion-exchange resins used in nuclear power plants to clean various loops of water used in power production.

Plutonium wastes from the Los Alamos National Laboratory in northern New Mexico were trucked for the first time to the federal Waste Isolation Pilot Plant in Carlsbad in March 1999. The 600 pounds (270 kg) of waste consisted of plutonium-contaminated clothing and metal cans, packed in boxes and stainless steel containers. Most of the material was from the laboratory's manufacture of nuclear batteries used in NASA's deep space probes and will be buried in the depository carved out of ancient salt caverns about half a mile (0.8 km) below ground.

Most current attention is focused on SNF for two reasons. It is highly radioactive and it can be seen as a "local" problem because it is made where electric customers live. Europe has reprocessing plants to recover the unused fissionable material for new fuel, but the United States disallowed the practice in the 1970s. This partially explains why spent fuel rods have been piling up at U.S. nuclear plants.

Research has focused on Yucca Mountain, Nevada, at the western edge of the National Test Site, for its suitability as a nuclear waste repository for SNF and some defense waste. Many political leaders of Nevada strongly oppose this plan, and they seriously question that nuclear waste can be safely kept out of the human environment for 10,000 years, as is required under the federal Nuclear Waste Policy Act.

The numbers describing SNF are barely comprehensible to most people. The volume of all existing SNF could cover a large football stadium to a depth of 4 or 5 feet, but no sensible person would want to confine that much heat and radioactivity to one place. Another description is the 70,000 metric tons of SNF generated to date in power plants, a figure that means little unless one understands thousand-kilogram quantities and knows the density of fission products. The plans for Yucca Mountain, should it be found to be a suitable site, will hold in its many miles of tunnels and caverns, all the SNF so far generated and that expected to be generated in the next few years.

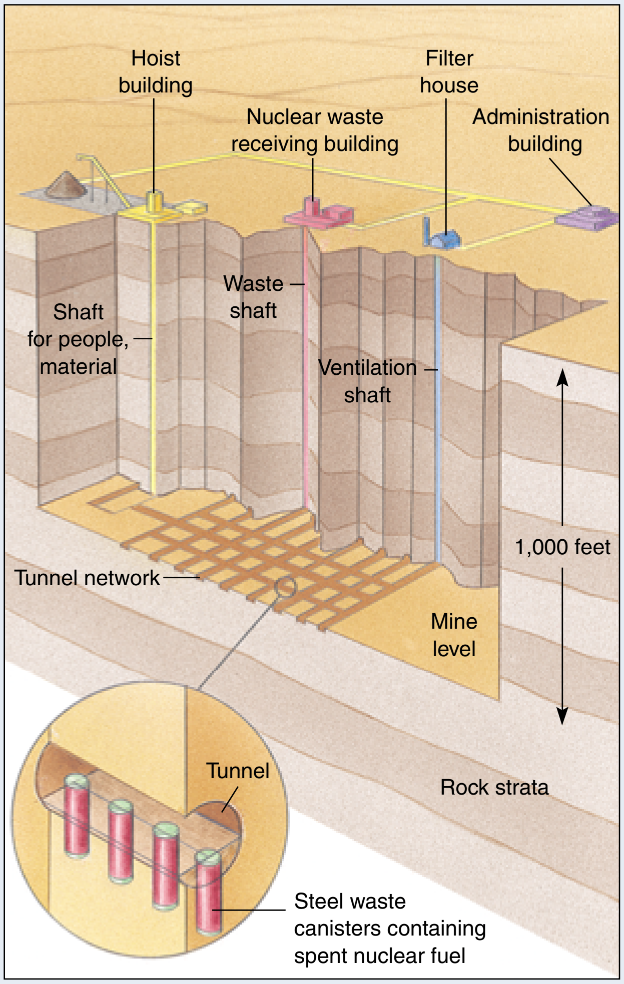
The SNF portion of HLW can be understood by chemists who see in it nearly every element on the periodic chart of the elements. After a ^{235}U nucleus undergoes fission and releases its excess nuclear binding energy, it leaves a pair of new atoms. These fission products are like newly born forms of the elements that are already well known and, like newborns, are unstable until they mature. There are about 1000 isotopes of about 100 different elements in SNF, and most are radioactive. They decay into stable elements at different rates, giving off alpha, beta, and gamma emissions. It will take about 7000 years until the SNF will be only as radioactive as the rocks and minerals that make up our planet.

These fission products are housed in long titanium rods, each about the diameter of a pencil, that constitute the fuel assembly in a nuclear power plant. Workers wearing gloves can handle fuel assemblies before fissioning occurs. But after removal from a nuclear reactor, the fuel assembly is stored in a cooling pool of water beside the reactor for at least 10 years. If the power plant has a small cooling pool, on-site storage of the oldest fuel assemblies occurs in specially constructed concrete casks until the federal government takes ownership and finds a suitable place for it. Fuel rod consolidation is sometimes practiced to save space because much of the space in a fuel assembly was present so power plant water could easily pass and pick up the heat generated by the fission process.

Other options that have been considered for HLW include outer space ejection and burial in deep ocean trenches. The consensus worldwide is that deep geological isolation is the best option. The United States leads in studying a specific site, Yucca Mountain. In other countries, even those generating a larger percentage of their power with nuclear power, the small volumes awaiting burial allow them more time to choose a location.

For the student who likes a challenge, nuclear waste management is a good one. From the cost-benefit analyses of all the ways we make and use electrical power to the way the wastes are handled, one can find an issue or a career. Here are a few key issues to study and discuss:

- *Transportation of the waste to its repository.* Should it be done by rail or by truck? Should there be public notification of the time of transport? Are there response measures in place in case of an accident?
- *The site's seismicity.* Will there be significant volcanic or seismic activity near the site in the next 10,000 years?
- *Hydrology.* Is there enough evidence to ensure that radionuclides will not seep into groundwater to any significant degree?
- *Public education.* Should conservation be taught, and should teachers promote or discourage the role of nuclear power in our nation's power mix?
- *Other technical options.* Should one investigate nuclear physics options that might transmute the long-lived radioisotopes into ones with shorter half-lives regardless of the costs?
- *Weapons disarmament.* Should the plutonium from "disarmed" nuclear weapons eventually be turned into nuclear fuel or made useless immediately and buried with other HLW?



In the United States, permanent storage sites for high-level radioactive wastes will probably be deep underground in rock formations. Shown is the kind of nuclear waste facility designed for Yucca Mountain, which would be a three-square-mile complex of interconnected tunnels located in dense volcanic rock 305 meters (1000 feet) beneath the mountain.

For more information, see the following Web sites:
The Department of Energy, http://www.doe.gov
Yucca Mountain studies project, http://www.ymp.gov
The American Nuclear Society, http://www.ans.org
See also *Radwaste* magazine.

Donald H. Williams
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26-16 NUCLEAR FUSION

Fusion, the joining of light nuclei to form heavier nuclei, is favorable for the very light atoms. In both fission and fusion, the energy liberated is equivalent to the loss of mass that accompanies the reactions. Much greater amounts of energy per unit mass of *reacting atoms* are produced in fusion than in fission.

Spectroscopic evidence indicates that the sun is a tremendous fusion reactor consisting of 73% H, 26% He, and 1% other elements. Its major fusion reaction is thought to involve the combination of a deuteron, ${}^{2}_{1}H$, and a triton ${}^{3}_{1}H$, at tremendously high temperatures to form a helium nucleus and a neutron.

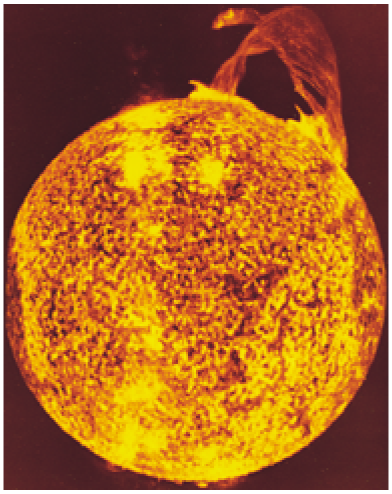
The deuteron and triton are the nuclei of two isotopes of hydrogen, called deuterium and tritium. Deuterium occurs naturally in water. When the D_2O is purified as “heavy water,” it can be used for several types of chemical analysis.

$${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$$

Thus, solar energy is actually a form of fusion energy.

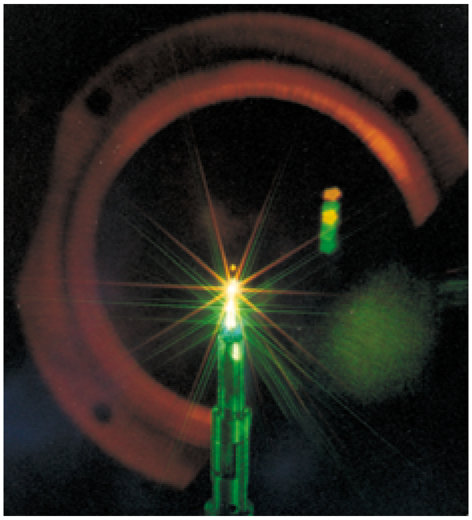
Fusion reactions are accompanied by even greater energy production per unit mass of reacting atoms than are fission reactions. They can be initiated only by extremely high temperatures, however. The fusion of ${}^{2}_{1}H$ and ${}^{3}_{1}H$ occurs at the lowest temperature of any fusion reaction known, but even this is 40,000,000 K! Such temperatures exist in the sun and other stars, but they are nearly impossible to achieve and contain on earth. **Thermonuclear** bombs (called fusion bombs or hydrogen bombs) of incredible energy have been detonated in tests but, thankfully, never in war. In them the necessary activation energy is supplied by the explosion of a fission bomb.

It is hoped that fusion reactions can be harnessed to generate energy for domestic power. Because of the tremendously high temperatures required, no currently known structural material can confine these reactions. At such high temperatures all molecules dissociate and most atoms ionize, resulting in the formation of a new state of matter called



Our sun supplies energy to the earth from a distance of 93,000,000 miles. Like other stars, it is a giant nuclear fusion reactor. Much of its energy comes from the fusion of deuterium, ${}^{2}_{1}H$, producing helium, ${}^{4}_{2}He$.

The explosion of a thermonuclear (hydrogen) bomb releases tremendous amounts of energy. If we could learn how to control this process, we would have nearly limitless amounts of energy.

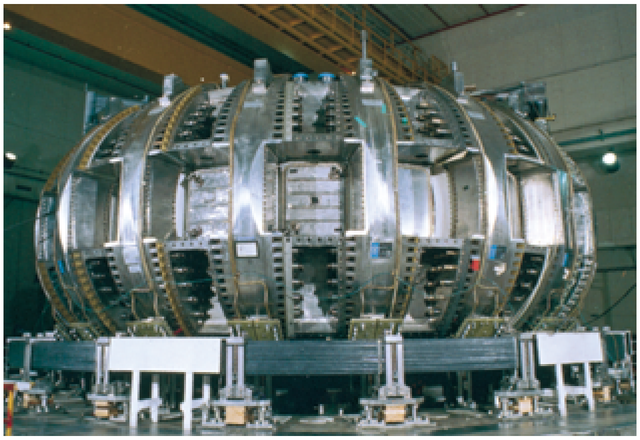


Nuclear fusion provides the energy of our sun and other stars. Development of controlled fusion as a practical source of energy requires methods to initiate and contain the fusion process. Here a very powerful laser beam has initiated a fusion reaction in a 1-mm target capsule that contained deuterium and tritium. In a 0.5-picosecond burst, 10^{13} neutrons were produced by the reaction $^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$.

a **plasma.** A very high temperature plasma is so hot that it melts and decomposes anything it touches, including structural components of a reactor. The technological innovation required to build a workable fusion reactor probably represents the greatest challenge ever faced by the scientific and engineering community.

Plasmas have been called the fourth state of matter.

Recent attempts at the containment of lower temperature plasmas by external magnetic fields have been successful, and they encourage our hopes. Fusion as a practical energy source, however, lies far in the future at best. The biggest advantages of its use would be that (1) the deuterium fuel can be found in virtually inexhaustible supply in the oceans; and (2) fusion reactions would produce only radionuclides of very short half-life, primarily tritium ($t_{1/2}$ = 12.3 years), so there would be no long-term waste disposal problem. If controlled fusion could be brought about, it could liberate us from dependence on uranium and fossil fuels.



The plasma in a fusion reactor must not touch the walls of its vacuum vessel, which would be vaporized. In the Tokamak fusion test reactor, the plasma is contained within a magnetic field shaped like a doughnut. The magnetic field is generated by D-shaped coils around the vacuum vessel.

Key Terms

Alpha particle (α) A particle that consists of two protons and two neutrons; identical to a helium nucleus.

Artificial transmutation An artificially induced nuclear reaction caused by bombardment of a nucleus with subatomic particles or small nuclei.

Band of stability A band containing stable (nonradioactive) nuclides in a plot of number of neutrons versus number of protons (atomic number).

Beta particle (β) An electron emitted from the nucleus when a neutron decays to a proton and an electron.

Binding energy (nuclear binding energy) The energy equivalent ($E = mc^2$) of the mass deficiency of an atom.

Breeder reactor A fission reactor that produces more fissionable material than it consumes.

Chain reaction A reaction that, once initiated, sustains itself and expands.

Cloud chamber A device for observing the paths of speeding particles as vapor molecules condense on the ionized air molecules in their tracks.

Control rods Rods of materials such as cadmium or boron steel that act as neutron absorbers (not merely moderators), used in nuclear reactors to control neutron fluxes and therefore rates of fission.

Critical mass The minimum mass of a particular fissionable nuclide, in a given volume, that is required to sustain a nuclear chain reaction.

Cyclotron A device for accelerating charged particles along a spiral path.

Daughter nuclide A nuclide that is produced in a nuclear decay.

Electron capture Absorption of an electron from the first energy level (*K* shell) by a proton as it is converted to a neutron; also *K* capture.

Fast neutron A neutron ejected at high kinetic energy in a nuclear reaction.

Fluorescence Absorption of high-energy radiation by a substance and the subsequent emission of visible light.

Gamma ray (γ) High-energy electromagnetic radiation.

Geiger-Müller counter A type of gas ionization counter used to detect radiation.

Half-life of a radionuclide The time required for half of a given sample to undergo radioactive decay.

Heavy water Water containing deuterium, a heavy isotope of hydrogen, ${}^2_1H$.

Linear accelerator A device used for accelerating charged particles along a straight-line path.

Mass deficiency The amount of matter that would be converted into energy if an atom were formed from constituent particles.

Moderator A substance such as hydrogen, deuterium, oxygen, or paraffin capable of slowing fast neutrons upon collision.

Nuclear binding energy The energy equivalent of the mass deficiency; energy released in the formation of an atom from subatomic particles.

Nuclear fission The process in which a heavy nucleus splits into nuclei of intermediate masses and one or more neutrons are emitted.

Nuclear fusion The combination of light nuclei to produce a heavier nucleus.

Nuclear reaction A reaction involving a change in the composition of a nucleus; it can evolve or absorb an extraordinarily large amount of energy.

Nuclear reactor A system in which controlled nuclear fission reactions generate heat energy on a large scale. The heat energy is subsequently converted into electrical energy.

Nucleons Particles comprising the nucleus; protons and neutrons.

Nuclides Different atomic forms of all elements (in contrast to isotopes, which are different atomic forms of a single element).

Parent nuclide A nuclide that undergoes nuclear decay.

Plasma A physical state of matter that exists at extremely high temperatures, in which all molecules are dissociated and most atoms are ionized.

Positron A nuclear particle with the mass of an electron but opposite charge.

Radiation High-energy particles or rays emitted in nuclear decay processes.

Radioactive dating A method of dating ancient objects by determining the ratio of amounts of a parent nuclide and one of its decay products present in an object and relating the ratio to the object's age via half-life calculations.

Radioactive tracer A small amount of radioisotope that replaces a nonradioactive isotope of the element in a compound whose path (e.g., in the body) or whose decomposition products are to be monitored by detection of radioactivity; also called a radioactive label.

Radioactivity The spontaneous disintegration of atomic nuclei.

Radioisotope A radioactive isotope of an element.

Radionuclide A radioactive nuclide.

Scintillation counter A device used for the quantitative detection of radiation.

Slow neutron A fast neutron slowed by collision with a moderator.

Thermonuclear energy Energy from nuclear fusion reactions.

Transuranium elements The elements with atomic numbers greater than 92 (uranium); none occurs naturally and all must be prepared by nuclear bombardment of other elements.

Exercises

Nuclear Stability and Radioactivity

1. Define and compare nuclear fission and nuclear fusion. Briefly describe current uses of nuclear fission and fusion.

2. Differentiate between natural and induced radioactivity. Use the periodic table to identify the locations of those elements that are the result of induced radioactivity.

3. How do nuclear reactions differ from ordinary chemical reactions?

4. What is the equation that relates the equivalence of matter and energy? What does each term in this equation represent?

5. What is mass deficiency? What is binding energy? How are the two related?

6. What are nucleons? What is the relationship between the number of protons and the atomic number? What is the relationship among the number of protons, the number of neutrons, and the mass number?

7. Define the term "binding energy per nucleon." How can this quantity be used to compare the stabilities of nuclei?

8. Describe the general shape of the plot of binding energy per nucleon against mass number.

9. (a) Briefly describe a plot of the number of neutrons against the atomic number (for the stable nuclides). Interpret the observation that the plot shows a band with a somewhat step-like shape. (b) Describe what is meant by "magic numbers" of nucleons.

10. Potassium, $Z = 19$, has a series of naturally occurring isotopes: ^{39}K, ^{40}K, ^{41}K. Identify the isotope(s) of potassium that is/are most likely to be stable and which tend to decay.

11. Platinum, $Z = 78$, has a series of naturally occurring isotopes: ^{190}Pt, ^{192}Pt, ^{194}Pt, ^{195}Pt, ^{196}Pt, and ^{198}Pt. Identify the isotope(s) of platinum that is/are most likely to be stable and which tend to decay.

12. Indicate the type of emission and the decay product predicted for each unstable isotope listed in Exercise 10.

13. Indicate the type of emission and the decay product predicted for each unstable isotope listed in Exercise 11.

14. The actual mass of a ^{62}Ni atom is 61.9283 amu. (a) Calculate the mass deficiency in amu/atom and in g/mol for this isotope. (b) What is the nuclear binding energy in kJ/mol for this isotope?

15. The actual mass of a ^{108}Pd atom is 107.90389 amu. (a) Calculate the mass deficiency in amu/atom and in g/mol for this isotope. (b) What is the nuclear binding energy in kJ/mol for this isotope?

16. Calculate the following for ^{64}Zn (actual mass = 63.9291 amu). (a) mass deficiency in amu/atom; (b) mass deficiency in g/mol; (c) binding energy in J/atom; (d) binding energy in kJ/mol; (e) binding energy in MeV/nucleon.

17. Calculate the following for ^{49}Ti (actual mass = 48.94787 amu). (a) mass deficiency in amu/atom; (b) mass deficiency in g/mol; (c) binding energy in J/atom; (d) binding energy in kJ/mol; (e) binding energy in MeV/nucleon.

18. Calculate the nuclear binding energy in kJ/mol for each of the following (a) $^{127}_{53}I$; (b) $^{81}_{35}Br$; (c) $^{35}_{17}Cl$. The atomic masses are 126.9044 amu, 80.9163 amu, and 34.96885 amu, respectively.

19. Repeat Exercise 18 for (a) $^{36}_{16}S$, (b) $^{39}_{19}Kr$, and (c) $^{24}_{12}Mg$. Their respective atomic masses are 35.96709 amu, 38.96371 amu, and 23.98504 amu. Which of these nuclides has the greatest binding energy per nucleon?

20. Compare the behaviors of α, β, and γ radiation (a) in an electrical field, (b) in a magnetic field, and (c) with respect to ability to penetrate various shielding materials, such as a piece of paper and concrete. What is the composition of each type of radiation?

21. Why are α-particles that are absorbed internally by the body particularly dangerous?

22. Name some radionuclides that have medical uses, and list the uses.

23. Describe how radionuclides can be used in (a) research, (b) agriculture, and (c) industry.

24. Name and describe four methods for detection of radiation.

25. Describe how (a) nuclear fission and (b) nuclear fusion generate more stable nuclei.

26. What evidence exists to support the theory that nucleons are arranged in "shells" or energy levels within the nucleus?

Nuclear Reactions

27. Consider a radioactive nuclide with a neutron/proton ratio that is larger than those for the stable isotopes of that element. What mode(s) of decay might be expected for this nuclide, and why?

28. Repeat Exercise 27 for a nuclide with a neutron/proton ratio that is smaller than those for the stable isotopes.

29. Calculate the neutron/proton ratio for each of the following radioactive nuclides, and predict how each of the nuclides might decay: (a) $^{13}_{5}B$ (stable mass numbers for B are 10 and 11); (b) $^{92}_{38}Sr$ (stable mass numbers for Sr are between 84 and 88); (c) $^{192}_{82}Pb$ (stable mass numbers for Pb are between 204 and 208).

30. Repeat Exercise 29 for (a) $^{193}_{79}Au$ (stable mass number for Au is 197), (b) $^{189}_{75}Re$ (stable mass numbers for Re are 185 and 187), and (c) $^{137}_{59}Pr$ (stable mass number for Pr is 141).

31. Write the symbols for the daughter nuclei in the following radioactive decays (β refers to an e^-).

(a) ${}^{125}\mathrm{Sn} \xrightarrow{-\beta}$ (d) ${}^{147}\mathrm{Sm} \xrightarrow{-\alpha}$

(b) ${}^{13}\mathrm{C} \xrightarrow{-n}$ (e) ${}^{184}\mathrm{Ir} \xrightarrow{-p}$

(c) ${}^{11}\mathrm{B} \xrightarrow{-\gamma}$ (f) ${}^{40}_{19}\mathrm{K} \xrightarrow{+\beta}$

32. Predict the kind of decays you would expect for the following radionuclides. (a) ${}^{60}_{27}\mathrm{Co}$ (*n/p* ratio too high); (b) ${}^{20}_{11}\mathrm{Na}$ (*n/p* ratio too low); (c) ${}^{222}_{86}\mathrm{Rn}$; (d) ${}^{67}_{29}\mathrm{Cu}$; (e) ${}^{238}_{92}\mathrm{U}$; (f) ${}^{11}_{6}\mathrm{C}$.

33. What are nuclear bombardment reactions? Explain the shorthand notation used to describe bombardment reactions.

34. Fill in the missing symbols in the following nuclear bombardment reactions.

(a) ${}^{23}_{11}\mathrm{Na} + \underline{?} \longrightarrow {}^{23}_{12}\mathrm{Mg} + {}^{1}_{0}n$

(b) ${}^{59}_{27}\mathrm{Co} + {}^{1}_{0}n \longrightarrow {}^{56}_{25}\mathrm{Mn} + \underline{?}$

(c) ${}^{96}_{42}\mathrm{Mo} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{100}_{43}\mathrm{Tc} + \underline{?}$

(d) ${}^{209}_{83}\mathrm{Bi} + \underline{?} \longrightarrow {}^{210}_{84}\mathrm{Po} + {}^{1}_{0}n$

(e) ${}^{238}_{92}\mathrm{U} + {}^{16}_{8}\mathrm{O} \longrightarrow \underline{?} + 5\,{}^{1}_{0}n$

35. Fill in the missing symbols in the following nuclear bombardment reactions.

(a) ${}^{232}_{90}\mathrm{Th} + \underline{?} \longrightarrow {}^{240}_{96}\mathrm{Cm} + 4\,{}^{1}_{0}n$

(b) $\underline{?} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{29}_{14}\mathrm{Si} + {}^{0}_{0}\gamma$

(c) ${}^{26}_{?}\mathrm{Mg} + \underline{?} \longrightarrow {}^{26}_{?}\mathrm{Al} + {}^{1}_{0}n$

(d) ${}^{40}_{18}\mathrm{Ar} + \underline{?} \longrightarrow {}^{43}_{?}\mathrm{K} + {}^{1}_{1}\mathrm{H}$

36. Write the symbols for the daughter nuclei in the following nuclear bombardment reactions. (a) ${}^{60}_{28}\mathrm{Ni}$ (n, p); (b) ${}^{98}_{42}\mathrm{Mo}$ $({}^{1}_{0}n, \beta)$; (c) ${}^{35}_{17}\mathrm{Cl}$ (p, α).

37. Write the symbols for the daughter nuclei in the following nuclear bombardment reactions. (a) ${}^{20}_{10}\mathrm{Ne}$ (α, γ); (b) ${}^{15}_{7}\mathrm{N}$ (p, α); (c) ${}^{10}_{5}\mathrm{B}$ (n, α).

38. Write the nuclear equation for each of the following bombardment processes. (a) ${}^{14}_{7}\mathrm{N}$ (α, p) ${}^{17}_{8}\mathrm{O}$; (b) ${}^{106}_{46}\mathrm{Pd}$ (n, p) ${}^{106}_{45}\mathrm{Rh}$; (c) ${}^{23}_{11}\mathrm{Na}$ (n, β^-)X. Identify X.

39. Repeat Exercise 38 for the following. (a) ${}^{113}_{48}\mathrm{Cd}$ (n, γ) ${}^{114}_{48}\mathrm{Cd}$; (b) ${}^{6}_{3}\mathrm{Li}$ (n, α) ${}^{3}_{1}\mathrm{H}$; (c) ${}^{2}_{1}\mathrm{H}$ (γ, p)X. Identify X.

40. Write the shorthand notation for each of the following nuclear reactions.

(a) ${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}n \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H}$

(b) ${}^{31}_{15}\mathrm{P} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{32}_{15}\mathrm{P} + {}^{1}_{1}\mathrm{H}$

(c) ${}^{238}_{92}\mathrm{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{93}\mathrm{Np} + {}^{\;0}_{-1}e$

41. Repeat Exercise 40 for the following.

(a) ${}^{253}_{99}\mathrm{Es} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{256}_{101}\mathrm{Md} + {}^{1}_{0}n$

(b) ${}^{27}_{13}\mathrm{Al} + {}^{1}_{0}n \longrightarrow {}^{26}_{13}\mathrm{Al} + 2\,{}^{1}_{0}n$

(c) ${}^{37}_{17}\mathrm{Cl} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{1}_{0}n + {}^{37}_{18}\mathrm{Ar}$

42. Write the nuclear equations for the following processes. (a) ${}^{63}_{28}\mathrm{Ni}$ undergoing β^- emission; (b) two deuterium ions undergoing fusion to give ${}^{3}_{2}\mathrm{He}$ and a neutron; (c) a nuclide being bombarded by a neutron to form ${}^{7}_{3}\mathrm{Li}$ and an α-particle (identify the unknown nuclide); (d) ${}^{14}_{7}\mathrm{N}$ being bombarded by a neutron to form three α-particles and an atom of tritium.

43. Write the nuclear equations for the following processes. (a) ${}^{220}_{86}\mathrm{Rn}$ undergoing α decay; (b) ${}^{110}_{49}\mathrm{In}$ undergoing positron emission; (c) ${}^{127}_{53}\mathrm{I}$ being bombarded by a proton to form ${}^{121}_{54}\mathrm{Xe}$ and seven neutrons; (d) tritium and deuterium undergoing fusion to form an α-particle and a neutron; (e) ${}^{95}_{42}\mathrm{Mo}$ being bombarded by a proton to form ${}^{95}_{43}\mathrm{Tc}$ and radiation (identify this radiation).

44. "Radioactinium" is produced in the actinium series from ${}^{235}_{92}\mathrm{U}$ by the successive emission of an α-particle, a β^--particle, an α-particle, and a β^--particle. What are the symbol, atomic number, and mass number for "radioactinium?"

45. An alkaline earth element (Group IIA) is radioactive. It undergoes decay by emitting three α-particles in succession. In what periodic table group is the resulting element found?

46. A nuclide of element rutherfordium, ${}^{257}_{104}\mathrm{Rf}$, is formed by the nuclear reaction of californium-249 and carbon-12, with the emission of four neutrons. This new nuclide rapidly decays by emitting an α-particle. Write the equation for each of these nuclear reactions.

47. Supply the missing information to each of the following equations.

(a) ${}^{53}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{1}_{0}n + \underline{?}$

(b) ${}^{187}_{75}\mathrm{Re} + \beta \longrightarrow \underline{?}$

(c) ${}^{243}_{95}\mathrm{Am} + {}^{1}_{0}n \longrightarrow {}^{244}_{?}\mathrm{Cm} + \underline{?} + \gamma$

(d) ${}^{35}_{17}\mathrm{Cl} + \underline{?} \longrightarrow {}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He}$

48. Supply the missing information to each of the following reactions.

(a) ${}^{14}_{?}\text{N} + \underline{?} \longrightarrow {}^{17}_{?}\text{O} + p$

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

(c) ${}^{241}_{95}\text{Am} + {}^{12}_{?}\text{C} \longrightarrow 4\,{}^{1}_{0}n + \underline{?}$

49. Describe how (a) cyclotrons and (b) linear accelerators work.

Rates of Decay

50. What does the half-life of a radionuclide represent? How do we compare the relative stabilities of radionuclides in terms of half-lives?

51. Why must all radioactive decays be first order?

52. Describe the process by which steady-state (constant) ratios of carbon-14 to (nonradioactive) carbon-12 are attained in living plants and organisms. Describe the method of radiocarbon dating. What factors limit the use of this method?

53. The half-life of ${}^{19}_{8}\text{O}$ is 29 s. What fraction of the isotope originally present would be left after 10.0 s?

54. The half-life of ${}^{11}_{6}\text{C}$ is 20.3 min. How long will it take for 95.0% of a sample to decay? How long will it take for 99.5% of the sample to decay?

55. The activity of a sample of tritium decreased by 5.5% over the period of a year. What is the half-life of ${}^{3}_{1}\text{H}$?

56. A very unstable isotope of beryllium, ${}^{8}\text{Be}$, undergoes α emission with a half-life of 0.07 fs. How long does it take for 99.99% of a 1.0-μg sample of ${}^{8}\text{Be}$ to undergo decay?

57. The ${}^{14}_{6}\text{C}$ activity of an artifact from a burial site was 8.6/min·g C. The half-life of ${}^{14}_{6}\text{C}$ is 5730 years, and the current ${}^{14}_{6}\text{C}$ activity is 15.3/min·g C (that is, 15.3 disintegrations per minute per gram of carbon). How old is the artifact?

58. A piece of wood from a burial site was analyzed using ${}^{14}_{6}\text{C}$ dating and was found to have an activity of 11.8/min·g C. Using the data given in Exercise 57 for ${}^{14}_{6}\text{C}$ dating, determine the age of this piece of wood.

59. Analysis of an ant found in a piece of amber provided 14.0 disintegrations of ${}^{14}_{6}\text{C}$/min·g C, whereas a living ant of the same species produces 17.0 disintegrations per minute. Calculate the approximate age of the fossilized ant. The half-life of carbon-14 is 5730 years.

60. A skeleton was found in the woods and the police would like to place the approximate time of death. A sample of bone from the skeleton produces 12.0 disintegrations per min per g of C. Bone of recent origin produces 14.0 disintegrations per min·per g C. Calculate the approximate age of the bone sample. The half-life of carbon-14 is 5730 years.

61. Strontium-90 is one of the harmful radionuclides that results from nuclear fission explosions. It decays by beta emission with a half-life of 28 years. How long would it take for 99.99% of a given sample released in an atmospheric test of an atomic bomb to disintegrate?

62. Carbon-14 decays by beta emission with a half-life of 5730 years. Assuming a particular object originally contained 7.50 μg of carbon-14 and now contains 0.80 μg of carbon-14, how old is the object?

Fission and Fusion

63. Briefly describe a nuclear fission process. What are the two most important fissionable materials?

64. What is a chain reaction? Why are nuclear fission processes considered chain reactions? What is the critical mass of a fissionable material?

65. Where have continuous nuclear fusion processes been observed? What is the main reaction that occurs in such sources?

66. The reaction that occurred in the first fusion bomb was ${}^{7}_{3}\text{Li}$ (p, α) X. (a) Write the complete equation for the process, and identify the product, X. (b) The atomic masses are 1.007825 amu for ${}^{1}_{1}\text{H}$, 4.00260 amu for α, and 7.01600 amu for ${}^{7}_{3}\text{Li}$. Find the energy for the reaction in kJ/mol.

67. Summarize how an atomic bomb works, including how the nuclear explosion is initiated.

68. Discuss the pros and cons of the use of nuclear energy instead of other, more conventional types of energy based on fossil fuels.

69. Describe and illustrate the essential features of a light water fission reactor.

70. How is fissionable uranium-235 separated from nonfissionable uranium-238?

71. Distinguish between moderators and control rods of nuclear reactors.

72. What are the major advantages and disadvantages of fusion as a potential energy source compared with fission? What is the major technological problem that must be solved to permit development of a fusion reactor?

Mixed Exercises

***73.** Calculate the binding energy, in kJ/mol of nucleons, for the following isotopes. (a) ${}^{15}_{8}\text{O}$ with a mass of 15.00300 amu; (b) ${}^{16}_{8}\text{O}$ with a mass of 15.99491 amu; (c) ${}^{17}_{8}\text{O}$ with a mass of 16.99913 amu; (d) ${}^{18}_{8}\text{O}$ with a mass of 17.99915 amu; (e) ${}^{19}_{8}\text{O}$ with a mass of 19.0035 amu. Which of these would you expect to be most stable?

***74.** The first nuclear transformation (discovered by Rutherford) can be represented by the shorthand notation ${}^{14}_{7}\text{N}$ (α, p) ${}^{17}_{8}\text{O}$. (a) Write the corresponding nuclear equation for this process. The respective atomic masses are 14.00307 amu for $^{14}_{7}N$, 4.00260 amu for $^{4}_{2}He$, 1.007825 amu for $^{1}_{1}H$, and 16.99913 amu for $^{17}_{8}O$. (b) Calculate the energy change of this reaction in kJ/mol.

75. A proposed series of reactions (known as the carbon–nitrogen cycle) that could be important in the very hottest region of the interior of the sun is

$$\begin{aligned} ^{12}C + {}^{1}H &\longrightarrow A + \gamma \\ A &\longrightarrow B + {}^{0}_{+1}e \\ B + {}^{1}H &\longrightarrow C + \gamma \\ C + {}^{1}H &\longrightarrow D + \gamma \\ D &\longrightarrow E + {}^{0}_{+1}e \\ E + {}^{1}H &\longrightarrow {}^{12}C + F \end{aligned}$$

Identify the species labeled *A–F*.

***76.** The ultimate stable product of ^{238}U decay is ^{206}Pb. A certain sample of pitchblende ore was found to contain ^{238}U and ^{206}Pb in the ratio 67.8 atoms ^{238}U : 32.2 atoms ^{206}Pb. Assuming that all the ^{206}Pb arose from uranium decay, and that no U or Pb has been lost by weathering, how old is the rock? The half-life of ^{238}U is 4.51×10^9 years.

***77.** Potassium-40 decays to ^{40}Ar with a half-life of 1.3×10^9 years. What is the age of a lunar rock sample that contains these isotopes in the ratio 33.4 atoms ^{40}K : 66.6 atoms ^{40}Ar? Assume that no argon was originally in the sample and that none has been lost by weathering.

CONCEPTUAL EXERCISES

78. Both nuclear and conventional power plants produce wastes to which the environment is sensitive. Discuss these wastes and the current problems created by the wastes.

79. If the earth is 4.5×10^9 years old and the amount of radioactivity in a sample becomes smaller with time, how is it possible for there to be any radioactive elements left on earth that have half-lives of less than a few million years?

BUILDING YOUR KNOWLEDGE

80. Show by calculation which reaction produces the larger amount of energy per atomic mass unit of material reacting.

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

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

The atomic masses are 235.0439 amu for $^{235}_{92}U$; 93.9061 amu for $^{94}_{40}Zr$; 139.9053 amu for $^{140}_{58}Ce$; 3.01605 amu for $^{3}_{1}H$; 1.007825 amu for $^{1}_{1}H$; 2.0140 amu for $^{2}_{1}H$.

81. What would be the volume of helium, measured at STP, generated from the decay of the ^{8}Be sample in Exercise 56?