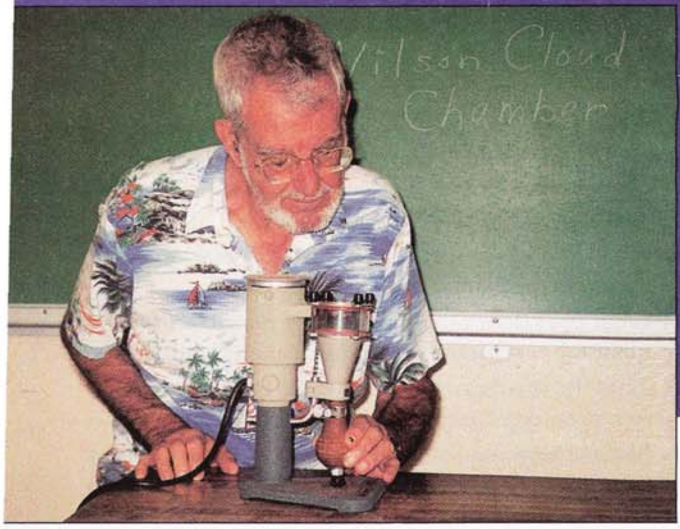

CHAPTER 33

The Atomic Nucleus and Radioactivity

Walter Steiger, first pioneer of telescopes in Hawaii, examines vapor trails in a small cloud chamber.

The Physics Place
Nuclear Physics

Radioactivity has been around since Earth's beginning.

Insights

In the previous chapter, we were concerned with *atomic physics*—the study of the clouds of electrons that make up the atom. In this chapter, we will burrow beneath the electrons and go deeper into the atom—to the atomic nucleus. Now we study *nuclear physics*, where available energies dwarf those available among electrons. Nuclear physics is a topic of great public interest—and public fear.

Public phobia about anything *nuclear* or anything *radioactive* is much like the phobia about electricity that was common more than a century ago. The fears of electricity in homes stemmed from ignorance. Indeed, electricity can be quite dangerous and even lethal when improperly handled. But, with safeguards and well-informed consumers, society has determined that the benefits of electricity outweigh its risks. Today, we are making similar decisions about nuclear technology's risks versus its benefits. These decisions should be made with an adequate understanding of the atomic nucleus and its inner properties.

Knowledge of the atomic nucleus began with the chance discovery of radioactivity in 1896, which, in turn, was based on the discovery of X-rays two months earlier. So, to begin our study of nuclear physics, we'll consider X-rays.

X-Rays and Radioactivity

Before the turn of the twentieth century, the German physicist Wilhelm Roentgen discovered a "new kind of ray" produced by a beam of "cathode rays" (later found to be electrons) striking the glass surface of a gas-discharge tube. He named these **X-rays**—rays of an unknown nature. Roentgen found that X-rays could pass through solid materials, could ionize the air, showed no refraction in glass, and were undeflected by magnetic fields. Today we know that X-rays are high-frequency electromagnetic waves, usually emitted by the de-excitation of the innermost orbital electrons of atoms. Whereas the electron current in a fluorescent lamp excites the outer electrons of atoms and produces ultraviolet and visible photons, a more energetic beam of electrons striking a solid surface excites the innermost electrons and produces higher-frequency photons of X-radiation.

X-ray photons have high energy and can penetrate many layers of atoms before being absorbed or scattered. X-rays do this when they pass through your soft tissues to produce images of the bones inside of your body (Figure 33.1).

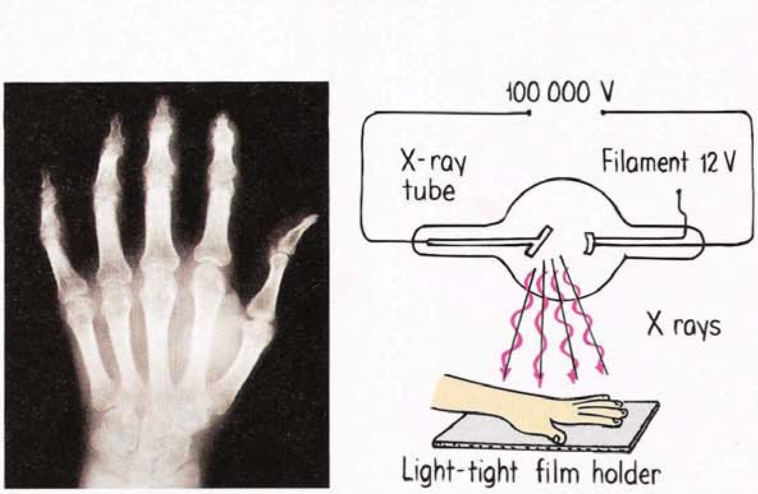

FIGURE 33.1
X-rays emitted by excited metallic atoms in the electrode penetrate flesh more readily than bone and produce an image on the film.

Marie Curie (1867–1934)

In a modern X-ray tube, the target of the electron beam is a metal plate rather than the glass wall of the tube.

Two months after Roentgen announced his discovery of X-rays, the French physicist Antoine Henri Becquerel tried to find out whether any elements spontaneously emitted X-rays. To do this, he wrapped a photographic plate in black paper to keep out the light and then put pieces of various elements against the wrapped plate. From Roentgen's work, Becquerel knew that, if these materials emitted X-rays, the rays would go through the paper and blacken the plate. He found that, although most elements produced no effect, uranium did produce rays. It was soon discovered that similar rays are emitted by other elements, such as thorium, actinium, and two new elements discovered by Marie and Pierre Curie—polonium and radium. The emission of these rays was evidence of much more drastic changes in the atom than atomic excitation. These rays were the result not of changes in the electron energy states of the atom but of changes occurring within the central atomic core—the nucleus. These rays were the result of a spontaneous chipping apart of the atomic nucleus—**radioactivity.**

Alpha, Beta, and Gamma Rays

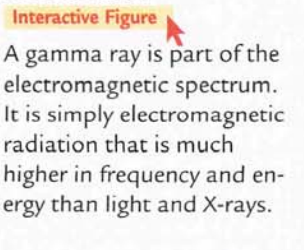

FIGURE 33.2
Interactive Figure
A gamma ray is part of the electromagnetic spectrum. It is simply electromagnetic radiation that is much higher in frequency and energy than light and X-rays.

More than 99.9% of the atoms in our everyday environment are stable. The nuclei in those atoms will likely not change over the lifetime of the universe. But some kinds of atoms are not stable. All elements having an atomic number greater than 82 (lead) are radioactive. These elements, and others, emit three distinct types of radiation, named by the first three letters of the Greek alphabet, α, β, γ—*alpha, beta,* and *gamma*. **Alpha rays** have a positive electrical charge, **beta rays** have a negative charge, and **gamma rays** have no charge at all. The three rays can be separated by placing a magnetic field across their paths (Figure 33.3). Further investigation has shown that an alpha ray is a stream of helium nuclei, and a beta ray is a stream of electrons. Hence, we often call these *alpha particles* and *beta particles*. A gamma ray is electromagnetic radiation (a stream of photons) whose frequency is even higher than that of X-rays. Whereas X-rays originate in the electron cloud outside the atomic nucleus, gamma rays originate in the nucleus. Gamma photons provide information about nuclear structure, much as visible and X-ray photons provide information about atomic electron structure.

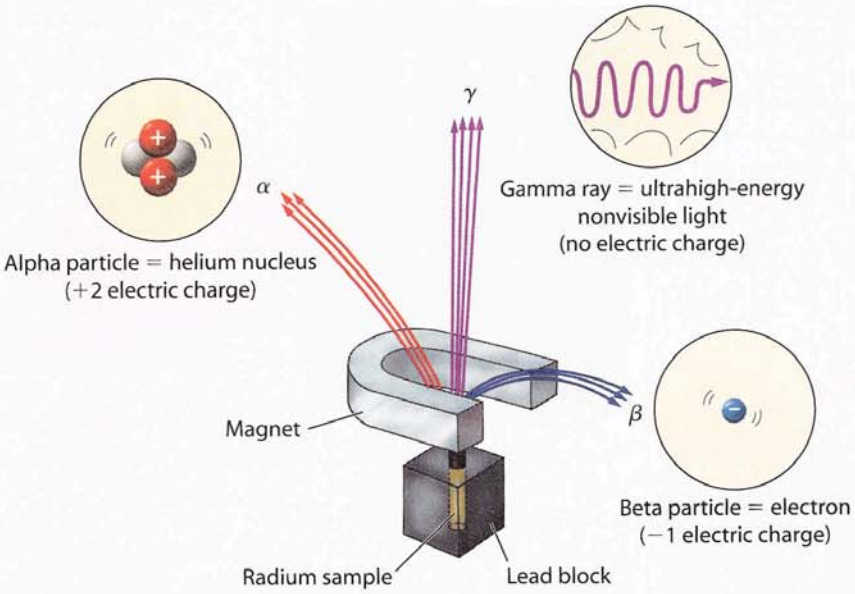

FIGURE 33.3 Interactive Figure

In a magnetic field, alpha rays bend one way, beta rays bend the other way, and gamma rays don't bend at all. The combined beam comes from a radioactive source placed at the bottom of a hole drilled in a lead block.

Once alpha and beta particles are slowed by collisions, they become harmless. They combine to become helium atoms.

Insights

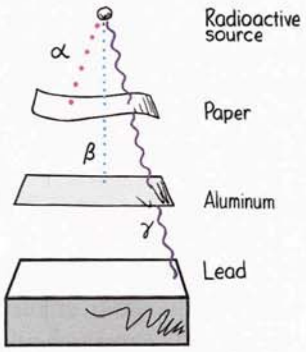

FIGURE 33.4 Interactive Figure

Alpha particles are the least penetrating and can be stopped by a few sheets of paper. Beta particles will readily pass through paper, but not through a sheet of aluminum. Gamma rays penetrate several centimeters into solid lead.

PRACTICING PHYSICS

Some watches and clocks have luminous hands that glow continuously. In some of these, what causes the glow is traces of radioactive radium bromide mixed with zinc sulfide. (Safer clock faces use light rather than radioactive decay as a means of excitation and, as a result, become progressively dimmer in the dark.) If you have a glow-all-the-time type of clock available, take it into a completely dark room and, after your eyes have adjusted to the dark, examine the hands of the clock with a very strong magnifying glass or the eyepiece of a microscope or telescope. You should be able to see individual tiny flashes, which together seem to be a steady source of light to the unaided eye. Each flash occurs when an alpha particle ejected by a radium nucleus strikes a molecule of zinc sulfide.

The Nucleus

Light is emitted by energy-level transitions in atoms; gamma rays are emitted by similar energy transitions within the atomic nucleus.

Insights

As described in earlier chapters, the atomic nucleus occupies only a few quadrillionths the volume of the atom, leaving most of the atom as empty space. Particles occupying the nucleus are called **nucleons.** If they are electrically charged, they are protons; if they are electrically neutral, they are neutrons. The positive charge of the proton is the same in magnitude as the negative charge of the electron. Nucleons have nearly 2000 times the mass of electrons, so the mass of an atom is practically equal to the mass of its nucleus. The neutron's mass is slightly greater than the proton's. We'll see that, when an electron is ejected from a neutron (beta emission), the neutron becomes a proton.

Nuclear radii range from about 10^{-15} meter for hydrogen to about seven times larger for uranium. Some nuclei are spherical, but most deviate from that shape in the "football" way and a few in the "doorknob" way. Protons and neutrons within the nucleus move relatively freely, yet provide a "skin" that gives the nucleus some properties of a liquid drop.

The emission of alpha particles is a quantum phenomenon that can be understood in terms of waves and probability. Just as orbital electrons form a probability cloud about the nucleus, inside the radioactive nucleus there is a similar probability cloud for the clustering of the two protons and two neutrons that constitute an alpha particle. A tiny part of the alpha particle's probability wave extends outside the nucleus, meaning that there is a small chance that the alpha particle will be outside. Once outside, it is hurled violently away by electric repulsion. The electron emitted in beta decay, on the other hand, is not "there" before it is emitted. It is created at the moment of radioactive decay when a neutron is transformed into a proton.

In addition to alpha, beta, and gamma rays, more than 200 various other particles have been detected coming from the nucleus when it is clobbered by energetic particles. We do not think of these so-called elementary particles as being buried within the nucleus and then popping out, just as we do not think of a spark as being buried in a match before it is struck. These particles, like the electrons in beta decay, come into being when the nucleus is disrupted. There are regularities in the masses of these particles as well as the particular characteristics of their creation. Almost all of the new particles created in nuclear collisions can be understood as combinations of just six subnuclear particles—the **quarks.**

Two of the six quarks are the fundamental building blocks of all nucleons. An unusual property of quarks is that they carry fractional electrical charges. One kind, the *up* quark, carries +2/3 the proton charge, and another kind, the *down* quark, has −1/3 the proton charge. (The name *quark,* inspired by a quotation from *Finnegans Wake* by James Joyce, was chosen in 1963 by Murray Gell-Mann, who first proposed their existence.) Each quark has an antiquark with opposite electric charge. The proton consists of the combination *up up down,* and the neutron of *up down down.* The other four quarks bear the whimsical names *strange, charm, top,* and *bottom.* All of the several hundred particles that feel the strong nuclear force appear to be composed of some combination of the six quarks. As with magnetic poles, no quarks have been isolated and experimentally observed—most theorists think quarks, by their nature, cannot be isolated.

Particles lighter than protons and neutrons, like electrons and muons, and still lighter particles called *neutrinos,* are members of a class of six particles called *leptons*. Leptons are not composed of quarks. The six quarks and six leptons are thought to be the truly *elementary particles,* particles not composed of more basic entities. Investigation of elementary particles is at the frontier of our present knowledge and the area of much current excitement and research.

Isotopes

Recall, from Chapter 11, that the nucleus of a hydrogen atom contains a single proton, a helium nucleus contains two protons, a lithium nucleus has three, and so forth. Every succeeding element in the list of elements has one more proton than the preceding element. Recall, also from Chapter 11, that the number of protons in the nucleus is the same as the **atomic number.** Hydrogen has atomic number 1; helium, atomic number 2; lithium, 3; and so on.

The number of neutrons in the nucleus of a given element may vary. Although the nucleus of every hydrogen atom contains one proton, some hydrogen nuclei contain a neutron in addition to the proton. In rare instances, a hydrogen nucleus may contain *two* neutrons in addition to the proton. Recall that atoms containing like numbers of protons but unlike numbers of neutrons are **isotopes** of a given element.

Tritium is used in various self-luminescent devices, such as exit signs in buildings, aircraft dials, gauges, luminous paints, and wristwatches. Tritium is also used in life science research, and in studies investigating the safety of potential new drugs.

Insights

The most common isotope of hydrogen is $^{1}_{1}\text{H}$. The subscript (lower) number refers to the atomic number and the superscript (upper) number refers to the **atomic mass.** The double-mass hydrogen isotope $^{2}_{1}\text{H}$ is called *deuterium.* "Heavy water" is the name usually given to H_2O in which one or both of the H atoms have been replaced by deuterium atoms. In all naturally occurring hydrogen compounds, such as hydrogen gas and water, there is 1 atom of deuterium to about 6000 atoms of hydrogen. The triple-mass hydrogen isotope $^{3}_{1}\text{H}$, which is radioactive and lives long enough to be a known constituent of atmospheric water, is called *tritium.* Tritium is present only in extremely minute amounts—less than 1 per 10^{17} atoms of ordinary hydrogen. The tritium used for practical purposes is made in nuclear reactors or accelerators, and not extracted from natural sources. (Interestingly, tritium occurs in abundance on the Moon's surface.)

All elements have a variety of isotopes. For instance, three isotopes of uranium naturally occur in the Earth's crust; the most common is $^{238}_{92}\text{U}$. In briefer notation, we can drop the atomic number and simply say uranium-238, or, more concisely, U-238. Of the 83 elements present in significant amounts on Earth, 20 have a single stable (nonradioactive) isotope. The others have from 2 to 10 stable isotopes. More than 2000 distinct isotopes, radioactive and stable, are known.

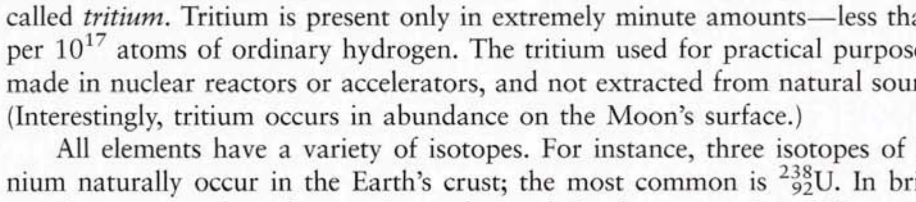

FIGURE 33.5
Three isotopes of hydrogen. Each nucleus has a single proton, which holds a single orbital electron, which, in turn, determines the chemical properties of the atom. The different number of neutrons (yellow) changes the mass of the atom but not its chemical properties.

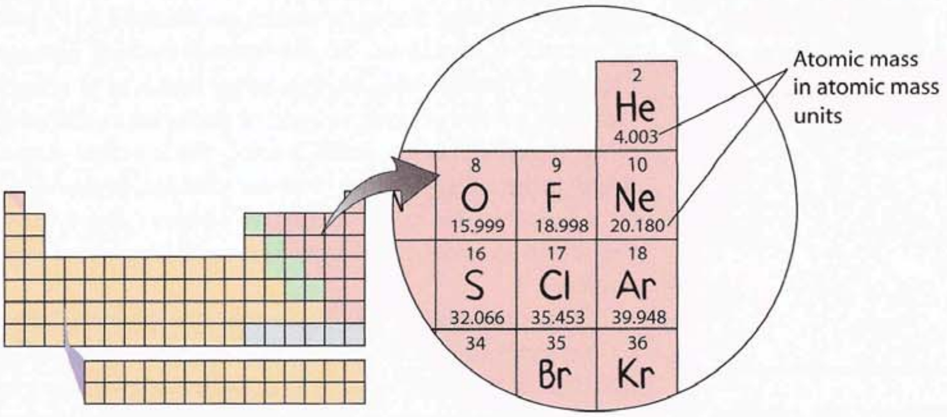

FIGURE 33.6
Helium, He, has an atomic mass of 4.003 amu, and neon, Ne, has an atomic mass of 20.180 amu. These values are averaged by isotopic abundances in Earth's surface.

Recall, from Chapter 11, that a special unit for atomic masses is the **atomic mass unit (amu),** which is based on the mass of the common carbon atom—which, by common agreement, is arbitrarily given the value of exactly 12. An amu of value 1 would be one-twelfth the mass of common carbon-12, equal to 1.661×10^{-27} kg, slightly less than the mass of a single proton. As shown in Figure 33.6, the atomic masses listed in the periodic table are in atomic mass units. The value listed for each element is the average atomic mass of its various isotopes.

CHECK YOURSELF

State the numbers of protons and neutrons in $^{1}_{1}H$, $^{14}_{6}C$, and $^{235}_{92}U$.

Why Atoms Are Radioactive

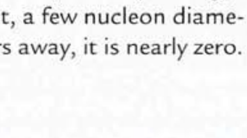

FIGURE 33.7
The nuclear strong interaction is a short-range force. For nucleons very close or in contact, it is very strong; but, a few nucleon diameters away, it is nearly zero.

The positively charged and closely spaced protons in a nucleus have huge electrical forces of repulsion between them. Why don't they fly apart in response to this huge repulsive force? Because there is an even more formidable force within the nucleus—the nuclear force. Both neutrons and protons are bound to each other by this attractive force. The nuclear force is much more complicated than the electrical force. The principal part of the nuclear force, the part that holds the nucleus together, is called the *strong interaction.*[1] The strong interaction is an attractive force that acts between protons, neutrons, and particles called *mesons,* all of which are called *hadrons*. This force acts over only a very short distance (Figure 33.7).

CHECK YOUR ANSWERS

The atomic number gives the number of protons. The number of neutrons is the atomic mass minus the atomic number. So we see 1 proton and no neutrons in $^{1}_{1}H$; 6 protons and 8 neutrons in $^{14}_{6}C$; and 92 protons and 143 neutrons in $^{235}_{92}U$.

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[1] Fundamental to the strong interaction is the *color force* (which has nothing to do with visible color). This color force interacts between quarks and holds them together by the exchange of "gluons." Read more about this in H. R. Pagels, *The Cosmic Code: Quantum Physics as the Language of Nature*. New York: Simon & Schuster, 1982.

The Physics Place
Radioactive Decay

It is very strong between nucleons about 10^{-15} meter apart, but close to zero at greater separations. So the strong nuclear interaction is a short-range force. Electrical interaction, on the other hand, is a relatively long-range force, for it weakens as the inverse square of separation distance. So as long as protons are close together, as in small nuclei, the nuclear force easily overcomes the electrical force of repulsion. But for distant protons, like those on opposite edges of a large nucleus, the attractive nuclear force may be small in comparison to the repulsive electrical force. Hence, a larger nucleus is not as stable as a smaller nucleus.

The presence of the neutrons also plays a large role in nuclear stability. It so happens that a proton and a neutron can be bound together a little more tightly, on average, than two protons or two neutrons. As a result, many of the first 20 or so elements have equal numbers of neutrons and protons.

For heavier elements, it is a different story, because protons repel each other electrically and neutrons do not. If you have a nucleus with 28 protons and 28 neutrons, for example, it can be made more stable by replacing two of the protons with neutrons, resulting in Fe-56, the iron isotope with 26 protons and 30 neutrons. The inequality of neutron and proton numbers becomes more pronounced for elements that are heavier still. For example, in U-238, which has 92 protons, there are 146 (238 − 92) neutrons. If the uranium nucleus were to have equal numbers of protons and neutrons, 92 protons and 92 neutrons, it would fly apart at once because of the electrical repulsion forces. The extra 54 neutrons are needed for relative stability. Even so, the U-238 nucleus is still fairly unstable because of the electrical forces.

To put the matter in another way: There is an electrical repulsion between *every pair* of protons in the nucleus, but there is not a substantial nuclear attractive force between every pair (Figure 33.8). Every proton in the uranium nucleus exerts a repulsion on each of the other 91 protons—those near and those far. However, each proton (and neutron) exerts an appreciable nuclear attraction only on those nucleons that happen to be near it.

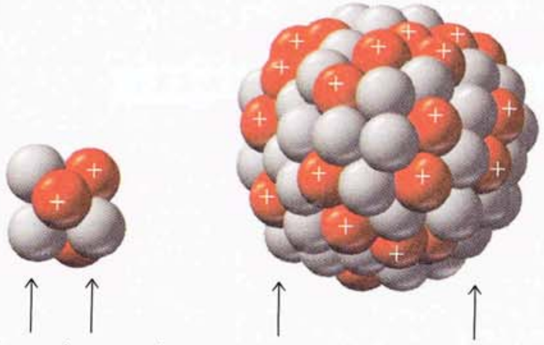
All nuclei having more than 82 protons are unstable. In this unstable environment, alpha and beta emissions take place. The force responsible for beta emission is called the *weak interaction:* It acts on leptons as well as nucleons. When an electron is created in beta decay, another lighter particle called an *antineutrino* is also created and also shoots out of the nucleus.

Without the nuclear strong force—strong interaction—there would be no atoms beyond hydrogen.

Insights

One ton of ordinary granite contains about 9 grams of uranium and 20 grams of thorium. One ton of basalt contains 3.5 grams of uranium and 7.7 grams of thorium.

Insights



(a) Nucleons close together (b) Nucleons far apart

FIGURE 33.8
(a) All nucleons in a small nucleus are close to one another; hence, they experience an attractive strong nuclear force. (b) Nucleons on opposite sides of a larger nucleus are not as close to one another, and so the attractive strong nuclear forces holding them together are much weaker. The result is that the large nucleus is less stable.

Half-Life

THE Physics Place
Half-Life

The radioactive decay rate of an element is measured in terms of a characteristic time, the **half-life.** This is the time it takes for half of an original quantity of a radioactive isotope to decay. Radium-226, for example, has a half-life of 1620 years. This means that half of any given specimen of radium-226 will be converted into other elements by the end of 1620 years. In the following 1620 years, half of the remaining radium will decay, leaving only one-fourth the original amount of radium (after 20 half-lives, the initial quantity radium-226 will be diminished by a factor of about one million). Cobalt-60, a standard source for radiotherapy, has a half-life of 5.27 years. The isotopes of some elements have a half-life of less than a millionth of a second, while uranium-238, for example, has a half-life of 4.5 billion years. Every isotope of every radioactive element has its own characteristic half-life.

The radioactive half-life of a material is also the time for its decay rate to reduce to half.

Insights

Many elementary particles have very short half-lives. The muon (a close relative of the electron), which is produced when cosmic rays bombard atomic nuclei in the upper atmosphere, has a half-life of 2 millionths of a second (2×10^{-6}s)—actually a very long time on the subnuclear scale. The shortest half-lives of elementary particles are on the order of 10^{-23} second, the time light takes to travel a distance equal to the diameter of a nucleus.

The half-lives of radioactive elements and elementary particles appear to be absolutely constant, unaffected by any external conditions, however drastic. Wide temperature and pressure extremes, strong electric and magnetic fields, and even violent chemical reactions have no detectable effect on the rate of decay of a given element. Any of these stresses, although severe by ordinary standards, is far too mild to affect the nucleus in the deep interior of the atom.

It is not necessary to wait through the duration of a half-life in order to measure it. The half-life of an element can be calculated at any given moment by measuring the rate of decay of a known quantity. This is easily done using a radiation detector. In general, the shorter the half-life of a substance, the faster it disintegrates and the greater its decay rate.

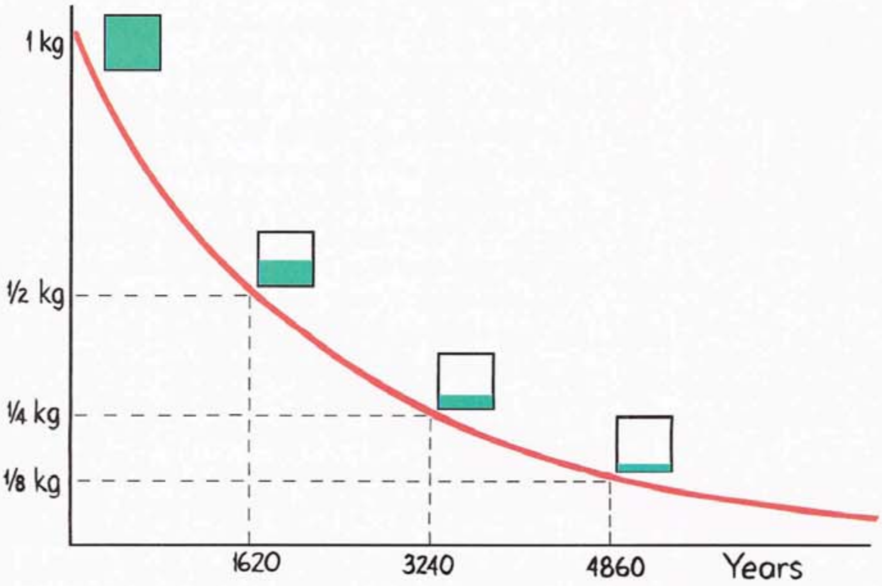


FIGURE 33.9
Interactive Figure
Every 1620 years, the amount of radium decreases by half.

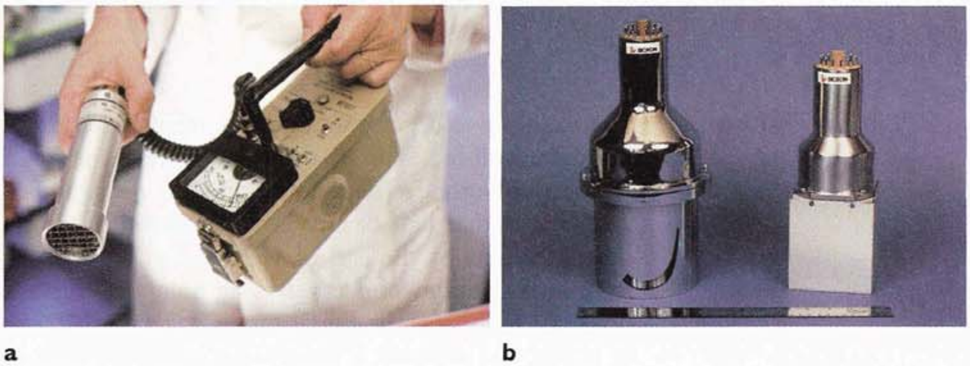


FIGURE 33.10
Radiation detectors. (a) A Geiger counter detects incoming radiation by the way the radiation ionizes a gas enclosed in the tube. (b) A scintillation counter indicates incoming radiation by flashes of light produced when charged particles or gamma rays pass through the counter.

Radiation Detectors

Ordinary thermal motions of atoms bumping one another in a gas or liquid are not energetic enough to dislodge electrons, and the atoms remain neutral. But, when an energetic particle such as an alpha or a beta particle shoots through matter, electrons one after another are knocked from the atoms in the particle's path. The result is a trail of freed electrons and positively charged ions. This ionization process is responsible for the harmful effects of high-energy radiation in living cells. Ionization also makes it relatively easy to trace the paths of high-energy particles. We will briefly discuss five radiation detection devices.

1. A *Geiger counter* consists of a central wire in a hollow metal cylinder filled with low-pressure gas. An electrical voltage is applied across the cylinder and wire so that the wire is more positive than the cylinder. If radiation enters the tube and ionizes an atom in the gas, the freed electron is attracted to the positively charged central wire. As this electron is accelerated toward the wire, it collides with other atoms and knocks out more electrons, which, in turn, produce more electrons, and so on, resulting in a cascade of electrons moving toward the wire. This makes a short pulse of electric current, which activates a counting device connected to the tube. Amplified, this pulse of current produces the familiar clicking sound we associate with radiation detectors.

FIGURE 33.11
A cloud chamber. Charged particles moving through supersaturated vapor leave trails. When the chamber is in a strong electric or magnetic field, bending of the tracks provides information about the charge, mass, and momentum of the particles.

2. A *cloud chamber* shows a visible path of ionizing radiation in the form of fog trails. It consists of a cylindrical glass chamber closed at the upper end by a glass window and at the lower end by a movable piston. Water vapor or alcohol vapor in the chamber can be saturated by adjusting the piston.

   The radioactive sample is placed inside the chamber, as shown in Figure 33.11, or outside the thin glass window. When radiation passes through the chamber, ions are produced along its path. If the saturated air in the chamber is then suddenly cooled by motion of the piston, tiny droplets of moisture condense about these ions and form vapor trails, showing the paths of the radiation. These are the atomic versions of the ice-crystal trails left in the sky by jet planes.

   Even simpler is the continuous cloud chamber. This has a steady supersaturated vapor, because it rests on a slab of dry ice, so there is a temperature gradient from near room temperature at the top to very low temperature at the bottom. In either version, the fog tracks that form are illuminated with a lamp and may be seen or photographed through the glass top. The chamber may be placed in a strong electric or magnetic field, which will bend the paths in a manner that provides information about the charge, mass, and momentum of the radiation particles. Positively and negatively charged particles will bend in opposite directions.

Cloud chambers, which were critically important tools in early cosmic-ray research, are now used principally for demonstration. Perhaps your instructor will show you one, as does Walter Steiger on page 634.

3. The particle trails seen in a *bubble chamber* are minute bubbles of gas in liquid hydrogen (Figure 33.12). The liquid hydrogen is heated under pressure in a glass and stainless steel chamber to a point just short of boiling. If the pressure in the chamber is suddenly released at the moment an ion-producing particle enters, a thin trail of bubbles is left along the particle's path. All the liquid erupts to a boil, but, in the few thousandths of a second before this happens, photographs are taken of the particle's short-lived trail. As with the cloud chamber, a magnetic field in the bubble chamber reveals the charge and relative mass of the particles being studied. Bubble chambers have been widely used by researchers in past decades, but presently there is greater interest in spark chambers.
4. A *spark chamber* is a counting device that consists of an array of closely spaced parallel plates; every other plate is grounded, and the plates in between are maintained at a high voltage (about 10 kV). Ions are produced in the gas between the plates as charged particles pass through the chamber. Discharge along the ionic path produces a visible spark between pairs of plates. A trail of many sparks reveals the path of the particle. A different design, called a *streamer chamber,* consists of only two widely spaced plates, between which an electric discharge, or "streamer," closely follows the path of the incident charged particle. The principal advantage of spark and streamer chambers over the bubble chamber is that more events can be monitored in a given time.
5. A *scintillation counter* uses the fact that certain substances are easily excited and emit light when charged particles or gamma rays pass through them. Tiny flashes of light, or scintillations, are converted into electric signals by special photomultiplier tubes. A scintillation counter is

FIGURE 33.12
Tracks of elementary particles in a bubble chamber. (The trained eye notes that two particles were destroyed at the point where the spirals emanate, with four others created in the collision.) Note that this image graces the cover of this book, illustrating both the micro and macro physics about us.

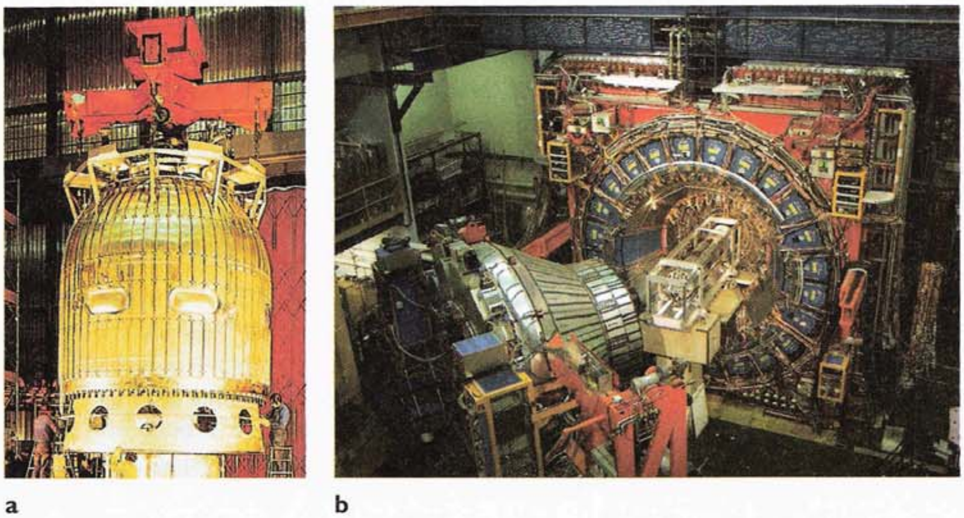


FIGURE 33.13
(a) Installation of the Big European Bubble Chamber (BEBC) at CERN, near Geneva, typical of the large bubble chambers used in the 1970s to study particles produced by high-energy accelerators. The 3.7-m cylinder contained liquid hydrogen at −173°C. (b) The collider detector at Fermilab, which detects and records myriad events when particle beams collide. The detector stands two stories tall, weighs 4500 tons, and was built by a collaboration of more than 170 physicists from the U.S., Japan, and Italy and was built by an international collaboration of about 500 physicists from various countries.

much more sensitive to gamma rays than a Geiger counter, and, in addition, it can measure the energy of charged particles or gamma rays absorbed in the detector. Ordinary water, when highly purified, can serve as a scintillator.

CHECK YOURSELF

1. If a sample of a radioactive isotope has a half-life of 1 day, how much remains at the end of the second day? At the end of the third day?
2. What becomes of isotopes that undergo alpha decay?
3. Which produces a higher counting rate on a radiation detector—a gram of radioactive material having a short half-life, or a gram having a long half-life?

Transmutation of Elements

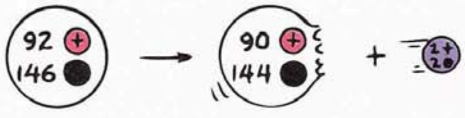
When a radioactive nucleus emits an alpha or a beta particle, there is a change in atomic number—a different element is formed. This changing of one chemical element to another is called **transmutation.** Transmutation occurs in natural events and is also initiated artificially in the laboratory.

CHECK YOUR ANSWERS

1. At the end of the first day, it decays to one-half. At the end of the second day, it decays to half of this half. Half of one-half is one-fourth. So it decays to one-fourth, and, for a pure sample, one-fourth of the original sample will remain. Can you see that, at the end of three days, one-eighth of the original isotope remains?
2. They become altogether different elements, elements two steps down in atomic number.
3. The material with the shorter half-life decays more quickly and registers a higher counting rate on a radiation detector.

Natural Transmutation

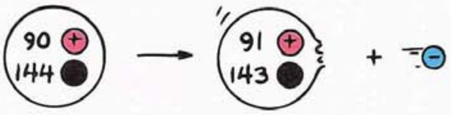
Consider uranium-238, the nucleus of which contains 92 protons and 146 neutrons. When an alpha particle is ejected, the nucleus is reduced by two protons and two neutrons (an alpha particle is a helium nucleus consisting of two protons and two neutrons). An element is defined by the number of protons in its nucleus, so the 90 protons and 144 neutrons left behind are no longer uranium but the nucleus of a different element—*thorium*. This reaction is expressed as



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

The arrow shows that $^{238}_{92}\mathrm{U}$ changes into the two elements to the right of the arrow. When this transmutation occurs, energy is released in three forms; partly as gamma radiation, partly as kinetic energy of the recoiling thorium atom, and mostly as kinetic energy of the alpha particle ($^{4}_{2}\mathrm{He}$). In equations such as this, the mass numbers at the top ($238 = 234 + 4$) and the atomic numbers at the bottom ($92 = 90 + 2$) balance.

Thorium-234, the product of this reaction, is also radioactive. When it decays, it emits a beta particle. Recall that a beta particle is an electron—not an orbital electron but one created within the nucleus. You may find it useful to think of a neutron as a combined proton and electron (although it's not really the case) because, when the electron is emitted, a neutron becomes a proton.[2] A neutron is ordinarily stable when it is locked in a nucleus, but a free neutron is radioactive and has a half-life of 12 minutes. It decays into a proton by beta emission. So, in the case of thorium, which has 90 protons, beta emission leaves the nucleus with one less neutron and one more proton. The new nucleus then has 91 protons and is no longer thorium but the element *protactinium*. Although the atomic number has increased by 1 in this process, the mass number (protons + neutrons) remains the same. The nuclear equation is



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

We write an electron as $^{0}_{-1}e$. The 0 indicates that the electron mass is closer to zero than to the 1 of protons and neutrons, which alone contribute to the mass number. The -1 is the charge of the electron. Remember that this electron is

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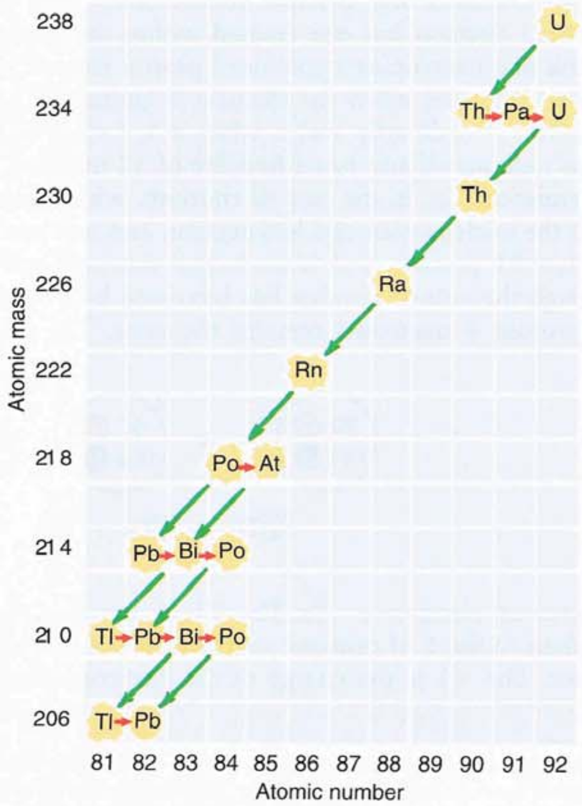
[2] Beta emission is always accompanied by the emission of a neutrino (actually an antineutrino), a neutral particle that travels at about the speed of light. The neutrino ("little neutral one," named by Enrico Fermi) was postulated to retain conservation laws by Wolfgang Pauli in 1930 and detected in 1956. Detecting neutrinos is difficult because they interact very weakly with matter. Millions of them fly through you every second of every day because the universe is filled with them. Only one or two times a year does a neutrino or two interact with the matter of your body.

a beta particle from the nucleus and not an electron from the electron cloud that surrounds the nucleus.

We can see that, when an element ejects an alpha particle from its nucleus, the mass number of the resulting atom decreases by 4 and its atomic number decreases by 2. The resulting atom belongs to an element two places back in the periodic table. When an element ejects a beta particle (electron) from its nucleus, the mass of the atom is practically unaffected, so there is no change in mass number, but its atomic number *increases* by 1. The resulting atom belongs to an element one place forward in the periodic table. Gamma emission results in no change in either the mass number or the atomic number. So we see that the emission of an alpha or beta particle by an atom produces a different atom in the periodic table. Alpha emission lowers the atomic number and beta emission increases it. Radioactive elements can decay backward or forward in the periodic table.[3]

The radioactive decay of $^{238}_{92}\text{U}$ to $^{206}_{82}\text{Pb}$, an isotope of lead, is shown in the decay-scheme chart in Figure 33.14. Each nucleus that plays a role in the decay scheme is shown by a burst. The vertical column containing the burst shows its atomic number, and the horizontal column shows its mass number. Each green arrow shows an alpha decay, and each red arrow shows a beta decay. Notice that some of the nuclei in the series can decay in both ways. This is one of several similar radioactive series that occur in nature.

FIGURE 33.14
U-238 decays to Pb-206 through a series of alpha (green) and beta (red) decays.



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[3] Sometimes a nucleus emits a positron, which is the "antiparticle" of an electron. In this case, a proton becomes a neutron, and the atomic number is decreased.

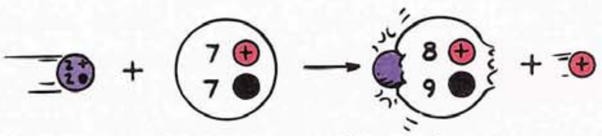
CHECK YOURSELF

1. Complete the following nuclear reactions.
   a. ${}^{228}_{88}\text{Ra} \rightarrow {}^{?}_{?}? + {}^{0}_{-1}e$
   b. ${}^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{?}_{?}?$
2. What is the end result of all the uranium-238 that undergoes radioactive decay?

Artificial Transmutation

The alchemists of old tried vainly for more than 2000 years to cause the transmutation of one element into another. Enormous efforts were expended and elaborate rituals performed in the quest to change lead into gold. They never succeeded. Lead, in fact, can be transformed into gold, but not by the chemical means employed by the alchemists. Chemical reactions involve alterations of the outermost shells of the electron clouds of atoms and molecules. To change an element from one kind to another, one must go deep within the electron clouds to the central nucleus, which is immune to the most violent chemical reactions. To change lead into gold, three positive charges must be extracted from the nucleus. Ironically enough, transmutations of atomic nuclei were constantly occurring all around the alchemists, as they are around us today. Radioactive decay of minerals in rocks has been occurring since their formation. But this was unknown to the alchemists, who lacked a model of matter that could have led to the discovery of these radiations. Had alchemists used the high-speed particles ejected from radioactive ores as bullets, they would have succeeded in transmuting some of the atoms in a substance. But the atoms so transmuted would most likely have escaped their notice.

Ernest Rutherford, in 1919, was the first of many investigators to succeed in deliberately transmuting a chemical element. He bombarded nitrogen nuclei with alpha particles and succeeded in transmuting nitrogen into oxygen:



$${}^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H}$$

CHECK YOUR ANSWERS

1. **a.** ${}^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}e$
   b. ${}^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{4}_{2}\text{He}$
2. All uranium-238 will ultimately become lead-206. Along the way to becoming lead, it will exist as various isotopes of various elements, as indicated in Figure 33.14.

TABLE 33.1
Transuranic Elements

Atomic Number	*Mass Number*	*Name*	*Symbol*	*Discovery Date*
93	237	Neptunium	Np	1940
94	244	Plutonium	Pu	1940
95	243	Americium	Am	1944
96	247	Curium	Cm	1944
97	247	Berkelium	Bk	1949
98	251	Californium	Cf	1950
99	252	Einsteinium	Es	1952
100	257	Fermium	Fm	1952
101	258	Mendelevium	Md	1955
102	259	Nobelium	No	1958
103	262	Lawrencium	Lr	1961
104	261	Rutherfordium	Rf	1964
105	262	Dubnium	Db	1967
106	266	Seaborgium	Sg	1974
107	264	Bohrium	Bh	1981
108	269	Hassium*	Hs	1984
109	268	Meitnerium	Mt	1982
110	271	Darmstadtium*	Ds	1994
111	272	Roentgenium	Rg	1994
112	285	Unnamed		1996
114	289	Unnamed		1998
116	292	Unnamed		2000

*Hassium is named for Hesse (in its Latin spelling), the German state in which the Darmstadt laboratory is located. Other locations recognized by element names are America, Berkeley, California, and Dubna. People honored by heavy-element names are Marie Curie, Albert Einstein, Enrico Fermi, Dmitri Mendele'ev, Alfred Nobel, Ernest Lawrence, Ernest Rutherford, Glenn Seaborg, Niels Bohr, Lise Meitner, and Wilhelm Roentgen, representing nine countries.

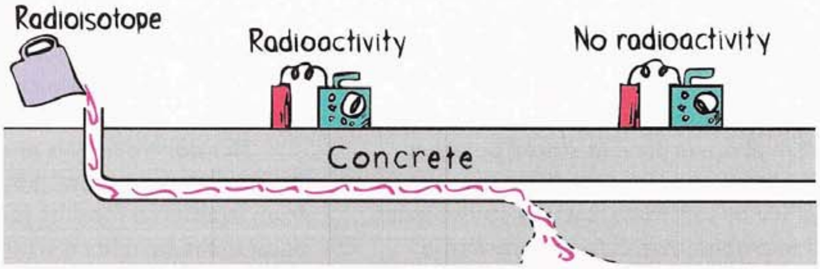
Rutherford's source of alpha particles was a radioactive piece of ore. From a quarter-of-a-million cloud-chamber tracks photographed on movie film, he showed seven examples of atomic transmutation. Analysis of tracks bent by a strong external magnetic field showed that, when an alpha particle collided with a nitrogen atom, a proton bounced out and the heavy atom recoiled a short distance. The alpha particle disappeared. The alpha particle was absorbed by the nitrogen nucleus, transforming nitrogen to oxygen.

Following Rutherford's success with transmutation, experimenters produced many such nuclear reactions, first with natural bombarding projectiles from radioactive ores and then with still more energetic projectiles—protons and electrons hurled by huge particle accelerators. Artificial transmutation is what produces the hitherto unknown elements from atomic number 93 to 116 (with the odd-numbered elements 113, 115, and beyond 117 yet to be discovered). Table 33.1 lists the known elements beyond uranium as of 2005. All these artificially made elements have short half-lives. Whatever transuranic elements existed naturally when Earth was formed have long since decayed.

Radioactive Isotopes

All the elements have been made radioactive by bombardment with neutrons and other particles. Radioactive materials are extremely useful in scientific research and industry. In order to check the action of a fertilizer, for example, researchers combine a small amount of radioactive material with the fertilizer and then apply the combination to a few plants. The amount of radioactive fertilizer absorbed by the plants can be easily measured with radiation detectors. From such measurements, scientists can inform farmers about proper usages of fertilizer. When used in this way, radioactive isotopes are called *tracers*.

FIGURE 33.15
Tracking pipe leaks with radioactive isotopes.



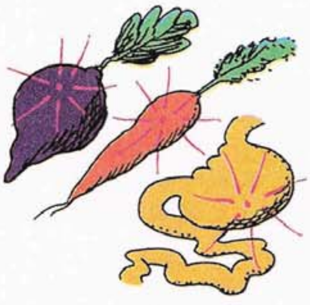


FIGURE 33.16
Radioisotopes are used to check the action of fertilizers in plants and the progression of food in digestion.

Tracers are widely used in medicine to diagnose disease. Small quantities of particular radioactive isotopes, after being injected into the bloodstream, concentrate at trouble spots, such as at bone fractures or tumors. Using radiation detectors, medical staff can locate isotope concentrations.

Engineers can study how the parts of an automobile engine wear away during use by making the cylinder walls radioactive. While the engine is running, the piston rings rub against the cylinder walls. The tiny particles of radioactive metal that are worn away fall into the lubricating oil, where they can be measured with a radiation detector. By repeating this test with different oils, the engineer can determine which oil provides the least wear and longest life to the engine.

Tire manufacturers also employ radioactive isotopes. If a known fraction of the carbon atoms used in an automobile tire is radioactive, the amount of rubber left on the road when the car is braked can be estimated through a count of the radioactive atoms.

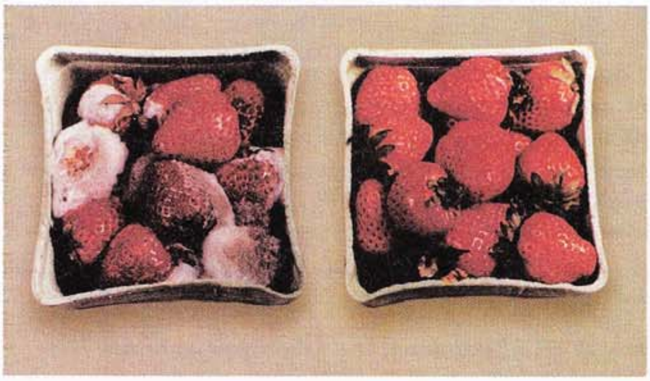


FIGURE 33.17
The shelf-life of fresh strawberries and other perishables is markedly increased when the food is subjected to gamma rays from a radioactive source. The strawberries on the right were treated with gamma radiation, which kills the microorganisms that normally lead to spoilage. The food is only a receiver of radiation and is in no way transformed into an emitter of radiation, as can be confirmed with a radiation detector.

FOOD IRRADIATION

Each week in the United States about 100 people, most of them children or elderly, die from illnesses they contract from food. People stricken ill each week from foodborne diseases number in the millions, according to the Centers for Disease Control and Prevention in Atlanta, Georgia. But never astronauts. Why? Because diarrhea in orbit is a no-no, and food taken on space missions is irradiated with high-energy gamma rays from a radioactive-cobalt source (Co-60). Astronauts, as well as patients in many hospitals and nursing homes, don't have to contend with salmonella, *E. coli*, microbes, or parasites in food irradiated by Co-60. So why isn't more irradiated food available in the marketplace? The answer is public phobia about the *r* word—*radiation*.

Food irradiation kills insects in grains, flour, fruits, and vegetables. Small doses prevent stored potatoes, onions, and garlic from sprouting, and significantly increase the shelf life of soft fruits, such as strawberries. Larger doses kill microbes, insects, and parasites in spices, pork, and poultry. Irradiation can penetrate through sealed cans and packages. What irradiation does *not* do is leave the irradiated food radioactive. No radioactive material touches the food. Gamma rays pass through the food like light passing through glass, destroying most bacteria that can cause disease. No food becomes radioactive, for the gamma rays lack the energy needed to knock neutrons from atomic nuclei.

Irradiation does, however, leave behind traces of broken compounds—identical to those resulting from pyrolysis when charbroiling foods we already eat. Compared with canning and cold storage, irradiation has less effect on nutrition and taste. It's been around for most of the 1900s, and it has been tested for more than 40 years, with no evidence of danger to consumers. Irradiation of foods is endorsed by all major scientific societies, the United Nations' World Health Organization, the U.S. Food and Drug Administration, and the American Medical Association. Irradiation is the method of choice for 37 countries worldwide. Although widely used in Belgium, France, and the Netherlands, its use in the United States is presently small, as controversy continues.

This controversy is another example of risk evaluation and management. Shouldn't risks of injury or death from irradiated food be judged rationally and weighed against the benefits it would bring? Shouldn't the choice be based upon the number of people who *might* die of irradiated food versus those who in fact *do* die because food is not irradiated?

Perhaps what is needed is a name change—expunging the *r* word, as was done with the *n* word when the resisted medical procedure once known as NMRI (nuclear magnetic resonance imaging) was given a more acceptable name, MRI (magnetic resonance imaging).

There are hundreds more examples of the use of trace amounts of radioactive isotopes. The important thing is that this technique provides a way to detect and count atoms in samples of materials too small to be seen with a microscope.

When radioactivity is used in medicine for treatment rather than diagnosis, intense radiation is needed. Strong, short-lived sources of radiation can be used to destroy cancer cells, such as in the thyroid gland or the prostate gland.

CHECK YOURSELF

Suppose that you want to find out how much gasoline is in an underground storage tank. You pour in one gallon of gasoline that contains some radioactive material with a long half-life that gives off 5000 counts per minute. The next day, you remove a gallon from the underground tank and measure its radioactivity to be 10 counts per minute. How much gasoline is in the tank?

CHECK YOUR ANSWER

There are 500 gallons in the tank since, after mixing, the gallon you withdraw has $10/5000 = 1/500$ of the original radioactive particles in it.

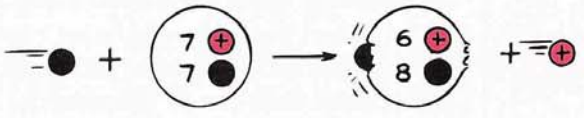
Radiometric Dating

Radioactive decay provides scientists who study Earth history and human history a remarkable method for determining the ages of materials. The method depends on a knowledge of the half-lives of radioactive materials. For materials that were once alive, age can be found by a comparison of carbon isotopes in the material. For nonorganic substances, isotopes of uranium, potassium, and other elements are examined.

Carbon Dating

THE Physics Place
Carbon Dating

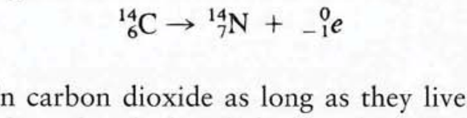
Earth's atmosphere is continuously bombarded by cosmic rays that produce transmutation of many atoms in the upper atmosphere. These transmutations result in many protons and neutrons being "sprayed out" into the environment. Most of the protons quickly capture electrons and become hydrogen atoms in the upper atmosphere. The neutrons, however, continue for longer distances because they have no charge and therefore do not interact electrically with matter. Eventually, many of them collide with atomic nuclei in the denser lower atmosphere. When nitrogen captures a neutron, it becomes an isotope of carbon by emitting a proton:



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

This carbon-14 isotope is radioactive and has 8 neutrons (the most common stable isotope, carbon-12, has 6 neutrons). Less than one-millionth of 1% of the carbon in the atmosphere is carbon-14. Both carbon-12 and carbon-14 join with oxygen to become carbon dioxide, which is absorbed by plants. This means that all plants contain a tiny bit of radioactive carbon-14. All animals eat either plants or plant-eating animals and therefore have a little carbon-14 in them. In short, all living things on Earth contain some carbon-14.

Carbon-14 is a beta emitter and decays back to nitrogen:



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

Because plants take in carbon dioxide as long as they live, any carbon-14 lost to decay is immediately replenished with fresh carbon-14 from the atmosphere. In this way, a radioactive equilibrium is reached where there is a ratio of about one carbon-14 atom to every 100 billion carbon-12 atoms. When a plant dies, replenishment stops. Then the percentage of carbon-14 decreases at a constant rate given by its radioactive half-life. The longer a plant or animal is dead, the less carbon-14 it contains.

The half-life of carbon-14 is about 5730 years. This means that half of the carbon-14 atoms now present in a plant or animal that dies today will decay

FIGURE 33.18
The radioactive carbon isotopes in the skeleton diminish by one-half every 5730 years. A skeleton today contains only a fraction of the carbon-14 it originally had. The red arrows symbolize relative amounts of carbon-14.

in the next 5730 years. Half of the remaining carbon-14 atoms will then decay in the following 5730 years, and so forth. The radioactivity of living things gradually decreases at a steady rate after they die.

With this knowledge, archeologists are able to calculate the age of carbon-containing artifacts, such as wooden tools or skeletons, by measuring their current level of radioactivity. This process, known as *carbon-14 dating,* enables us to probe as much as 50,000 years into the past.

Carbon dating would be an extremely simple and accurate dating method if the amount of radioactive carbon in the atmosphere had been constant over the ages. But it hasn't been. Fluctuations in the Sun's and Earth's magnetic fields affect cosmic-ray intensities in Earth's atmosphere, which, in turn, produce fluctuations in the amount of carbon-14 in the atmosphere at any given time. In addition, changes in Earth's climate affect the amount of carbon dioxide in the atmosphere. The oceans are great reservoirs of carbon dioxide. When the oceans are cold, they release less carbon dioxide into the atmosphere than when they are warm. Because of all these fluctuations in the production of carbon-14 through the centuries, carbon dating has an uncertainty of about 15%. This means, for example, that the straw of an old adobe brick that is dated to be 500 years old may really be only 425 years old on the low side, or 575 years old on the high side. For many purposes, this is an acceptable level of uncertainty. Laser-enrichment techniques using milligrams of carbon produce smaller uncertainties, and these techniques are used for dating more ancient relics. A technique that bypasses a radioactive measure altogether uses a mass spectrometer device that makes a C-14/C-12 count directly.

CHECK YOURSELF

Suppose an archeologist extracts 1 gram of carbon from an ancient ax handle and finds it to be one-fourth as radioactive as 1 gram of carbon extracted from a freshly cut tree branch. About how old is the ax handle?

CHECK YOUR ANSWER

Assuming the ratio of C-14/C-12 was the same when the ax was made, the ax handle is as old as two half-lives of C-14, or about 11,460 years old.

Uranium Dating

The dating of older, but nonliving, things is accomplished with radioactive minerals such as uranium. The naturally occurring isotopes U-238 and U-235 decay very slowly and ultimately become isotopes of lead—but not the common lead isotope Pb-208. For example, U-238 decays through several stages to finally become Pb-206. U-235, on the other hand, decays to become the isotope Pb-207. Thus, any Pb-206 and Pb-207 that now exist in a uranium-bearing rock were, at one time, uranium. The older the rock, the higher the percentage of these remnant isotopes.

From the half-lives of uranium isotopes and the percentage of lead isotopes in uranium-bearing rock, it is possible to calculate the date at which the rock was formed. Rocks dated in this way have been found to be as much as 3.7 *billion* years old. Samples from the Moon, where there has been an absence of erosion, have been dated at 4.2 billion years, an age that agrees closely with the estimated 4.6-billion-year age of Earth and the rest of the solar system.

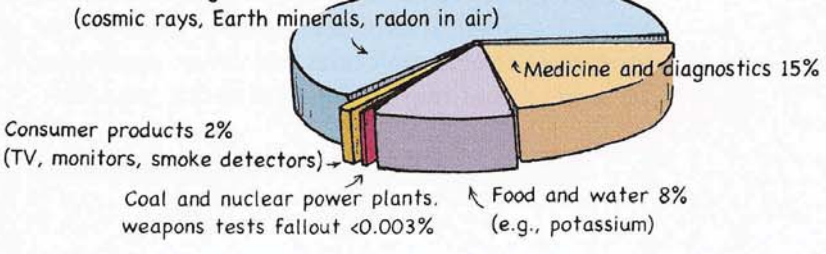
Other widely used isotopes include potassium-40 (with a half-life of 1.25 billion years) and rubidium-87 (with a half-life of 49 billion years). As with uranium dating, age is determined by measuring the relative percentage of a given isotope in the material in question.

Effects of Radiation on Humans

A common misconception is that radioactivity is something new in the environment. But radioactivity has been around far longer than the human race. It is as much a part of our surroundings as the Sun and the rain. It is what warms the interior of the Earth and makes it molten. In fact, radioactive decay inside the Earth is what heats the water that spurts from a geyser or that wells up from a natural hot spring. Even the helium in a child's balloon is the offspring of radioactivity. Its nuclei are nothing more than the alpha particles that were once ejected by radioactive nuclei.

As Figure 33.19 shows, more than 98% of our annual exposure to radiation comes from food and water, natural background radiation, and medical and dental X-rays. Fallout from nuclear testing and the coal and nuclear power industries are minor contributors in comparison. Amazingly, the coal industry far outranks the nuclear power industry as a source of radiation. The global combustion of coal annually releases about 16,000 tons of radioactive thorium and about 7000 tons of radioactive uranium into the atmosphere (with nearly 50 tons being fissionable U-235!). Worldwide, the nuclear power industries

FIGURE 33.19
Origins of radiation exposure for an average individual in the United States.



generate about 10,000 tons of radioactive waste each year. Most all of this waste, however, is contained and *not* released into the environment.

An average ton of coal contains 1.3 ppm of uranium and 3.2 ppm of thorium. That's why the average coal-burning power plant is a far greater source of airborne radioactive material than a nuclear power plant.

Insights

Most of the radiation we encounter originates in the natural environment. It is in the ground we stand on and in the bricks and stones of surrounding buildings. Every ton of ordinary granite contains, on average, some 20 grams of thorium and 9 grams of uranium. Because of the traces of radioactive elements in most all rocks, people who live in brick, concrete, or stone buildings are exposed to greater amounts of radiation than people who live in wooden buildings. This natural background radiation was present before humans emerged in the world. If our bodies couldn't tolerate it, we wouldn't be here. Apart from radioactivity, we are bombarded by cosmic rays. At sea level, the protective blanket of the atmosphere reduces cosmic-ray intensity; at higher altitudes, radiation is more intense. In Denver, the "mile-high city," a person receives more than twice as much radiation from cosmic rays as at sea level. Frequent flyers receive significant radiation exposure. (Is the air time of airline personnel limited because of this extra radiation?)

Even the human body is a source of natural radiation, primarily from the potassium in the food we eat. Our bodies contain about 200 grams of potassium. Of this quantity, about 20 milligrams is the radioactive isotope potassium-40. Between every heartbeat, about 5,000 potassium-40 atoms undergo spontaneous radioactive decay. Added to this are some 3,000 beta particles per second emitted by the carbon-14 in your body. We and all living creatures are to some degree radioactive.

FIGURE 33.20
A commercially available radon test kit for the home.

The leading source of naturally occurring external radiation is radon-222, an inert gas arising from uranium deposits. Radon is a heavy gas that tends to accumulate in basements after it seeps up through cracks in the basement floor. Levels of radon vary from region to region, depending upon local geology. You can check the radon level in your home with a radon detector kit. If levels are abnormally high, corrective measures, such as sealing the basement foundation and maintaining adequate ventilation, are recommended.

Exposure to radiation greater than normal background should be avoided because of the damage it can do.[4] The cells of living tissue are composed of intricately structured molecules in a watery, ion-rich brine. When X-radiation or nuclear radiation encounters this highly ordered soup, it produces chaos on the atomic scale. A beta particle, for example, passing through living matter collides with a small percentage of the molecules and leaves a randomly dotted trail of altered or broken molecules along with newly formed, chemically active ions and free radicals. Free radicals are unbonded, electrically neutral, very chemically active atoms or molecular fragments. The ions and free radicals may dissociate more molecular bonds or they may quickly form strong new bonds, forming molecules that may be useless or harmful to the cell. Gamma radiation produces a similar effect. As a high-energy gamma-ray photon moves through matter, it may rebound from an electron and give the electron a high kinetic energy. The electron then may careen through the tissue, creating havoc in the ways described above. All types of high-energy radiation break or alter the structure of some molecules and create conditions in which other molecules will be formed that may be harmful to life processes.

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[4] For some cancer patients, a high level of radiation, carefully directed, can be beneficial by selectively killing cancer cells. This is the province of radiation oncology.

Cells are able to repair most kinds of molecular damage, if the radiation is not too intense. A cell can survive an otherwise lethal dose of radiation if the dose is spread over a long period of time to allow intervals for healing. When radiation is sufficient to kill cells, the dead cells can be replaced by new ones. An important exception to this is most nerve cells, which are irreplaceable. Sometimes a radiated cell will survive with a damaged DNA molecule. Defective genetic information will be transmitted to offspring cells when the damaged cell reproduces, and a cell *mutation* will occur. Mutations are usually insignificant, but, if they are significant, they will probably result in cells that do not function as well as undamaged ones. A genetic change of this type could also be part of the cause of a cancer that will develop later. In rare cases, a mutation may be an improvement.

The concentration of disorder produced along the trajectory of a particle depends upon its energy, charge, and mass. Gamma-ray photons and very energetic beta particles spread their damage out over a long track. They penetrate deeply with widely separated interactions, like a very fast BB fired through a hailstorm. Slow, massive, highly charged particles, such as low-energy alpha particles, do their damage in the shortest distance. They have collisions that are close together, more like a bull charging through a flock of sleepy sheep. They do not penetrate deeply because their energy is absorbed by many closely spaced collisions. Particles that produce especially concentrated damage are the assorted nuclei (called *heavy primaries*) flung outward by the Sun in solar flares and existing in small percentages of cosmic radiation. These include all the elements found on Earth. Some of them are captured in Earth's magnetic field and some are stopped by collisions in the atmosphere, so practically none reaches Earth's surface. We are shielded from most of these dangerous particles by the very property that makes them a threat—their tendency to have many collisions close together.

Astronauts do not have this protection, and they absorb large doses of radiation during their time in space. Every few decades there is an exceptionally powerful solar flare that would almost certainly kill any conventionally protected astronaut who is unprotected by Earth's atmosphere and magnetic field.

We are bombarded most by what harms us least—neutrinos. Neutrinos are the most weakly interacting particles. They have near-zero mass, no charge, and are produced frequently in radioactive decays. They are the most common high-speed particles known, zapping the universe and passing unhindered through our bodies by many millions every second. They pass completely through the Earth with only occasional encounters. It would take a "piece" of lead 6 light years in thickness to absorb half the neutrinos incident upon it. Only about once per year, on the average, a neutrino triggers a nuclear reaction in your body. We don't hear much about neutrinos because they fail to interact with us.

Of the radiations we have focused upon in this chapter, gamma radiation is the most penetrating and therefore the hardest to shield against. This, combined with its ability to interact with the matter in our bodies, makes it potentially the most dangerous radiation. It emanates from radioactive materials, and it makes up a substantial part of the normal background radiation. Exposure to it should be minimized.

FIGURE 33.21
International symbol that indicates an area where radioactive material is being handled or produced.

CHECK YOURSELF

1. People working around radioactivity wear film badges to monitor radiation levels reaching their bodies. These badges consist of a small piece of photographic film enclosed in a light-proof wrapper. What type of radiation do these devices monitor, and how can they determine the amount of radiation a body receives?
2. Suppose you are given three radioactive cookies—one an alpha emitter, one a beta emitter, and one a gamma emitter. You must eat one, hold one in you hand, and put the third in your pocket. What can you do to minimize your exposure to radiation?

Radiation Dosage

FIGURE 33.22
The film badges attached to the lapels of Tammy's and Larry's lab coats contain audible alerts for both radiation surge and accumulated exposure. The badges are individualized and information from them is periodically downloaded to a database and a complete picture of these lab workers' exposure levels and those of others in the same radioactive environment are analyzed.

Radiation dosage is measured in *rads* (short for radiation), a unit of absorbed energy of ionizing radiation. The number of rads indicates the amount of radiation energy absorbed per gram of exposed material. However, in contexts in which we are concerned with the potential ability of radiation to affect human beings, dosage is measured in *rems* (*r*oentgen *e*quivalent *m*an). In calculating the dosage in rems, the number of rads is multiplied by a factor allowing for the different health effects of different types of radiation. For example, 1 rad of slow alpha particles has the same biological effect as 10 rads of fast electrons. Both of these dosages are 10 rems.

The average person in the United States is exposed to about 0.2 rem per year. This comes from within the body itself, from the ground, buildings, cosmic rays, diagnostic X-rays, television, and so on. It varies widely from place to place on the planet, but it is stronger at higher elevations, where cosmic radiation is more intense, and strongest near the poles, where the Earth's magnetic field doesn't shield against cosmic rays.

A lethal dose of radiation is on the order of 500 rems; that is, a person has about a 50% chance of surviving a dose of this magnitude if it is received over a short period of time. Under radiotherapy—the use of radiation to kill cancer cells—a patient may receive localized doses in excess of 200 rems each day for a period of weeks. A typical diagnostic chest X-ray exposes a person to 5 to 30 millirems, less than one ten-thousandth of the lethal dose. However, even small doses of radiation can produce long-term effects due to mutations within

CHECK YOUR ANSWERS

1. Alpha rays and most beta rays don't penetrate the film wrapper, so the type of radiation that makes it to the film is mostly gamma radiation. Like light on photographic film, greater intensity means greater exposure, as noted by how black the film becomes.
2. Ideally, you should get far away from all the cookies. But, if you must eat one, hold one, and put one in your pocket, hold the alpha because the skin on your hand will shield you. Put the beta in your pocket because your clothing will likely shield you. Eat the gamma because it will penetrate your body in any of these cases anyway.

the body's tissues. And, because a small fraction of any X-ray dose reaches the gonads, some mutations occasionally occur that are passed on to the next generation. Medical X-rays for diagnosis and therapy have a far larger effect on the human genetic heritage than any other artificial source of radiation. Perspective dictates that we keep in mind the fact that we normally receive significantly more radiation from natural minerals in the Earth than from all artificial sources of radiation combined.

Taking all causes into account, most of us will receive a lifetime exposure of less than 20 rems, distributed over several decades. This makes us a little more susceptible to cancer and other disorders. But more significant is the fact that all living beings have always absorbed natural radiation and that the radiation received in the reproductive cells has produced genetic changes in all species for generation after generation. Small mutations selected by nature for their contributions to survival can, over billions of years, gradually produce some interesting organisms—*us,* for example!

Summary of Terms

X-ray Electromagnetic radiation of higher frequencies than ultraviolet; emitted by electron transitions to the lowest energy states in atoms.

Radioactivity Process of the atomic nucleus that results in the emission of energetic subatomic particles.

Alpha ray A stream of alpha particles (helium nuclei) ejected by certain radioactive elements.

Beta ray A stream of electrons (or positrons) emitted during the radioactive decay of certain nuclei.

Gamma ray High-frequency electromagnetic radiation emitted by the nuclei of radioactive atoms.

Nucleon A nuclear proton or neutron; the collective name for either or both.

Quarks The elementary constituent particles or building blocks of nuclear matter.

Atomic number A number associated with an atom, equal to the number of protons in the nucleus or, equivalently, to the number of electrons in the electron cloud of a neutral atom.

Isotopes Atoms whose nuclei have the same number of protons but different numbers of neutrons.

Atomic mass A number associated with an atom, equal to the number of nucleons in the nucleus.

Atomic mass unit (amu) Standard unit of atomic mass, based on the mass of the common carbon nucleus, which is arbitrarily given the value of exactly 12. An amu of value 1 is one-twelfth the mass of this common carbon nucleus.

Half-life The time required for half the atoms in a sample of a radioactive isotope to decay.

Transmutation The conversion of an atomic nucleus of one element into an atomic nucleus of another element through a loss or gain in the number of protons.

Review Questions

X-Rays and Radioactivity

1. What did the physicist Roentgen discover about a cathode-ray beam striking a glass surface?
2. What is the similarity between a beam of X-rays and a beam of light? What is the principal difference between the two?
3. What did the physicist Becquerel discover about uranium?
4. What two elements did Pierre and Marie Curie discover?

Alpha, Beta, and Gamma Rays

5. Why are gamma rays not deflected in a magnetic field?
6. What is the origin of a beam of gamma rays? A beam of X-rays?

The Nucleus

7. Why is the mass of an atom practically equal to the mass of its nucleus?
8. What are *quarks*?
9. Name three different leptons.

Isotopes

10. Give the atomic number for deuterium and the atomic number for tritium.
11. Give the atomic mass number for deuterium and the atomic mass number for tritium.
12. Distinguish between an *isotope* and an *ion*.

Why Atoms Are Radioactive

13. What prevents protons in the nucleus from flying apart due to electrical repulsion?

14. Why do protons in a very large nucleus have a greater chance of flying apart?

15. Why is a larger nucleus generally less stable than a smaller nucleus?

Half-Life

16. What is meant by *radioactive half-life*?

17. What is the half-life of Ra-226? Of a muon?

Radiation Detectors

18. What kind of trail is left when an energetic particle shoots through matter?

19. Which two radiation detectors operate primarily by sensing the trails left by energetic particles that shoot through matter?

Transmutation of Elements

20. What is transmutation?

Natural Transmutation

21. When thorium (atomic number 90) decays by emitting an alpha particle, what is the atomic number of the resulting nucleus?

22. When thorium decays by emitting a beta particle, what is the atomic number of the resulting nucleus?

23. What is the change in atomic mass for each of the above two reactions?

24. What change in atomic number occurs when a nucleus emits an alpha particle? A beta particle? A gamma ray?

25. What is the long-range fate of all the uranium that exists in the world?

Artificial Transmutation

26. The alchemists of old believed that elements could be changed into other elements. Were they correct? Were they effective? Why or why not?

27. When, and by whom, did the first successful intentional transmutation of an element occur?

28. Why are the elements beyond uranium not common in the Earth's crust?

Radioactive Isotopes

29. How are radioactive isotopes produced?

30. What is a radioactive *tracer*?

Radiometric Dating

31. What specific knowledge is needed to enable the dating of historic objects?

Carbon Dating

32. What occurs when a nitrogen nucleus captures an extra neutron?

33. How many carbon-14 atoms are present in nature compared with carbon-12?

34. Why is the quantity of C-14 in new bones greater than in old bones of the same mass?

Uranium Dating

35. Why is lead found in all deposits of uranium ores?

36. What does the proportion of lead and uranium in a rock tell us about the age of the rock?

Effects of Radiation on Humans

37. Where does most of the radiation you encounter originate?

38. Is the human body radioactive?

Radiation Dosage

39. What is the average annual radiation dosage for the average person in the U.S.? What is an average dose from medical X-rays? What is the lethal dose?

40. Which gives humans the greatest radiation dose, radiation from natural minerals in Earth or from artificial sources?

Project

Write a letter to Grandma to dispel any notion she or her friends might have about radioactivity being something new in the world. Tie this to the idea that many people have the strongest views on that which they understand the least.

Exercises

1. In the nineteenth century, the famous physicist Lord Kelvin estimated the age of the Earth to be much much less than the present estimate. What information that Kelvin did not have might have allowed him to avoid making his erroneous estimate?

2. X-rays are most similar to which of the following—alpha, beta, or gamma rays?

3. Gamma radiation is fundamentally different from alpha and beta radiation. What is this basic difference?

4. Why is a sample of radioactive material always a little warmer than its surroundings?

5. Some people say that all things are possible. Is it at all possible for a common hydrogen nucleus to emit an alpha particle? Defend your answer.

6. Why are alpha and beta rays deflected in opposite directions in a magnetic field? Why are gamma rays not deflected?

7. The alpha particle has twice the electric charge of the beta particle but, for the same kinetic energy, deflects less than the beta in a magnetic field. Why is this so?

8. How do the paths of alpha, beta, and gamma rays compare in an electric field?

9. Which type of radiation—alpha, beta, or gamma—produces the greatest change in *mass number* when emitted by an atomic nucleus? Which produces the greatest change in *atomic number*?

10. Which type of radiation—alpha, beta, or gamma—produces the least change in mass number? In atomic number?

11. Which type of radiation—alpha, beta, or gamma—predominates within an enclosed elevator descending into a uranium mine?

12. In bombarding atomic nuclei with proton "bullets," why must the protons be accelerated to high energies if they are to make contact with the target nuclei?

13. Just after an alpha particle leaves the nucleus, would you expect it to speed up? Defend your answer.

14. What do all isotopes of the same element have in common? How do they differ?

15. Why would you expect alpha particles, with their greater charge, to be less able to penetrate into materials than beta particles of the same energy?

16. Two protons in an atomic nucleus repel each other, but they are also attracted to each other. Explain.

17. Which interaction tends to hold the particles in an atomic nucleus together and which interaction tends to push them apart?

18. What evidence supports the contention that the strong nuclear interaction can dominate over the electrical interaction at short distances within the nucleus?

19. Can it be truthfully said that, whenever a nucleus emits an alpha or beta particle, it necessarily becomes the nucleus of another element?

20. Exactly what is a positively charged hydrogen atom?

21. Why do different isotopes of the same element have the same chemical properties?

22. If you make an account of 1000 people born in the year 2000 and find that half of them are still living in 2060, does this mean that one-quarter of them will be alive in 2120 and one-eighth of them alive in 2180? What is different about the death rates of people and the "death rates" of radioactive atoms?

23. Radiation from a point source obeys the inverse-square law. If a Geiger counter 1 m from a small sample registers 360 counts per minute, what will be its counting rate 2 m from the source? What will it be 3 m from the source?

24. Why do the charged particles flying through bubble chambers travel in spiral paths rather than in the circular or helical paths they might ideally follow?

25. What two quantities are always conserved in all nuclear equations?

26. Judging from Figure 33.14, how many alpha and beta particles are emitted in the series of radioactive decay events from a U-238 nucleus to a Pb-206 nucleus?

27. If an atom has 104 electrons, 157 neutrons, and 104 protons, what is its approximate atomic mass? What is the name of this element?

28. When a ${}^{226}_{88}\text{Ra}$ nucleus decays by emitting an alpha particle, what is the atomic number of the resulting nucleus? What is the resulting atomic mass?

29. When a nucleus of ${}^{218}_{84}\text{Po}$ emits a beta particle, it transforms into the nucleus of a new element. What is the atomic number and the atomic mass of this new element?

30. When a nucleus of ${}^{218}_{84}\text{Po}$ emits an alpha particle, what is the atomic number and the atomic mass of the resulting element?

31. Which has the greater number of protons, U-235 or U-238? Which has the greater number of neutrons?

32. State the number of neutrons and protons in each of the following nuclei: ${}^{2}_{1}\text{H}$, ${}^{12}_{6}\text{C}$, ${}^{56}_{26}\text{Fe}$, ${}^{197}_{79}\text{Au}$, ${}^{90}_{38}\text{Sr}$, and ${}^{238}_{92}\text{U}$.

33. How is it possible for an element to decay "forward in the periodic table"—that is, to decay to an element of higher atomic number?

34. How could an element emit alpha and beta particles and result in the same element?

35. When radioactive phosphorus (P) decays, it emits a positron. Will the resulting nucleus be another isotope of phosphorus? If not, what will it be?

36. "Strontium-90 is a pure beta source." How could a physicist test this statement?

37. A friend suggests that nuclei are composed of equal numbers of protons and electrons, and not neutrons. What evidence can you cite to show that your friend is mistaken?

38. Radium-226 is a common isotope on Earth, but it has a half-life of about 1600 years. Given that the Earth is some 5 billion years old, why is there any radium left at all?

39. Elements above uranium in the periodic table do not exist in any appreciable amounts in nature because they have short half-lives. Yet there are several elements below uranium in atomic number with equally short half-lives that do exist in appreciable amounts in nature. How can you account for this?

40. Your friend says that the helium used to inflate balloons is a product of radioactive decay. Another friend disagrees. With whom do you agree?

41. Another friend, fretful about living near a fission power plant, wishes to get away from radiation by traveling to the high mountains and sleeping out at night on granite outcroppings. What comment do you have about this?

42. Still another friend has journeyed to the mountain foothills to escape the effects of radioactivity altogether. While bathing in the warmth of a natural hot spring, she wonders aloud how the spring gets its heat. What do you tell her?

43. Although coal contains only minute quantities of radioactive materials, there is more radiation emitted by a coal-fired power plant than a fission power plant simply because of the vast amount of coal that is burned in coal-fired plants. What does this indicate about methods of preventing the release of radioactivity that are typically implemented at the two kinds of power plants?

44. A friend produces a Geiger counter to check the local normal background radiation. It clicks, randomly but repeatedly. Another friend, whose tendency is to fear most that which is least understood, makes an effort to avoid Geiger counters and looks to you for advice. What do you say?

45. When food is irradiated with gamma rays from a cobalt-60 source, does the food become radioactive? Defend your answer.

46. When the author attended high school some 50 years ago, his teacher showed a piece of uranium ore and measured its radioactivity with a Geiger counter. Would that reading for the same piece of ore be different today?

47. Why is carbon dating ineffective in finding the ages of dinosaur bones?

48. Is carbon dating appropriate for measuring the age of materials that are a few years old? A few thousand years old? A few million years old?

49. The age of the Dead Sea Scrolls was found by carbon dating. Could this technique apply if they were carved in stone tablets? Explain.

50. Make up two multiple-choice questions that would check a classmate's understanding of radioactive dating.

Problems

1. If a sample of a radioactive isotope has a half-life of 1 year, how much of the original sample will be left at the end of the second year? At the end of the third year? At the end of the fourth year?

2. A sample of a particular radioisotope is placed near a Geiger counter, which is observed to register 160 counts per minute. Eight hours later, the detector counts at a rate of 10 counts per minute. What is the half-life of the material?

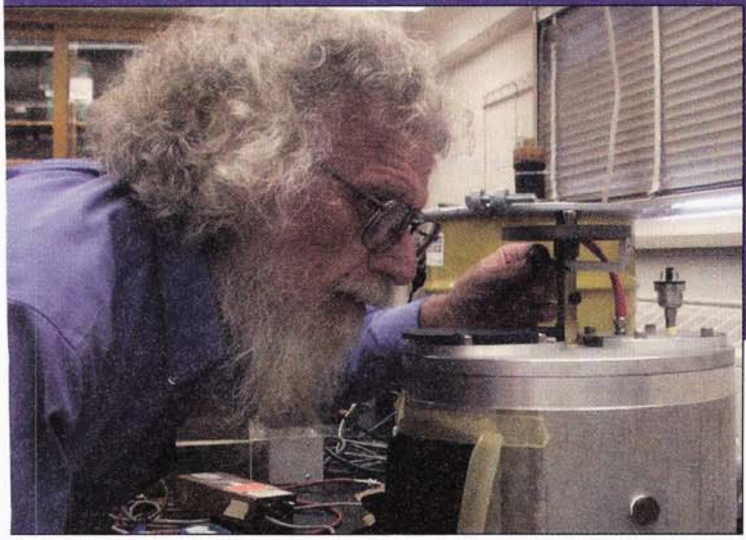
3. The isotope cesium-137, which has a half-life of 30 years, is a product of nuclear power plants. How long will it take for this isotope to decay to about one-sixteenth its original amount?

4. A certain radioactive isotope has a half-life of one hour. If you start with 1 g of the material at noon, how much of the original isotope will the sample contain at 3:00 p.m.? At 6:00 p.m.? At 10:00 p.m.?

5. Suppose that you measure the intensity of radiation from carbon-14 in an ancient piece of wood to be 6% of what it would be in a freshly cut piece of wood. How old is this artifact?

CHAPTER 34

Nuclear Fission and Fusion



Dean Zollman investigates nuclear properties with a modern version of Rutherford's scattering experiment.

THE Physics Place
Nuclear Physics

In December 1938, two German scientists, Otto Hahn and Fritz Strassmann, made an accidental discovery that was to change the world. While bombarding a sample of uranium with neutrons in the hope of creating new heavier elements, they were astonished to find chemical evidence for the production of barium, an element about half the mass of uranium. They were reluctant to believe their own results. Hahn sent news of this discovery to his former colleague Lise Meitner, a refugee from Nazism working in Sweden. Over the Christmas holidays, she discussed it with her nephew Otto Frisch, also a German refugee, who was visiting her from Denmark, where he worked with Niels Bohr. Together, they came up with the explanation: The uranium nucleus, activated by neutron bombardment, had split in two. Meitner and Frisch named the process *fission*, after the similar process of cell division in biology.[1]

Nuclear Fission

THE Physics Place
Nuclear Fission

Nuclear fission involves a delicate balance within the nucleus between nuclear attraction and the electrical repulsion between protons. In all known nuclei, the nuclear forces dominate. In uranium, however, this domination is tenuous. If the uranium nucleus is stretched into an elongated shape (Figure 34.1), the electrical forces may push it into an even more elongated shape. If the elongation passes a critical point, nuclear forces yield to electrical ones, and the nucleus separates. This is fission.[2] The absorption of a neutron by a uranium nucleus

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[1] Similarly, Ernest Rutherford used a biological term when he chose the word *nucleus* for the center of an atom.

[2] Fission resulting from neutron absorption is called *induced fission*. In rare instances nuclei can also undergo *spontaneous fission* without initial neutron absorption. There is evidence that at least one such major spontaneous fission event occurred in Africa almost two billion years ago when the percentage of U-235 in uranium deposits was greater (see *Scientific American*, July 1976). Interestingly, when U-235 absorbs a neutron it momentarily becomes U-236, which splits in half almost instantaneously. So, strictly speaking, it is U-236, not U-235, that undergoes fission. It's common, however, to speak of the fission of U-235.