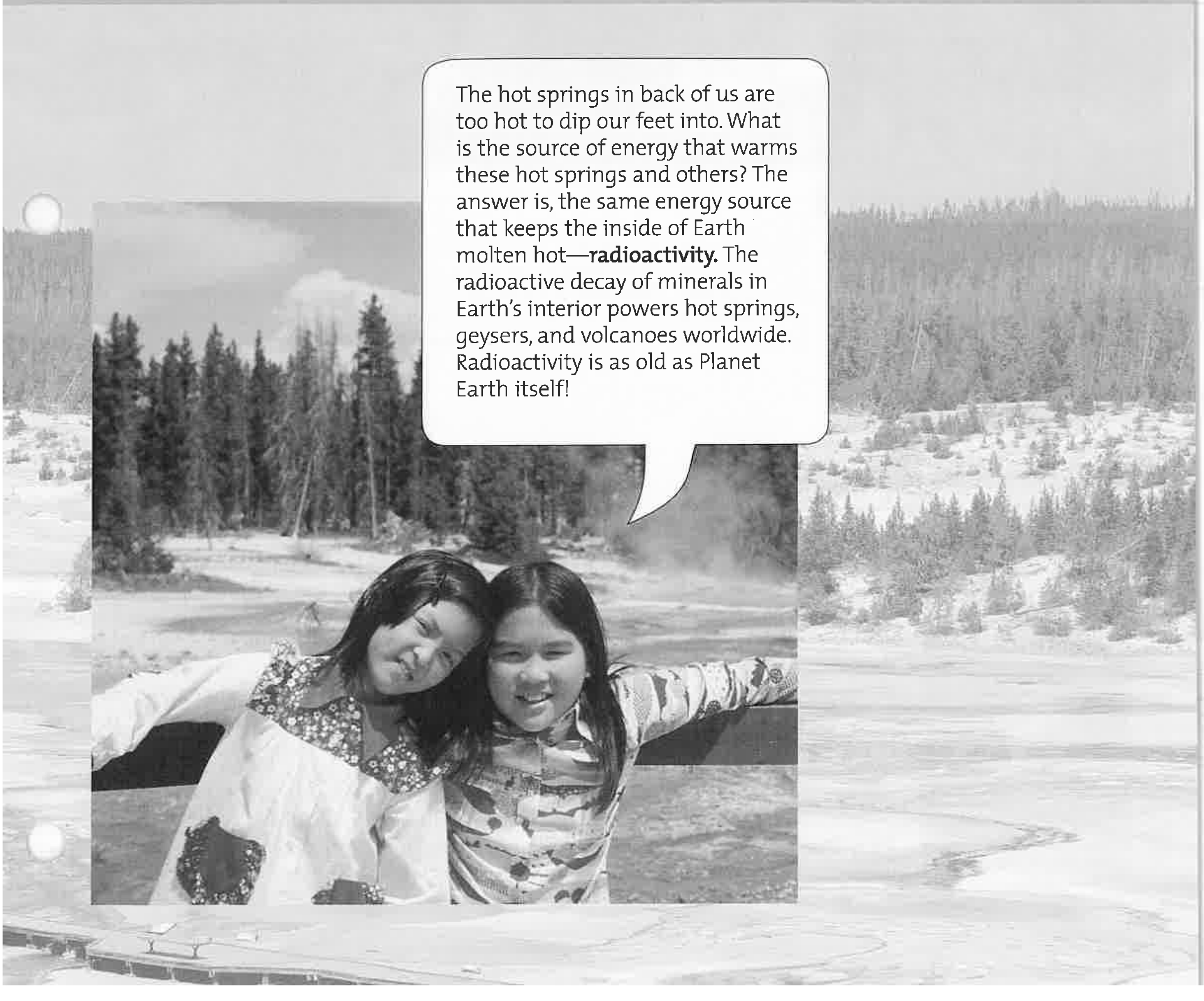
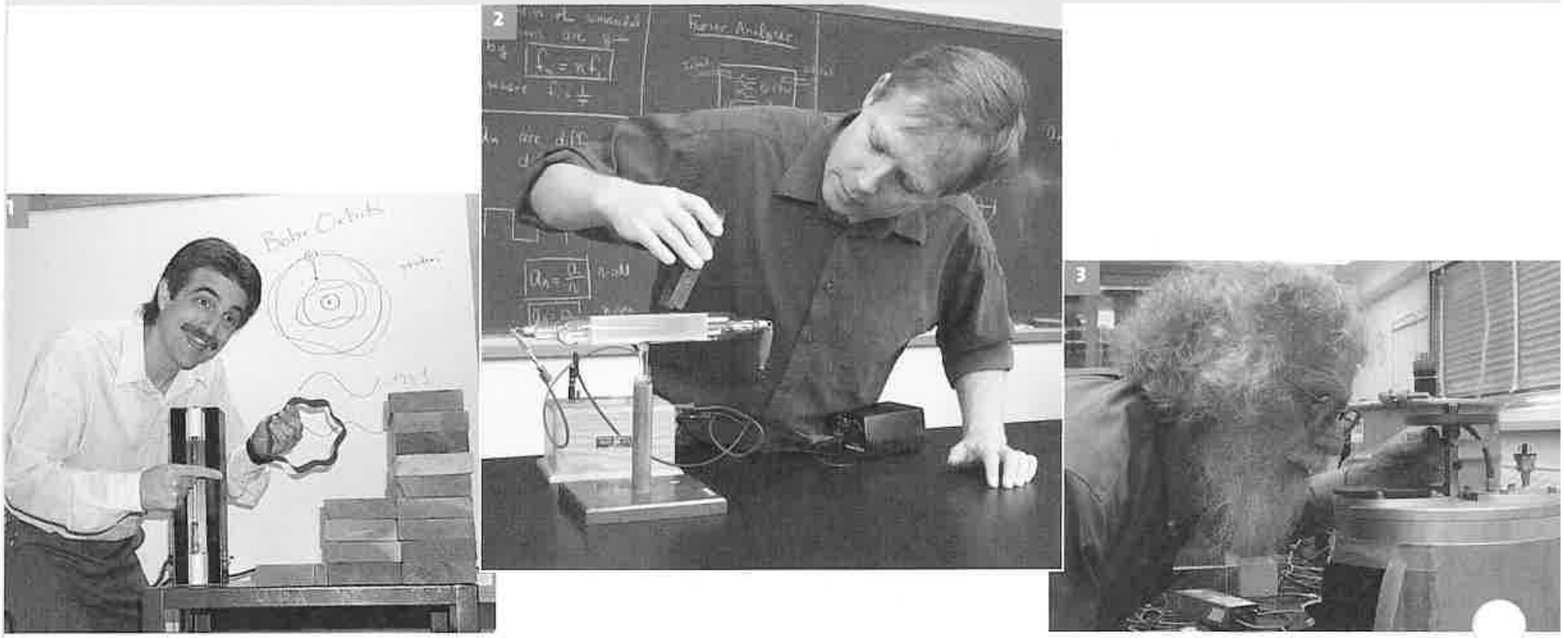
Part Seven

Atomic and Nuclear Physics



The hot springs in back of us are too hot to dip our feet into. What is the source of energy that warms these hot springs and others? The answer is, the same energy source that keeps the inside of Earth molten hot—**radioactivity.** The radioactive decay of minerals in Earth's interior powers hot springs, geysers, and volcanoes worldwide. Radioactivity is as old as Planet Earth itself!

32 The Atom and the Quantum



These three physicists who excel in their teaching bring quantum physics down to Earth for their students. 1 David Kagan uses a strip of corrugated plastic in class to model an orbiting electron. The stacked wood blocks model electron energy levels. 2 Roger King uses a magnet to bend an electron beam in a Crooke's tube. 3 Dean Zollman investigates nuclear properties with a modern version of Rutherford's scattering experiment.

Niels Bohr was born in Copenhagen, Denmark, in 1885. His father, a Lutheran, was a professor of physiology at the University of Copenhagen. His mother came from a wealthy Jewish family prominent in Danish banking and parliamentary circles. His brother, Harald Bohr, was a mathematician and Olympic soccer player on the Danish national team. Niels was passionate about soccer as well, and the two brothers played a number of national matches in Copenhagen.

Neils Bohr (1885–1962)

Bohr earned his physics doctorate in Denmark in 1911. He then worked for a time in the laboratory of J. J. Thomson, the discoverer of the electron, at Trinity College in Cambridge, England, before going on to continue his research under Ernest Rutherford at the University of Manchester, also in England. Rutherford had just discovered that a tiny, positively charged nucleus sits at the center of every atom, surrounded, presumably, by Thomson's electrons. Bohr pondered this new picture of the atom and added quantum principles to it. He published his model of atomic structure in 1913, in which electrons travel only in certain orbits around the atomic nucleus, and the atom emits light when electrons make "quantum jumps" from one orbit to another. His theory brilliantly accounted for the observed spectral lines of hydrogen, the so-called Balmer series as well as other series.

Bohr won the Nobel Prize in physics in 1922 for his work on the quantum theory of atoms, a year after Albert Einstein won the Nobel Prize for his work on the photoelectric effect. After quantum theory evolved and matured in the mid-1920s, Einstein had great reservations about its probabilistic nature, much preferring the determinism of classical physics. He and Bohr debated these two views of physics throughout their lives, always maintaining the greatest respect for each other.

Because Bohr's mother was Jewish, he was in danger in Nazi-occupied Denmark during World War II. In 1943, shortly before an impending arrest, he escaped to Sweden with his family. The Allies, recognizing Bohr's importance, flew him from Sweden to London tucked into the bomb bay of an unarmed Mosquito bomber. Because he forgot to put on his oxygen mask, he passed out. Fortunately, the pilot, sensing that something was wrong when Bohr didn't respond to intercom messages, descended to lower altitude and delivered a still-living passenger to London. Bohr reportedly said that he had slept like a baby during the flight. He then went on to the United States to work on the U.S. Manhattan Project at the top-secret Los Alamos laboratory in New Mexico. For security reasons he was assigned the name of Nicholas Baker during the project.

After the war, Bohr returned to Copenhagen, advocating the peaceful use of nuclear energy and the sharing of nuclear information. When awarded the Order of the Elephant by the Danish government, he designed his own coat of arms, which featured a symbol of yin and yang, with the Latin motto *contraria sunt complementa:* "opposites are complementary."

Bohr's son Aage went on to become a very successful physicist and, like his father, won a Nobel Prize in physics, his in 1975. Niels Bohr died in Copenhagen in 1962. Much of this chapter involves his view of physics.

Discovery of the Atomic Nucleus

Half-a-dozen years after Einstein announced the photoelectric effect, the New Zealand-born British physicist Ernest Rutherford oversaw his now famous gold-foil experiment.[1] This significant experiment showed that the atom is mostly empty space, with most of its mass concentrated in the central region—the *atomic nucleus.*

In Rutherford's experiment, a beam of positively charged particles (alpha particles) from a radioactive source was directed through a sheet of extremely thin gold foil. Because alpha particles are thousands of times more massive than electrons, it was expected that the stream of alpha particles would not be impeded as it passed through the "atomic pudding." This was indeed observed—for the most part. Nearly all alpha particles passed through the gold foil with little or no deflection and produced a spot of light when they hit a fluorescent screen beyond the foil. But some particles were deflected from their straight-line paths as they emerged. A few alpha particles were widely deflected, and a small number were even scattered backward! These alpha particles must have hit something relatively massive—but what? Rutherford reasoned that the undeflected particles traveled through empty space in regions of the gold foil, while the small number of deflected particles were repelled from extremely dense, positively charged central cores. Each atom, he concluded, must contain one of these cores, which he named the **atomic nucleus.**

Rutherford later related that the discovery of alpha particles rebounding backward was the most incredible event of his life—as incredible as if a 15-inch cannon shell rebounded from a piece of tissue paper.

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Atoms and Isotopes

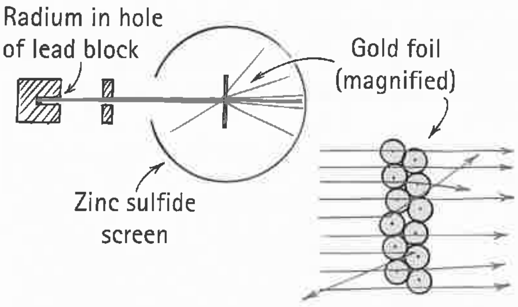

FIGURE 32.1

The occasional large-angle scattering of alpha particles from gold atoms led Rutherford to the discovery of the very massive small nuclei at their centers.

Ernest Rutherford (1871–1937)

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[1] Why "oversaw"? To indicate that more investigators than Rutherford were involved in this experiment. The widespread practice of elevating a single scientist to the position of sole investigator, which seldom is the case, too often denies the involvement of other investigators. There's substance to the saying, "There are two things more important to people than sex and money—*recognition and appreciation.*"

FIGURE 32.2
Franklin's kite-flying experiment.

CHECK POINT

1. What convinced Rutherford that the gold foil was mostly empty space?
2. What convinced him that the particles in empty space were massive?

Check Your Answers

1. Finding most alpha particles were undeflected indicated much empty space.
2. Finding some bounced backward indicated something massive in the empty space.

You'll note much of this chapter is background for chapters already covered—hopefully a "tying-it-together" chapter.

Discovery of the Electron

Surrounding the atomic nucleus are electrons. The name *electron* comes from the Greek word for amber, a brownish-yellow fossil resin studied by the early Greeks. They found that when amber was rubbed by a piece of cloth, it attracted such things as bits of straw. This phenomenon, known as the *amber effect,* remained a mystery for almost 2000 years. In the late 1500s, William Gilbert, Queen Elizabeth's physician, found other materials that behaved like amber, and he called them "electrics." The concept of electric charge awaited experiments by the American scientist-statesman Benjamin Franklin nearly two centuries later. Recall from Chapter 22 that Franklin experimented with electricity and postulated the existence of an electric fluid that could flow from place to place. An object with an excess of this fluid he called *electrically positive,* and one with a deficiency of the fluid he called *electrically negative.* The fluid was thought to attract ordinary matter but to repel itself. Although we no longer talk about electric fluid, we still follow Franklin's lead in how we define positive and negative electricity. Franklin's 1752 experiment with the kite in the lightning storm showed that lightning is an electrical discharge between clouds and the ground. This discovery told him that electricity is not restricted to solid or liquid objects and that it can travel through a gas.

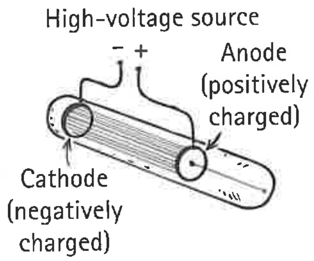

FIGURE 32.3
A simple cathode-ray tube. An electric current is produced in the gas when a high voltage is imposed across the electrodes inside the tube.

Franklin's experiments later inspired other scientists to produce electric currents through various dilute gases in sealed glass tubes. Among these, in the 1870s, was Sir William Crookes, an unorthodox English scientist who believed he could communicate with the dead. He is better remembered for his "Crookes's tube," a sealed glass tube containing gas under very low pressure and with electrodes inside the tube near each end (the forerunner to today's neon signs). The gas glowed when the electrodes were connected to a voltage source (such as a battery). Different gases glowed with different colors. Experiments conducted with tubes containing metal slits and plates showed that the gas was made to glow by some sort of a "ray" emerging from the negative terminal (the *cathode*). Slits could make the ray narrow and plates could prevent the ray from reaching the positive terminal (the *anode*). The apparatus was named the *cathode-ray tube* or CRT (Figure 32.3). When electric charges were brought near the tube, the ray was deflected. It bent toward positive

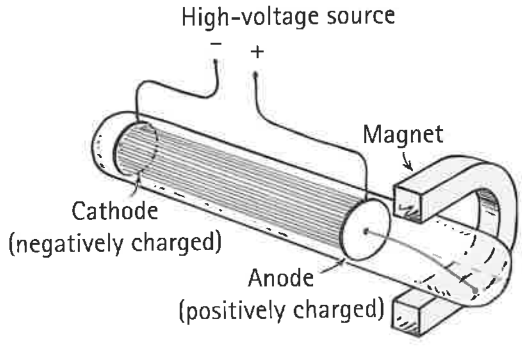

FIGURE 32.4
A cathode ray (electron beam) is deflected by a magnetic field. Deflection is at right angles to the field (not toward either pole).

charges and away from negative charges. The ray was also deflected by the presence of a magnet. These findings indicated that the ray consisted of negatively charged particles.

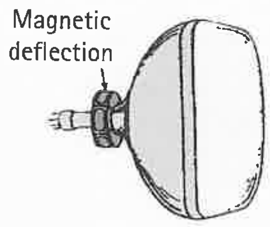

FIGURE 32.5

CRTs like this were common before flat-screen displays largely replaced them.

In 1897, the English physicist Joseph John Thomson ("J. J.," as his friends called him) showed that the cathode rays were particles smaller and lighter than atoms. He created narrow beams of cathode rays and measured their deflection in electric and magnetic fields. Thomson reasoned that the amount of the beams' deflection depended on the mass of the particles and their electrical charge. How? The greater each particle's mass, the greater the inertia and the less the deflection. The greater each particle's charge, the greater the force and the greater the deflection. The greater the speed, the less the deflection.

From careful measurements of the deflection of the beam, Thomson succeeded in calculating the mass-to-charge ratio of the cathode-ray particle, which was named the **electron.** All electrons are identical; they are copies of one another. For establishing the existence of the electron, J. J. Thomson was awarded the Nobel Prize in Physics in 1906.

A dozen years later, in 1909, American physicist Robert Millikan carried out an experiment that enabled him to calculate the numerical value of a single unit of electric charge. In his experiment, Millikan sprayed tiny oil droplets into a chamber between electrically charged plates—into an *electric field.* When the field was strong, some of the droplets moved upward, indicating that they carried a very slight negative charge. Millikan adjusted the field so that droplets hovered motionless. He knew that the downward force of gravity on the droplets was exactly balanced by the upward electrical force. Investigation showed that the charge on each drop was always some multiple of a single very small value, which he proposed to be the fundamental unit of charge carried by each electron. Using this value and the mass-to-charge ratio discovered by Thomson, he calculated the mass of an electron to be about 1/2000 the mass of the lightest known atom, hydrogen. This confirmed Thomson's supposition that the electron is a lightweight and it established the quantum unit of charge. For his work in physics, Millikan received the 1923 Nobel Prize.

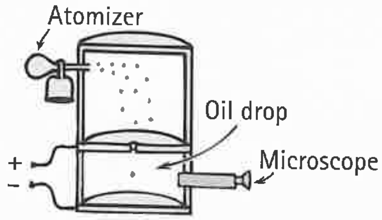

FIGURE 32.6

Millikan's oil-drop experiment for determining the charge on the electron. The pull of gravity on a particular drop can be balanced by an upward electrical force.

If atoms contained negatively charged electrons, it stood to reason that atoms must also contain some balancing positively charged matter. J. J. Thomson proposed what he called a "plum-pudding" model of the atom in which electrons were like plums in a sea of positively charged pudding. The experimentation of Rutherford and the gold-foil experiment, previously mentioned, proved this model wrong.

The electron was the first of many fundamental particles that were later discovered.

Atomic Spectra: Clues to Atomic Structure

During the period of Rutherford's experiments, chemists were using the spectroscope (discussed in Chapter 30) for chemical analysis, while physicists were busily occupied trying to find order in the confusing arrays of spectral lines. It had long been known that the lightest element, hydrogen, has a far more orderly spectrum than the other elements (Figure 32.7). An important sequence of lines in the hydrogen spectrum starts with a line in the red region, followed by one in the blue, then by several lines in the violet, and many in the ultraviolet. Spacing between successive lines becomes smaller and smaller from the first in the red to the last in the ultraviolet, until the lines become so close that they seem to merge. A Swiss schoolteacher, Johann Jakob Balmer, first expressed the wavelengths of these lines in a single mathematical formula in 1884. Balmer, however, was unable to provide a reason why his formula worked so successfully. His guess that his formula could be extended to predict other lines of hydrogen proved to be correct, leading to the prediction of lines that had not yet been measured.

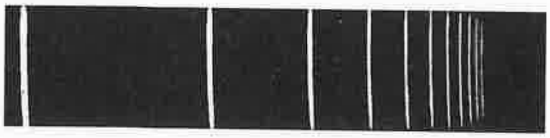

FIGURE 32.7

A portion of the hydrogen spectrum. Each line, an image of the slit in the spectroscope, represents light of a specific frequency emitted by hydrogen gas when excited (higher frequency is to the right).

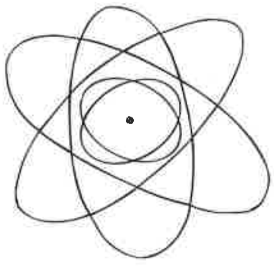

FIGURE 32.8

The Bohr model of the atom. Although this model is very oversimplified, it is still useful in understanding light emission.

Another regularity in atomic spectra was found by the Swedish physicist and mathematician Johannes Rydberg. He noticed that the frequencies of lines in certain series in other elements followed a formula similar to Balmer's and that the sum of the frequencies of two lines in such series often equals the frequency of a third line. This relationship was later advanced as a general principle by the Swiss physicist Walter Ritz and is called the **Ritz combination principle.** It states that the spectral lines of any element include frequencies that are either the sum or the difference of the frequencies of two other lines. Like Balmer, Ritz was unable to offer an explanation for this regularity. These regularities were the clues that the Danish physicist Niels Bohr used to understand the structure of the atom itself.

Bohr Model of the Atom

In 1913, Bohr applied the quantum theory of Planck and Einstein to the nuclear atom of Rutherford and formulated the well-known planetary model of the atom.[2] Bohr reasoned that electrons occupy "stationary" states (of fixed energy, not fixed position) at different distances from the nucleus and that the electrons can make "quantum jumps" from one energy state to another. He reasoned that light is emitted when such a quantum jump occurs (from a higher to a lower energy state). Furthermore, Bohr realized that the frequency of emitted radiation is determined by $E = hf$ (actually, $f = E/h$), where E is the difference in the atom's energy when the electron is in the different orbits. This was an important breakthrough, because he said that the emitted photon's frequency is not the classic frequency at which an electron is vibrating but, instead, is determined by the energy *differences* in the atom (as discussed in Chapter 30). From there, Bohr could advance to the next step and determine the energies of the individual orbits.

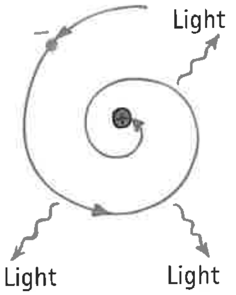

FIGURE 32.9

According to classical theory, an electron accelerating around its orbit should continuously emit radiation. This loss of energy should cause it to spiral rapidly into the nucleus. But this does not happen.

Bohr's planetary model of the atom begged a major question. Accelerated electrons, according to Maxwell's theory, radiate energy in the form of electromagnetic waves. So an electron accelerating around a nucleus should radiate energy continuously. This radiating away of energy should cause the electron to spiral into the nucleus (Figure 32.9). Bohr boldly deviated from classical physics by stating that the electron doesn't radiate light while it accelerates around the nucleus in a single orbit, but that radiation of light occurs only when the electron makes a transition from a higher energy level to a lower energy level. As we now know, the atom emits a photon whose energy is equal to the *difference* in energy between the two energy levels, $E = hf$. As we learned in Chapter 30, the frequency of the emitted photon, its color, depends on the size of the jump. So the quantization of light energy neatly corresponds to the quantization of electron energy.

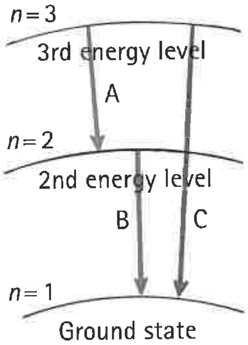

FIGURE 32.10

Three of many energy levels in an atom. An electron jumping from the third level to the second level (red A), and one jumping from the second level to the ground state (green B). The sum of the energies (and the frequencies) for these two jumps equals the energy (and the frequency) of the single jump from the third level to the ground state (blue C).

Bohr's views, as outlandish as they seemed at the time, explained the regularities found in atomic spectra. Bohr's explanation of the Ritz combination principle is shown in Figure 32.10. If an electron is raised to the third energy level, it can return to its initial level either by a single jump from the third to the first level or by a double jump, first to the second level and then to the first level. These two return paths will produce three spectral lines. Note that the sum of the energy jumps along paths A and B is equal to the single energy jump along path C. Since frequency is proportional to energy, the frequencies of light emitted along paths A and B when added equal the frequency of light emitted when the transition is along path C. Now we can see why the sum of two frequencies in the spectrum is equal to a third frequency in the spectrum.

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[2] This model, like most models, has major defects because the electrons do not revolve in planes as planets do. The model was revised; "orbits" became "shells" and "clouds." We use *orbit* because it was, and still is, commonly used. Electrons are not just bodies, like planets, but rather behave like waves concentrated in certain parts of the atom.

Bohr was able to account for X-rays in heavier elements, showing that they are emitted when electrons jump from outer to innermost orbits. He predicted X-ray frequencies that were later experimentally confirmed. Bohr was also able to calculate the "ionization energy" of a hydrogen atom—the energy needed to knock the electron out of the atom completely. This also was verified by experiment.

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Bohr's Shell Model

Using measured frequencies of X-rays as well as visible, infrared, and ultraviolet light, scientists could map energy levels of all the atomic elements. Bohr's model had electrons orbiting in neat circles (or ellipses) arranged in groups or shells. This model of the atom accounted for the general chemical properties of the elements. It also predicted a missing element, which led to the discovery of hafnium.

Bohr solved the mystery of atomic spectra while providing an extremely useful model of the atom. He was quick to stress that his model was to be interpreted as a crude beginning, and the picture of electrons whirling about the nucleus like planets about the Sun was not to be taken literally (to which popularizers of science paid no heed). His sharply defined orbits were conceptual representations of an atom whose later description involved waves—quantum mechanics. His ideas of quantum jumps and frequencies being proportional to energy differences remain part of today's modern theory.

CHECK POINT

1. What is the maximum number of paths for de-excitation available to a hydrogen atom excited to level 3 in changing to the ground state?
2. Two predominant spectral lines in the hydrogen spectrum, an infrared one and a red one, have frequencies 2.7×10^{14} Hz and 4.6×10^{14} Hz, respectively. Can you predict a higher-frequency line in the hydrogen spectrum?

Check Your Answers

1. Two (a single jump and a double jump), as shown in Figure 32.10.
2. The sum of the frequencies is $2.7 \times 10^{14} + 4.6 \times 10^{14} = 7.3 \times 10^{14}$ Hz, which happens to be the frequency of a violet line in the hydrogen spectrum. Using Figure 32.10 as a model, can you see that if the infrared line is produced by a transition similar to path A and the red line corresponds to path B, then the violet line corresponds to path C?

Explanation of Quantized Energy Levels: Electron Waves

Back in Chapter 11 we discussed the different sizes of atoms. This was shown in Figure 11.10. In Chapter 30 we discussed atomic excitation and how atoms emit photons when their electrons make energy-level transitions. The idea that electrons may occupy only certain levels was very perplexing to early investigators and to Bohr himself. It was perplexing because the electron was at first thought to be analogous to a particle, a tiny BB, whirling around the nucleus like a planet whirling around the Sun. Just as a satellite can orbit at any distance from the Sun, it would seem that an electron should be able to orbit around the nucleus at any radial distance—depending, of course, like the satellite, on its speed. Moving among all orbits would enable the electrons to emit all energies of light. But this doesn't happen (recall Figure 32.9). Why the electron occupies only discrete levels is understood by considering the electron to be not a particle but a *wave*.

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Electron Waves

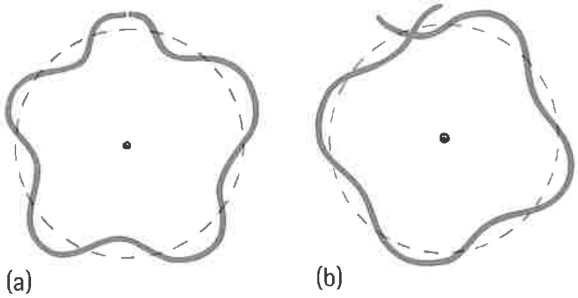

FIGURE 32.11

(a) An orbiting electron forms a standing wave only when the circumference of its orbit is equal to a whole-number multiple of the wavelength.
(b) When the wave does not close in on itself in phase, it undergoes destructive interference. Hence, orbits exist only where waves close in on themselves in phase.

Louis de Broglie introduced the concept of matter waves in 1924. He hypothesized that a wave is associated with every particle and that the wavelength of a matter wave is inversely related to a particle's momentum. These *matter waves* behave just like other waves; they can be reflected, refracted, diffracted, and caused to interfere. Using the idea of interference, de Broglie showed that the discrete values of radii of Bohr's orbits are a natural consequence of standing electron waves. A Bohr orbit exists where an electron wave closes on itself constructively. The electron wave becomes a standing wave, like a wave on a musical string. In this view, the electron is thought of not as a particle located at some point in the atom but as if its mass and charge were spread out into a standing wave surrounding the atomic nucleus—with an integral number of wavelengths fitting evenly into the circumferences of the orbits (Figure 32.11). The circumference of the innermost orbit, according to this picture, is equal to one wavelength. The second orbit has a circumference of two electron wavelengths, the third has three, and so forth (Figure 32.12). This is similar to a chain necklace made of paper clips. No matter what size necklace is made, its circumference is equal to some multiple of the length of a single paper clip.[3] Since the circumferences of electron orbits are discrete, it follows that the radii of these orbits, and hence the energy levels, are also discrete.

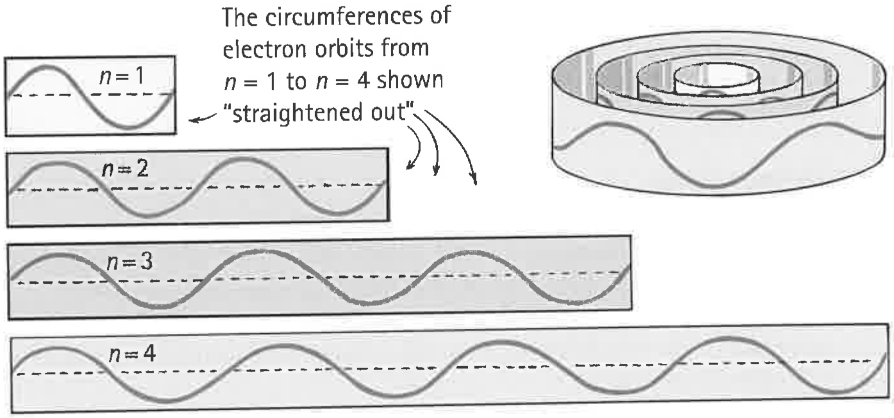

FIGURE 32.12

INTERACTIVE FIGURE

The electron orbits in an atom have discrete radii because the circumferences of the orbits are whole-number multiples of the electron wavelength. This results in a discrete energy state for each orbit. (The figure is greatly oversimplified, as the standing waves make up spherical and ellipsoidal shells rather than flat, circular ones.)

This model explains why electrons don't spiral closer and closer to the nucleus, causing atoms to shrink to the size of the tiny nucleus. If each electron orbit is described by a standing wave, the circumference of the smallest orbit can be no smaller than one wavelength—no fraction of a wavelength is possible in a circular (or elliptical) standing wave. As long as an electron carries the momentum necessary for wave behavior, atoms don't shrink in on themselves.

In the still more modern wave model of the atom, electron waves move not only around the nucleus but also in and out, toward and away from the nucleus. The electron wave is spread out in three dimensions, leading to the picture of an electron "cloud." As we shall see, this is a cloud of *probability*, not a cloud made up of a pulverized electron scattered over space. The electron, when detected, remains a point particle.

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[3] For each orbit, the electron has a unique speed, which determines its wavelength. Electron speeds are less, and wavelengths are longer, for orbits of increasing radii; so, for our analogy to be accurate, we'd have to use not only more paper clips to make increasingly longer necklaces but increasingly larger paper clips as well.

Quantum Mechanics

Many changes in physics occurred in the mid-1920s. Not only was the particle nature of light established experimentally but particles of matter were found to have wave properties. Starting with de Broglie's matter waves, the Austrian physicist Erwin Schrödinger formulated an equation that describes how matter waves change under the influence of external forces. Schrödinger's equation plays the same role in **quantum mechanics** that Newton's equation (acceleration = force/mass) plays in classical physics.[4] The matter waves in Schrödinger's equation are mathematical entities that are not directly observable, so the equation provides us with a purely mathematical rather than a visual model of the atom—which places it beyond the scope of this book. So our discussion will be brief.[5]

In **Schrödinger's wave equation,** the thing that "waves" is the nonmaterial *matter wave amplitude*—a mathematical entity called a *wave function,* represented by the symbol ψ (the Greek letter psi). The wave function given by Schrödinger's equation represents the possibilities that can occur for a system. For example, the location of the electron in a hydrogen atom may be anywhere from the center of the nucleus to a radial distance far away. An electron's possible position and its probable position at a particular time are not the same. A physicist can calculate its probable position by multiplying the wave function by itself ($|\psi|^2$). This produces a second mathematical entity called a *probability density function,* which at a given time indicates the probability per unit volume for each of the possibilities represented by ψ.

Experimentally, there is a finite probability (chance) of finding an electron in a particular region at any instant. The value of this probability lies between the limits 0 and 1, where 0 indicates never and 1 indicates always. For example, if the probability is 0.4 for finding the electron within a certain radius, this signifies a 40% chance that the electron will exist there. So the Schrödinger equation cannot tell a physicist where an electron can be found in an atom at any moment, but only the *likelihood* of finding it there—or, for a large number of measurements, what fraction of measurements will find the electron in each region. When an electron's position in its Bohr energy level (state) is repeatedly measured and each of its locations is plotted as a dot, the resulting pattern resembles a sort of electron cloud (Figure 32.13). An individual electron may, at various times, be detected anywhere in this probability cloud; it even has an extremely small but finite probability of momentarily existing inside the nucleus. It is detected most of the time, however, close to an average distance from the nucleus, which fits the orbital radius described by Niels Bohr.


Erwin Schrödinger (1887–1961)

"I think it is safe to say that no one understands quantum mechanics."—*Richard P. Feynman*

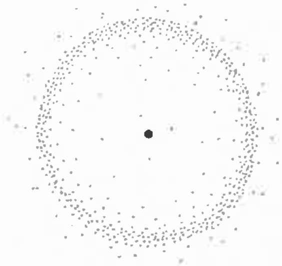
FIGURE 32.13

Probability distribution of an electron cloud for a particular excited state.

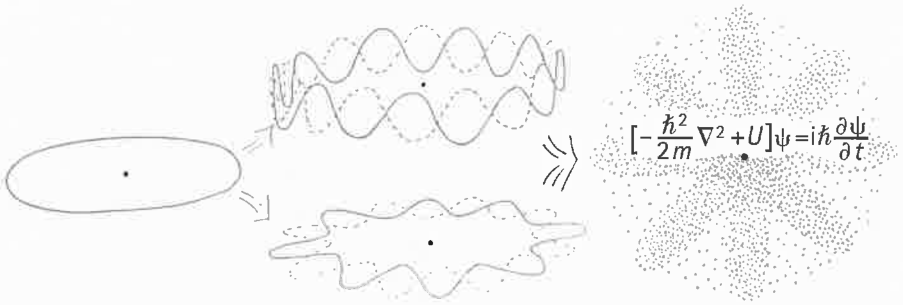

FIGURE 32.14

From the Bohr model of the atom, to the modified model with de Broglie waves, to a wave model with the electrons distributed in a "cloud" throughout the atomic volume.

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[4] Schrödinger's wave equation, strictly for math types, is $\left(-\frac{\hbar^2}{2m}\nabla^2 + U\right)\psi = i\hbar\frac{\partial\psi}{\partial t}$.

[5] Our short treatment of this complex subject is hardly conducive to any real understanding of quantum mechanics. At best, it serves as a brief overview and possible introduction to further study. For example, read Ken Ford's *The Quantum World: Quantum Physics for Everyone.* Harvard University Press, paperback edition 2005.

Most physicists, but not all, view quantum mechanics as a fundamental theory of nature. Interestingly enough, Albert Einstein, one of the founders of quantum physics, never accepted it as fundamental; he considered the probabilistic nature of quantum phenomena as the outcome of a deeper, as yet undiscovered, physics. He stated, "Quantum mechanics is certainly imposing. But an inner voice tells me it is not yet the real thing. The theory says a lot, but does not really bring us closer to the secret of 'the Old One.'"[6]

Considering something to be impossible may reflect a *lack* of understanding, as when scientists thought a single atom could never be seen. Or it may represent a *deep* understanding, as when scientists (and the Patent Office!) reject perpetual motion machines.

CHECK POINT

1. Consider 100 photons diffracting through a thin slit to form a diffraction pattern. If we detect 5 photons in a certain region in the pattern, what is the probability (between 0 and 1) of detecting a photon in this region?
2. Suppose that you open a second identical slit and that the diffraction pattern is one of bright and dark bands. Suppose the region where 5 photons hit before now has none. A wave theory says that waves that hit before are now canceled by waves from the other slit—that crests and troughs combine to zero. But our measurement is of photons that either make a hit or don't. How does quantum mechanics reconcile this?

Check Your Answers

1. We have approximately a 0.05 probability of detecting a photon at this location. The true probability could be somewhat more or less than 0.05. Put the other way around, if the true probability is 0.05, the number detected could be somewhat more or less than 5.
2. Quantum mechanics says that photons propagate as waves and are absorbed as particles, with the probability of absorption governed by the maxima and minima of wave interference. Where the combined wave from the two slits has zero amplitude, the probability of a particle being absorbed is zero.

Correspondence Principle

The correspondence principle is a general rule not only for good science but for all good theory—even in areas as far removed from science as government, religion, and ethics. If a new theory is valid, it must account for the verified results of the old theory. This is the **correspondence principle,** first articulated by Bohr. New theory and old theory must correspond; that is, they must overlap and agree in the region where the results of the old theory have been fully verified.

Bohr introduced the correspondence principle in connection with his 1913 theory of the hydrogen atom. He reasoned that when an electron is in a highly excited state, orbiting far from the atomic nucleus, its behavior should resemble (correspond to) classical behavior. And indeed when an electron in such a highly excited state makes a series of quantum jumps, from one state to the next lower one and on downward, it emits photons of gradually increasing frequency that match its own frequency of motion. It seems to spiral inward, as classical physics predicts.

When the techniques of quantum mechanics are applied to still larger systems, the results are essentially identical with those of classical mechanics. The two domains blend when the de Broglie wavelength is small compared with the dimensions of the system or of the pieces of matter in the system. It is satisfying to know that quantum theory and classical theory, which make such completely different

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[6] Although Einstein practiced no religion, he often invoked God as the "Old One" in his statements about the mysteries of nature.

predictions at the level of a single atom, blend smoothly into a description of nature that extends from the smallest to the largest things in the universe.

SUMMARY OF TERMS

Atomic nucleus Positively charged center of an atom, containing protons and neutrons and almost the entire mass of the atom, but only a tiny fraction of its volume.

Electron Negative particle in the outer part of an atom.

Ritz combination principle The statement that the frequencies of some spectral lines of the elements are either the sums or the differences of the frequencies of two other lines.

Quantum mechanics The theory of the microworld based on wave functions and probabilities developed especially by Werner Heisenberg (1925) and Erwin Schrödinger (1926).

Schrödinger's wave equation A fundamental equation of quantum mechanics, which relates probability wave amplitudes to the forces acting on a system. It is as basic to quantum mechanics as Newton's laws of motion are to classical mechanics.

Correspondence principle The rule that a new theory must produce the same results as the old theory where the old theory is known to be valid.

REVIEW QUESTIONS

Discovery of the Atomic Nucleus

1. Why do most alpha particles fired through a piece of gold foil emerge almost undeflected, and why do others bounce backward?
2. What did Rutherford discover about the atomic nucleus?

Discovery of the Electron

3. What did Benjamin Franklin postulate about electricity?
4. What is a cathode ray?
5. What property of a cathode ray is indicated when a magnet is brought near the tube?
6. What did J. J. Thomson discover about the cathode ray?
7. What did Robert Millikan discover about the electron?

Atomic Spectra: Clues to Atomic Structure

8. What did Johann Jakob Balmer discover about the spectrum of hydrogen?
9. What did Johannes Rydberg and Walter Ritz discover about atomic spectra?

Bohr Model of the Atom

10. What relationship between electron orbits and light emission did Bohr postulate?
11. According to Niels Bohr, can a single electron in one excited state give off more than one photon when it jumps to a lower energy state?
12. What is the relationship between the energy differences of orbits in an atom and the light emitted by the atom?

Explanation of Quantized Energy Levels: Electron Waves

13. How does treating the electron as a wave rather than as a particle solve the riddle of why electron orbits are discrete?
14. According to the simple de Broglie model, how many wavelengths are there in an electron wave in the first orbit? In the second orbit? In the *n*th orbit?
15. How can we explain why electrons don't spiral into the attracting nucleus?

Quantum Mechanics

16. What does the wave function Ψ represent?
17. Distinguish between a *wave function* and a *probability density function.*
18. How does the probability cloud of the electron in a hydrogen atom relate to the orbit described by Niels Bohr?

Correspondence Principle

19. Exactly what is it that "corresponds" in the correspondence principle?
20. Would Schrödinger's equation be valid if applied to the solar system? Would it be useful?

EXERCISES

1. Consider photons emitted from an ultraviolet lamp and a TV transmitter. Which has the greater (a) wavelength, (b) energy, (c) frequency, and (d) momentum?
2. Which color light is the result of a greater energy transition, red or blue?
3. In what way did Rutherford's gold-foil scattering experiment show that the atomic nucleus is both small and very massive?
4. How does Rutherford's model of the atom account for the back-scattering of alpha particles directed at the gold foil?

5. At the time of Rutherford's gold-foil experiment, scientists knew that negatively charged electrons exist within the atom, but they did not know where the positive charge resides. What information about the positive charge was provided by Rutherford's experiment?
6. Why does classical physics predict that atoms should collapse?
7. If the electron in a hydrogen atom obeyed classical mechanics instead of quantum mechanics, would it emit a continuous spectrum or a line spectrum? Explain.
8. Why are spectral lines often referred to as "atomic fingerprints"?
9. When an electron makes a transition from its first quantum level to ground level, the energy difference is carried by the emitted photon. In comparison, how much energy is needed to return an electron at ground level to the first quantum level?
10. Figure 32.10 shows three transitions among three energy levels that would produce three spectral lines in a spectroscope. If the energy spacing between the levels were equal, would this affect the number of spectral lines?
11. How can elements with low atomic numbers have so many spectral lines?
12. In terms of wavelength, what is the smallest orbit that an electron can have about the atomic nucleus?
13. Which best explains the photoelectric effect—the particle nature or the wave nature of the electron? Which best explains the discrete levels in the Bohr model of the atom? Defend your answers.
14. How does the wave model of electrons orbiting the nucleus account for discrete energy values rather than a continuous range of energy values?
15. Why do helium and lithium exhibit very different chemical behavior, even though they differ by only one electron?
16. The Ritz combination principle can be considered to be a statement of energy conservation. Explain.
17. Does the de Broglie model assert that an electron must be moving in order to have wave properties? Defend your answer.
18. Why does no stable electron orbit with a circumference of 2.5 de Broglie wavelengths exist in any atom?
19. An orbit is a distinct path followed by an object in its revolution around another object. An atomic orbital is an electron spread out over a *volume of space* in which the electron is most likely to be found. What do orbits and orbitals have in common?
20. Can a particle be diffracted? Can it exhibit interference?
21. How does the amplitude of a matter wave relate to probability?
22. If Planck's constant, *h*, were larger, would atoms be larger also? Defend your answer.
23. What is it that waves in the Schrödinger wave equation?
24. If the world of the atom is so uncertain and subject to the laws of probabilities, how can we accurately measure such things as light intensity, electric current, and temperature?
25. When we say that electrons have particle properties and then continue to say that electrons have wave properties, aren't we contradicting ourselves? Explain.
26. Did Einstein support quantum mechanics as being fundamental physics, or did he think quantum mechanics was incomplete?
27. When only a few photons are observed, classical physics fails. When many are observed, classical physics is valid. Which of these two facts is consistent with the correspondence principle?
28. When and where do Newton's laws of motion and quantum mechanics overlap?
29. What does Bohr's correspondence principle say about quantum mechanics versus classical mechanics?
30. Does the correspondence principle have application to macroscopic events in the everyday macroworld?
31. Richard Feynman, in his book *The Character of Physical Law,* states: "A philosopher once said, 'It is necessary for the very existence of science that the same conditions always produce the same results.' Well, they don't!" Who was speaking of classical physics, and who was speaking of quantum physics?
32. What does the wave nature of matter have to do with the fact that we can't walk through solid walls, as Hollywood movies often show using special effects?
33. Largeness or smallness has meaning only relative to something else. Why do we usually call the speed of light "large" and Planck's constant "small"?
34. Make up a multiple-choice question that would check a classmate's understanding of the difference between the domains of classical mechanics and quantum mechanics.

CHAPTER 32 ONLINE RESOURCES

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Interactive Figure

- 32.12

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- Bohr's Shell Model

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33 The Atomic Nucleus and Radioactivity

1 When Rosa Alvis moves the tube of a Geiger counter close to a piece of uranium ore (carnotite), an increased rate of clicks is heard by students in her Conceptual Physics class at City College of San Francisco. 2 Radioactive decay in Earth's interior heats the water that feeds hot springs worldwide. These impressive ones, loaded with calcium carbonate, are in Pamukkale, Turkey. 3 University of Melbourne professor Roger Rassool uses a scintillation counter to show that the paths of gamma rays are unaffected by a magnetic field, as illustrated in Figure 33.3.

What physicist won two Nobel Prizes, one in physics and one in chemistry, and had a daughter who also earned a Nobel Prize in chemistry? The answer is Madame Curie. Born in 1867 as Marie Sklodowska in Warsaw, then part of the Russian Empire, she received her general education in local schools with some scientific training from her father, a secondary-school teacher. Encouraged by her elder sister Bronislawa, who was a physician and had relocated to Paris, Marie moved to Paris to continue her studies at the Sorbonne. There she lived in a primitive garret, which she chose because it was affordable and close to the university. In 1894, after earning her first degree, she met the love of her life, physics professor Pierre Curie. In 1895, they were married and soon began working together.

In 1896, the French physicist Henri Becquerel discovered that uranium salts emitted rays that resembled X-rays in their ability to penetrate solid matter. Marie and Pierre began investigating uranium. They were the first to coin the word *radioactivity*. It became Marie's life's work. By this time (1898) a French citizen, Marie named the first new chemical element that she and Pierre discovered polonium—for her native country. They also discovered and named the element radium. In 1903, Pierre and Marie shared the Nobel Prize in Physics with Henri Becquerel for their work with radioactivity. Some sources say that the Curies shared money from the prize with needy acquaintances, including students. The Sorbonne in Paris honored Pierre with a professorship and a laboratory in which Marie became chief of laboratory work.

Marie Curie (1867–1934)

In 1906, Pierre was struck by a horse-drawn vehicle while crossing a street in the rain. Pierre fell under its wheels and was killed by a skull fracture. Marie was devastated by her husband's death. The Sorbonne physics department entrusted Pierre's chair to Marie. She was the first female professor at the Sorbonne, where she continued her work and earned her Nobel Prize in Chemistry in 1911. She was also appointed Director of the Curie Laboratory in the Radium Institute of the University of Paris, founded in 1914.

During World War I she donated her Nobel Prize gold medals to the war effort. In 1921, she was welcomed triumphantly on her first tour of the United States, where she raised funds for radium research. She toured America again in 1929, when President Hoover presented her with a check for $50,000, enough to buy 1 gram of radium for the Radium Institute in Paris.

Madame Curie visited Poland for the last time in 1934. A couple of months later she died—probably from the excessive exposures to radiation she endured during her lifetime of work. At that time, the damaging effects of ionizing radiation were not fully appreciated. She was buried at the cemetery in Sceaux, alongside her husband Pierre. Sixty years later, in 1995, in honor of their achievements, the remains of both were transferred to the Paris Panthéon. She became the first woman so honored.

X-rays and Radioactivity

Deeper probing into the atom began in 1895 when the German physicist Wilhelm Roentgen discovered **X-rays**—rays of an unknown nature. Roentgen discovered these "new kind of rays" produced by a beam of "cathode rays" (later found to be electrons) striking the glass surface of a gas-discharge tube. He 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 tissue to produce an image of the bones inside your body (Figure 33.1). In a modern X-ray tube, the target of the electron beam is a metal plate rather than the glass wall of the tube.

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- So far we've treated *atomic physics*—the study of the clouds of electrons that make up the atom. Now we'll burrow beneath the electrons and go deeper into the atom—to the atomic nucleus—where available energies dwarf those available to electrons. This is *nuclear physics*, a topic of great public interest—and public fear—not unlike the fear of electricity more than a century ago. With safeguards and well-informed consumers, society has determined that the benefits of electricity outweigh its risks. Likewise today with nuclear technology's risks versus its benefits.

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Tutorial
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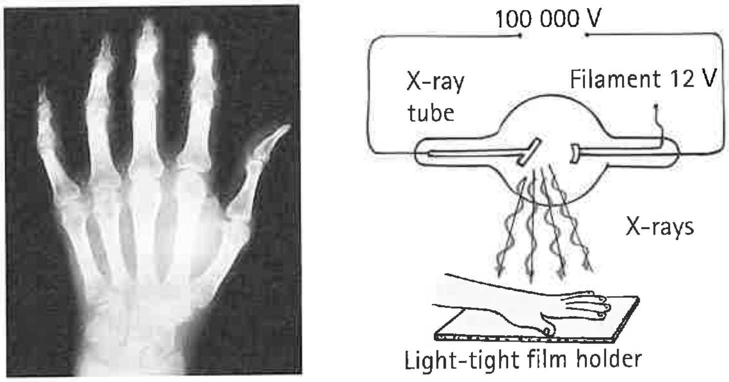

FIGURE 33.1
X-rays emitted by excited metallic atoms in the electrode penetrate flesh more readily than bone and produce an image on the film.

In early 1896, a few months after Roentgen announced his discovery of X-rays, the French physicist Antoine Henri Becquerel stumbled upon a new kind of penetrating radiation. Becquerel was studying fluorescence and phosphorescence created by both light and the newly discovered X-rays, and one evening happened to leave a wrapped photographic plate in a drawer next to some crystals that contained uranium. The next day he discovered to his surprise that the photographic plate had been darkened, apparently by spontaneous radiation from the uranium. He went on to show that this new radiation differed from X-rays in that it could ionize air and could be deflected by electric and magnetic fields.

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, as it turned out, 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. This process is **radioactivity,** which, because it involves the decay of the atomic nucleus, is often called *radioactive decay.*

A common misconception is that radioactivity is something new in the environment, but it has been around far longer than the human race. It is as much a part of our environment as the Sun and the rain. It has always been in the soil we walk on and in the air we breathe, and it is what warms the interior of Earth and makes it molten. In fact, radioactive decay in Earth's interior is what heats the water that spurts from a geyser or wells up from a natural hot spring. Even the helium in a child's balloon is nothing more than the product of radioactive decay. Radioactivity is as natural as sunshine and rain.

Radioactivity has been around since Earth's beginning.

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Video
Radioactive Decay

Alpha, Beta, and Gamma Rays

More than 99.9% of the atoms in our everyday environment are stable. The nuclei in those atoms will be unlikely to change over the lifetime of the universe. But some kinds of atoms are unstable. 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.*

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

Alpha rays have a positive electrical charge, **beta rays** have a negative electrical charge, and **gamma rays** have no charge at all (Figure 33.2). 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,

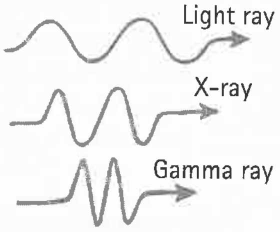

FIGURE 33.2
INTERACTIVE FIGURE
A gamma ray is part of the electromagnetic spectrum. It is simply electromagnetic radiation that is much higher in frequency and energy than light and X-rays.

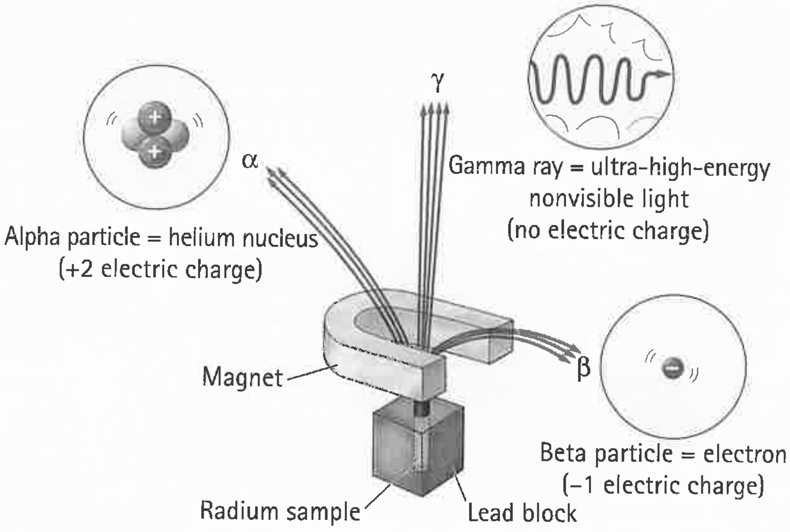

FIGURE 33.3
INTERACTIVE FIGURE
In a magnetic field, alpha rays bend one way, beta rays bend the other way, and gamma rays don't bend at all. The combined beam comes from a radioactive source placed at the bottom of a hole drilled in a lead block.

alpha, beta, and 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.

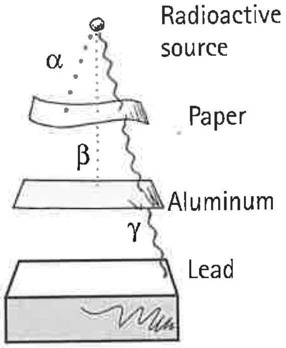

FIGURE 33.4

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.

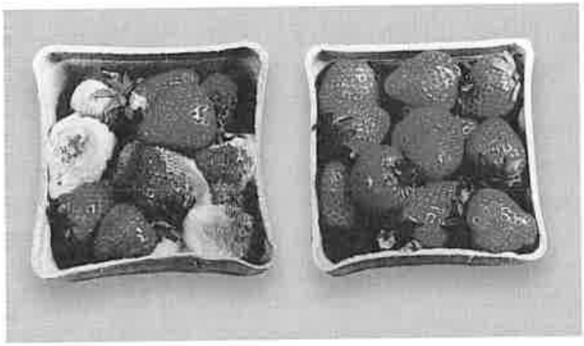

FIGURE 33.5

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.

CHECK POINT

Pretend you are given three radioactive rocks—one an alpha emitter, one a beta emitter, and one a gamma emitter. You can throw away one, but of the remaining two, you must hold one in your hand and the other you must place in your pocket. What can you do to minimize your exposure to radiation?

Check Your Answer

Hold the alpha emitter in your hand because the skin on your hand will shield you. Put the beta emitter in your pocket because beta particles will likely be stopped by the combined thickness of your clothing and skin. Throw away the gamma emitter because it would penetrate your body from any of these locations. Ideally, of course, you should distance yourself as much as possible from all the rocks.

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

Environmental Radiation

Common rock and minerals in our environment contain significant quantities of radioactive isotopes because most of them contain trace amounts of uranium. As a matter of fact, people who live in brick, concrete, or stone buildings are exposed to greater amounts of radiation than people who live in wooden buildings.

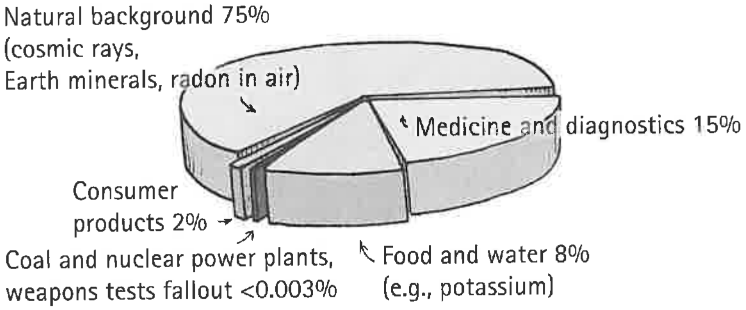

FIGURE 33.6

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

The leading source of naturally occurring 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 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 (Figure 33.7). If levels are abnormally high, corrective measures, such as sealing the basement floor and walls and maintaining adequate ventilation, are recommended.

About one-sixth of our annual exposure to radiation comes from nonnatural sources, primarily medical procedures. Smoke detectors, fallout from long-ago nuclear testing, and the coal and nuclear power industries are also contributors. The coal industry far outranks the nuclear power industry as a source of radiation. Globally, the combustion of coal annually releases about 13,000 tons of radioactive thorium and uranium into the atmosphere. Both these minerals are found naturally in coal deposits so that their release is a natural consequence of burning coal. Worldwide, the nuclear power industries generate about 10,000 tons of radioactive waste each year. Most all of this waste, however, is contained and *not* released into the environment.

FIGURE 33.7

A commercially available radon test kit for the home.

UNITS OF RADIATION

Radiation dosage is commonly measured in *rads* (*r*adiation *a*bsorbed *d*ose), a unit of absorbed energy. One **rad** is equal to 0.01 joule of radiant energy absorbed per kilogram of tissue.

The capacity for nuclear radiation to cause damage is not just a function of its level of energy, however. Some forms of radiation are more harmful than others. For example, suppose you have two arrows, one with a pointed tip and one with a suction cup at its tip. Shoot both arrows at an apple at the same speed and both have the same kinetic energy. The one with the pointed tip, however, will invariably do more damage to the apple than the one with the suction cup. Similarly, some forms of radiation cause greater harm than other forms even when we receive the same number of rads from both forms.

The unit of measure for radiation dosage based on potential damage is the **rem** (*r*oentgen *e*quivalent *m*an).[1] In calculating the dosage in rems, we multiply the number of rads by a factor that corresponds to different health effects of different types of radiation determined by clinical studies. For example, 1 rad of alpha particles has the same biological effect as 10 rads of beta particles.[2] We call both of these dosages 10 rems.

Particle	Radiation Dosage		Factor		Health Effect
alpha	1 rad	×	10	=	10 rems
beta	10 rad	×	1	=	10 rems

CHECK POINT

Which is more harmful, being exposed to 1 rad of alpha particles or 1 rad of beta particles?

Check Your Answer

Alpha particles: Multiply these quantities of radiation by the appropriate factor to get the dosages in rems. Alpha: 1 rad × 10 = 10 rems; beta: 1 rad × 1 = 1 rem. The factors show us that, physiologically speaking, alpha particles are 10 times more damaging than beta particles.

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[1] This unit is named for Wilhelm Roentgen, the discoverer of X-rays.

[2] This is true even though beta particles have more penetrating power, as previously discussed.

DOSES OF RADIATION

Lethal doses of radiation begin at 500 rems. A person has about a 50% chance of surviving a dose of this magnitude delivered to the whole body over a short period of time. During radiation therapy, a patient may receive localized doses in excess of 200 rems each day for a period of weeks (Figure 33.8).

FIGURE 33.8

Nuclear radiation is focused on harmful tissue, such as a cancerous tumor, to selectively kill or shrink the tissue in a technique known as *radiation therapy*. This application of nuclear radiation has saved millions of lives—a clear-cut example of the benefits of nuclear technology. The inset shows the internationally used symbol indicating an area where radioactive material is being handled or produced.

All the radiation we receive from natural sources and from diagnostic medical procedures is only a fraction of 1 rem per year. For convenience, the smaller unit *millirem* is used, where 1 millirem (mrem) is 1/1000th of a rem. The average person in the United States is exposed to about 360 mrem a year, as Table 33.1 indicates. About 80% of this radiation comes from natural sources, such as cosmic rays and Earth itself. A typical chest X-ray exposes a person to 5 to 30 mrem (0.005 to 0.030 rem), less than one ten-thousandth of the lethal dose. Interestingly, the human body is a significant source of natural radiation, primarily from the potassium we ingest. Our bodies contain about 200 grams of potassium. Of this quantity, about 20 milligrams is the radioactive isotope potassium-40, which is a gamma-ray emitter. Between every heartbeat about 60,000 potassium-40 isotopes in the average human body undergo spontaneous radioactive decay. Radiation is indeed everywhere.

When radiation encounters the intricately structured molecules in the watery, ion-rich brine that makes up our cells, the radiation can create chaos on the atomic scale. Some molecules are broken, and this change alters other molecules, which can be harmful to life processes.

FIGURE 33.9

The film badges worn by Tammy and Larry contain audible alerts for both radiation surge and accumulated exposure. Information from the individualized badges is periodically downloaded to a database for analysis and storage.

TABLE 33.1

Annual Radiation Exposure

Source	Typical Dose (mrem) Received Annually
Natural Origin	
Cosmic radiation	26
Ground	33
Air (radon-222)	198
Human tissues (K-40; Ra-226)	35
Human Origin	
Medical procedures	
Diagnostic X-rays	40
Nuclear diagnostics	15
Consumer products	8
Weapons-test fallout	1
Commercial fossil-fuel power plants	<1
Commercial nuclear power plants	$\ll 1$

Cells are able to repair most kinds of molecular damage caused by radiation if the radiation is not too severe. 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 (except for most nerve cells, which are irreplaceable). Sometimes a radiated cell will survive with a damaged DNA molecule. New cells arising from the damaged cell retain the altered genetic information, producing a *mutation.* Usually the effects of a mutation are insignificant, but occasionally the mutation results in cells that do not function as well as unaffected ones, sometimes leading to a cancer. If the damaged DNA is in an individual's reproductive cells, the genetic code of the individual's offspring may retain the mutation.

RADIOACTIVE TRACERS

In scientific laboratories radioactive samples of all the elements have been made. This is accomplished by bombardment with neutrons or other particles. Radioactive materials are extremely useful in scientific research and industry. 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 taken up by the plants can be easily measured with radiation detectors. From such measurements, scientists can inform farmers of the proper amount of fertilizer to use. Radioactive isotopes used to trace such pathways are called *tracers.*

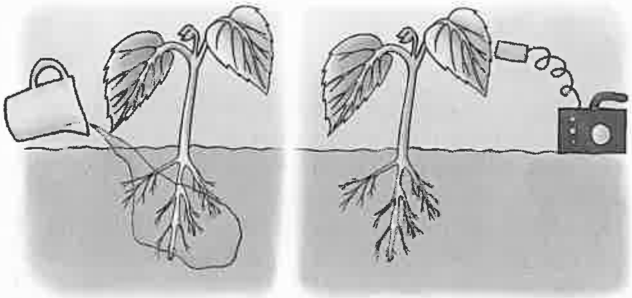

FIGURE 33.10

Tracking fertilizer uptake with a radioactive isotope.

In a technique known as medical imaging, tracers are used for the diagnosis of internal disorders. This technique works because the path the tracer takes is influenced only by its physical and chemical properties, not by its radioactivity. The tracer may be introduced alone or along with some other chemical that helps target the tracer to a particular type of tissue in the body.

FIGURE 33.11

The thyroid gland, located in the neck, absorbs much of the iodine that enters the body through food and drink. Images of the thyroid gland, such as the one shown here, can be obtained by giving a patient a small amount of the radioactive isotope iodine-131. These images are useful in diagnosing metabolic disorders.

The Atomic Nucleus and the Strong Force

The atomic nucleus occupies only a few quadrillionths of the volume of the atom, leaving most of the atom as empty space. The nucleus is composed of **nucleons,** which is the collective name for protons and neutrons. (Each nucleon is composed of three smaller particles called **quarks**—believed to be fundamental, not made of smaller parts.)

Just as there are energy levels for the orbital electrons of an atom, there are energy levels within the nucleus. Whereas orbiting electrons emit photons when making transitions to lower orbits, similar changes of energy states in radioactive nuclei result in the emission of gamma-ray photons. This is gamma radiation.

We know that electrical charges of like sign repel one another. So how is it possible that positively charged protons in the nucleus stay clumped together? This question led to the discovery of an attraction called the **strong force,** which acts between all nucleons. This force is very strong, but only over extremely short distances (about 10^{-15} m, the approximate diameter of a proton or neutron). Repulsive electrical interactions, on the other hand, are relatively long-ranged. Figure 33.12 suggests a comparison of the strengths of these two forces over distance. For protons that are close together, as in small nuclei, the attractive strong nuclear force easily overcomes the repulsive electrical force. But for protons that are far apart, like those on opposite edges of a large nucleus, the attractive strong nuclear force may be weaker than the repulsive electrical force.

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- Among nature's fundamental particles are six kinds of *quark*, of which two are the fundamental building blocks of all nucleons (protons and neutrons). Quarks carry fractional electrical charges. One kind, the *up* quark, carries +2/3 the proton charge, and another, 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.) Quarks in the proton are the combination *up up down*, and in the neutron *up down down*. The other four quarks bear the whimsical names *strange, charm, top,* and *bottom*. No quarks have been isolated and experimentally observed. Most theorists think quarks, by their nature, cannot be isolated.

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

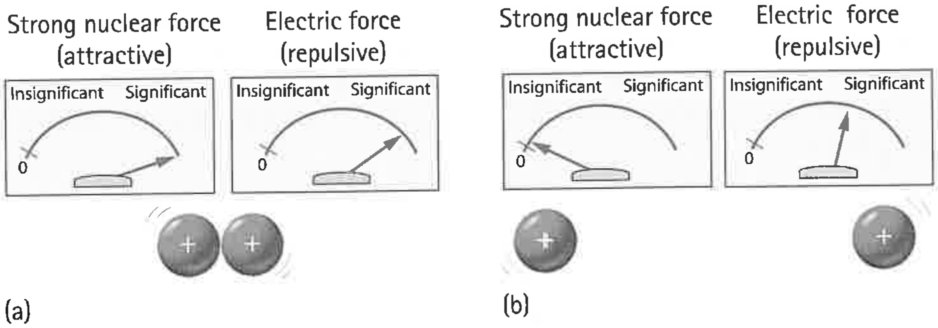


FIGURE 33.12

Imaginary meter readings of comparative forces: (a) Two nearby protons experience both an attractive strong nuclear force and a repulsive electric force. At this tiny separation distance, the strong nuclear force overcomes the electric force, and they stay together. (b) When they are far apart, the electric force predominates and they repel. This proton–proton repulsion in large atomic nuclei reduces nuclear stability.

A large nucleus is not as stable as a small one. In a helium nucleus, for example, each of the two protons feels the repulsive effect of the other. In a uranium nucleus, each of the 92 protons feels the repulsive effects of the other 91 protons! The nucleus is unstable. We see that there is a limit to the size of the atomic nucleus. It is for this reason that all nuclei having more than 82 protons are radioactive (number 83, bismuth, just barely so).

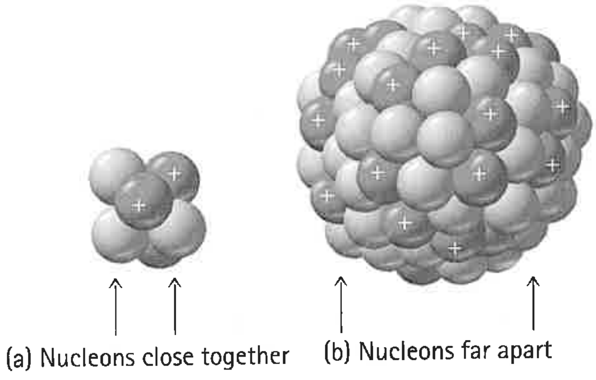


FIGURE 33.13

(a) All nucleons in a small atomic 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.

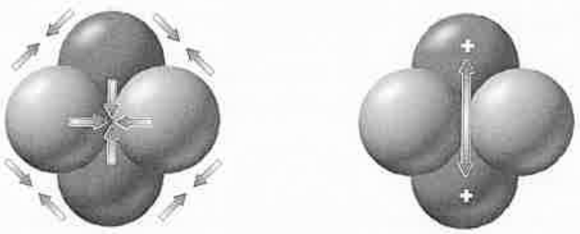
CHECK POINT

Two protons in the atomic nucleus repel each other, but they also attract each other. Why?

Check Your Answer

Two forces are acting—electrical and nuclear. While protons electrically repel each other, they also simultaneously attract each other by the strong nuclear force. When the attractive strong nuclear force is stronger than the repulsive electric force, the protons remain together. When far apart, the electrical force can overcome the nuclear force, and they tend to fly apart.

Neutrons serve as a "nuclear cement" that holds the atomic nucleus together. Protons attract both protons and neutrons by the strong nuclear force. Protons also repel other protons by the electric force. Neutrons, on the other hand, have no electric charge and so only attract other protons and neutrons by the strong nuclear force. The presence of neutrons therefore adds to the attraction among nucleons and helps hold the nucleus together (Figure 33.14).



All nucleons, both protons and neutrons, attract one another by the strong nuclear force.

Only protons repel one another by the electric force.

FIGURE 33.14

The presence of neutrons helps hold the nucleus together by increasing the effect of the strong nuclear force, represented by the single-headed arrows.

The more protons there are in a nucleus, the more neutrons are needed to help balance the repulsive electric forces. For light elements, it is sufficient to have about as many neutrons as protons. The most common isotope of carbon, C-12, for instance, has equal numbers of each—six protons and six neutrons. For large nuclei, more neutrons than protons are needed. Because the strong nuclear force diminishes rapidly over distance, nucleons must be practically touching in order for the strong nuclear force to be effective. Nucleons on opposite sides of a large atomic nucleus are not as attracted to one another. The electric force, however, does not diminish by much across the diameter of a large nucleus and so begins to win out over the strong nuclear force. To compensate for the weakening of the strong nuclear force across the diameter of the nucleus, large nuclei have more neutrons than protons. Lead, for example, has about one-and-a-half times as many neutrons as protons.

So we see that neutrons are stabilizing and large nuclei require an abundance of them—up to a point beyond which not even neutrons can hold a nucleus together. Interestingly, neutrons are not stable when they are by themselves. A lone neutron is radioactive and spontaneously transforms to a proton and an electron (Figure 33.15a). A neutron needs protons around to keep this from happening. The alpha particles emitted in alpha decay are literally nuclear "chunks," and only heavy nuclei emit them.[3] Beta and gamma particles, on the other hand, can be emitted by

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[3] An exception to the rule that alpha decay is limited to heavy nuclei is the highly radioactive nucleus of beryllium 8, with four protons and four neutrons, which splits into two alpha particles—a form of nuclear fission.

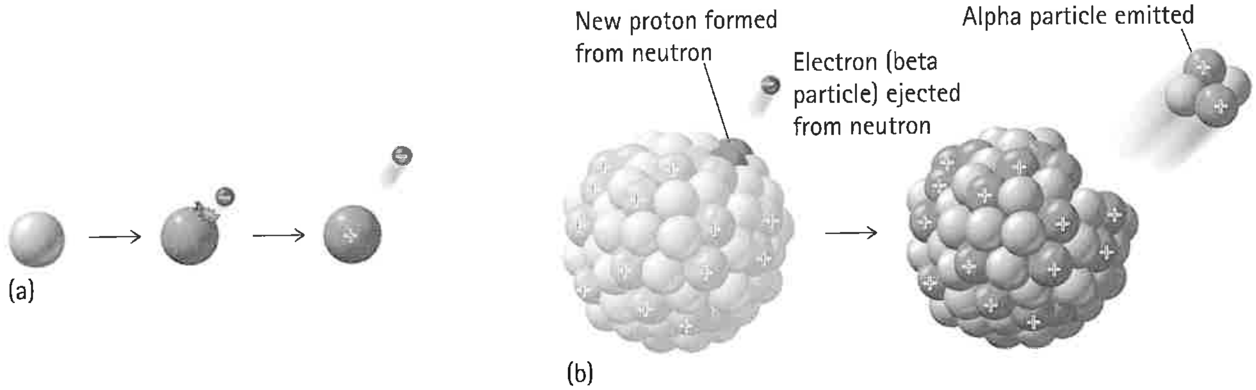

FIGURE 33.15

(a) A neutron near a proton is stable, but a neutron by itself is unstable and decays to a proton by emitting an electron. (b) Destabilized by an increase in the number of protons, the nucleus begins to shed fragments, such as alpha particles.

radioactive nuclei both heavy and light. The beta decay of a single neutron and the alpha decay of a heavy nucleus are shown in Figure 33.15b.

CHECK POINT

What role do neutrons serve in the atomic nucleus? What is the fate of a neutron when alone or distant from one or more protons?

Check Your Answers

Neutrons serve as a nuclear cement in nuclei and add to nuclear stability. But when alone, a neutron is radioactive and spontaneously transforms to a proton and an electron.

Radioactive 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

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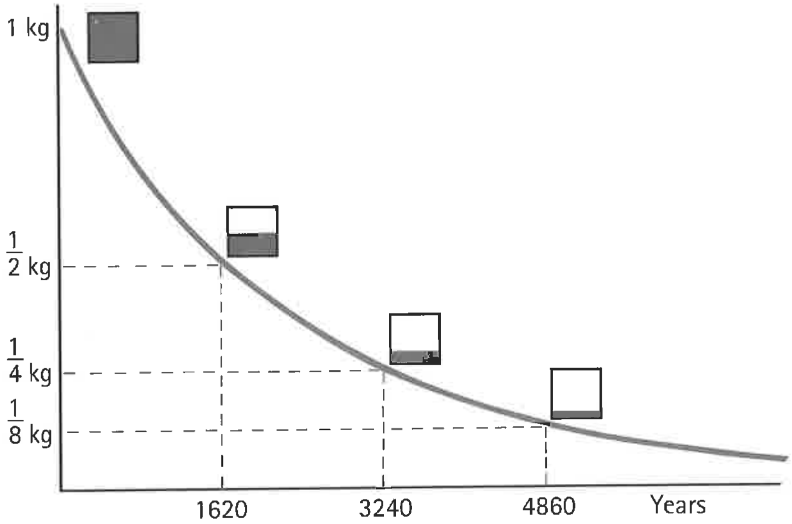


FIGURE 33.16

INTERACTIVE FIGURE

Every 1620 years, the amount of radium decreases by half.

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 1 million).

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

Half-lives are remarkably constant and not affected by external conditions.[4] Some radioactive isotopes have half-lives that are less than a millionth of a second, while others have half-lives of more than a billion years. Uranium-238 has a half-life of 4.5 billion years. All uranium eventually decays in a series of steps to lead. In 4.5 billion years, half the uranium presently in Earth today will be lead.

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 more radioactivity per amount is detected.

CHECK POINT

If a sample of radioactive isotopes has a half-life of 1 day, how much of the original sample will be left at the end of the second day? The third day?

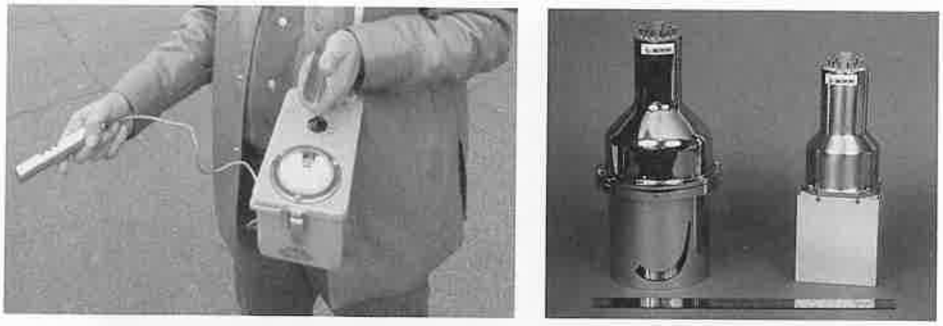
Check Your Answers

One-quarter at the end of the second day, one-eighth at the end of the third day.

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



(a) (b)

FIGURE 33.17

Radiation detectors. (a) A Geiger counter detects incoming radiation by a short pulse of current triggered when radiation ionizes a gas 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.

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[4] In 2008, researchers at Purdue University claimed to see a small solar influence on radioactive decay rates. As of this writing, the claim remains to be checked.

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.

2. A *cloud chamber* shows a visible path of ionizing radiation in the form of fog trails. It consists of a cylindrical 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 source of radiation can be outside the chamber or inside it, as shown in Figure 33.18. When a charged particle 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. It contains a steady supersaturated vapor, because it rests on a slab of dry ice, with a temperature gradient from near room temperature at the top to very low temperature at the bottom. 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 classroom demonstrations. Perhaps your instructor will show you one, as does Walter Steiger in Figure 33.19.

3. The particle trails seen in a *bubble chamber* are minute bubbles of gas in liquid hydrogen (Figure 33.20). 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 then 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 information about 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

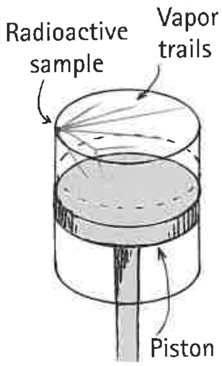


FIGURE 33.18

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.

FIGURE 33.19

Walter Steiger examines vapor trails in a small cloud chamber.

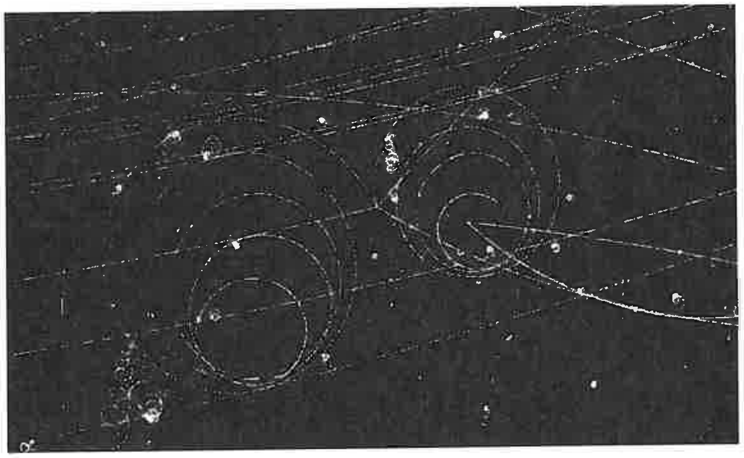


FIGURE 33.20

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.)

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 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. The radiation detector that Roger Rassool shows in the chapter-opener photo is a scintillator. Interestingly, ordinary water, when highly purified, can serve as a scintillator.

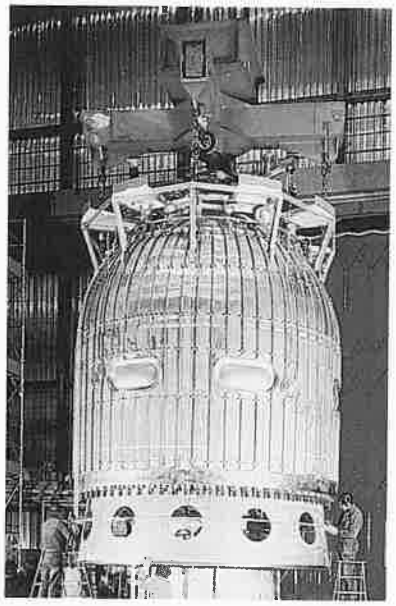


FIGURE 33.21

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.

CHECK POINT

Which will give a higher counting rate on a radiation detector, radioactive material that has a short half-life or radioactive material that has a long half-life?

Check Your Answer

The material with the shorter half-life is more active and will show a higher counting rate on a radiation detector.

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. The changing of one chemical element to another is called **transmutation.** Transmutation occurs in natural events, and is also initiated artificially in the laboratory.

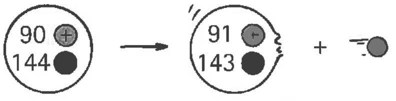
NATURAL TRANSMUTATION

Consider uranium-238, the nucleus of which contains 92 protons and 146 neutrons. When an alpha particle is ejected, the nucleus loses two protons and two neutrons. Because an element is defined by the number of protons in its nucleus, the 90 protons and 144 neutrons left behind are no longer identified as being uranium. What we have is the nucleus of a different element—*thorium.* This transmutation can be written as a nuclear equation:

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

We see that $^{238}_{92}\mathrm{U}$ transmutes to the two elements written to the right of the arrow. When this transmutation occurs, energy is released, partly in the form of kinetic energy of the alpha particle ($^{4}_{2}\mathrm{He}$), partly in the kinetic energy of the thorium nucleus, and partly in the form of gamma radiation. In this and all such equations, the mass numbers at the top balance ($238 = 234 + 4$) and the atomic numbers at the bottom also balance ($92 = 90 + 2$).

Thorium-234, the product of this reaction, is also radioactive. When it decays, it emits a beta particle.[5] Since a beta particle is an electron, the atomic number of the resulting nucleus is *increased* by 1. So after beta emission by thorium with 90 protons, the resulting element has 91 protons. It 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



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

We write an electron as ${}^{0}_{-1}e$. The superscript 0 indicates that the electron's mass is insignificant relative to that of protons and neutrons. The subscript -1 is the electric charge of the electron.

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.

So we see that when an element ejects an alpha particle from its nucleus, the mass number of the resulting atom is decreased by 4 and its atomic number is decreased by 2. The resulting atom is an element two spaces back in the periodic table of the elements. When an element ejects a beta particle from its nucleus, the mass of the atom is practically unaffected, meaning 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 radioactive elements can decay backward or forward in the periodic table.[6]

The successions of radioactive decays of ${}^{238}_{92}\text{U}$ to ${}^{260}_{82}\text{Pb}$, an isotope of lead, is shown in Figure 33.22. Each blue 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.

CHECK POINT

1. Complete the following nuclear reactions.
   a. ${}^{226}_{88}\text{Ra} \rightarrow {}^{?}_{?}? + {}^{0}_{-1}e$
   b. ${}^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{?}_{?}?$
2. What finally becomes of all the uranium that undergoes radioactive decay?

Check Your Answers

1. **a.** ${}^{226}_{88}\text{Ra} \rightarrow {}^{226}_{89}\text{Ac} + {}^{0}_{-1}e$
   b. ${}^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{4}_{2}\text{He}$
2. All uranium will ultimately become lead. On the way to becoming lead, it will exist as a series of elements, as indicated in Figure 33.22.

---

[5] Beta emission is always accompanied by the emission of a neutrino (actually, an antineutrino), a neutral particle with nearly zero mass that travels at about the speed of light. The neutrino ("little neutral one") was postulated by Wolfgang Pauli in 1930 and detected in 1956. Neutrinos are hard to detect because they interact very weakly with matter. Whereas a piece of solid lead a few centimeters thick will stop most gamma rays from a radium source, a piece of lead about 8 light-years thick would be needed to stop half the neutrinos produced in typical nuclear decays. Thousands of neutrinos are flying through you every second of every day, because the universe is filled with them. Only occasionally, one or two times a year or so, does a neutrino interact with the matter of your body.

At this writing, the mass of neutrinos is unknown, but is established to be no more than about a millionth the mass of an electron. Yet neutrinos are so numerous they might comprise most of the mass of the universe. Neutrinos may be the "glue" that holds the universe together.

[6] 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.

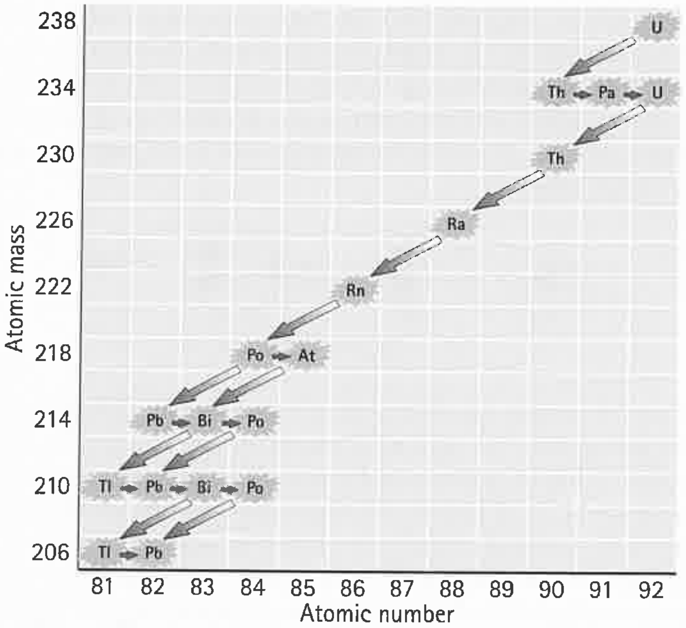
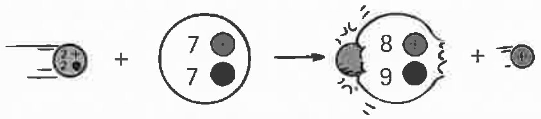


FIGURE 33.22
U-238 decays to Pb-206 through a series of alpha and beta decays.

ARTIFICIAL TRANSMUTATION

Ernest Rutherford, in 1919, was the first of many investigators to succeed in deliberately transmuting a chemical element. He bombarded nitrogen gas with alpha particles from a piece of radioactive ore. The impact of an alpha particle on a nitrogen nucleus can transmute nitrogen into oxygen:



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

Rutherford used a cloud chamber to record this event. 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 sometimes 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 in the process, transforming nitrogen to oxygen.

Since Rutherford's announcement in 1919, experimenters have carried out many other nuclear reactions, first with natural bombarding projectiles from radioactive ores and then with still more energetic projectiles—protons and other particles hurled by huge particle accelerators. Artificial transmutation is what produces the hitherto unknown synthetic elements from atomic number 93 to 118. All these artificially made elements have short half-lives. Any that may have existed naturally when Earth was formed have long since decayed.

Radiometric Dating

Earth's atmosphere is continuously bombarded by cosmic rays, and this bombardment causes many atoms in the upper atmosphere to transmute. These transmutations result in many protons and neutrons being "sprayed out" into the environment. Most of the protons are stopped as they collide with the atoms of

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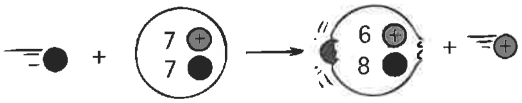
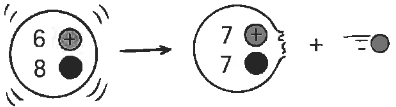
the upper atmosphere, stripping electrons from these atoms to become hydrogen atoms. The neutrons, however, keep going for longer distances because they have no electrical charge and therefore do not interact electrically with matter. Eventually, many of them collide with the nuclei in the denser lower atmosphere. A nitrogen nucleus that captures a neutron, for instance, can emit a proton and become the nucleus of a carbon isotope:



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

This carbon-14 isotope, which makes up less than one-millionth of 1% of the carbon in the atmosphere, has eight neutrons and is radioactive. (The most common isotope, carbon-12, has six neutrons and is not radioactive.) Because both carbon-12 and carbon-14 are forms of carbon, they have the same chemical properties. Both these isotopes can chemically react with oxygen to form carbon dioxide, which is taken in by plants. This means that all plants contain a tiny bit of radioactive carbon-14. All animals eat plants (or other animals that ate plants), 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 by the following reaction:



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

Because plants continue to take in carbon dioxide as long as they live, any carbon-14 lost by decay is immediately replenished with fresh carbon-14 from the atmosphere. In this way, a radioactive equilibrium is reached where there is a constant ratio of about one carbon-14 atom to every 100 billion carbon-12 atoms. When a plant dies, replenishment of carbon-14 stops. Then the percentage of carbon-14 decreases at a constant rate given by its half-life.[7] The longer a plant or other organism is dead, therefore, the less carbon-14 it contains relative to the constant amount of carbon-12.

The half-life of carbon-14 is about 5730 years. This means that half of the carbon-14 atoms that are now present in a plant or animal that dies today will decay in the next 5730 years. Half of the remaining carbon-14 atoms will then decay in the following 5730 years, and so forth.

FIGURE 33.23

The amount of radioactive carbon-14 in the skeleton diminish by one-half every 5730 years, with the result that today the skeleton contains only a fraction of the carbon-14 it originally had. The red arrows symbolize relative amounts of carbon-14.

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[7] A 1-g sample of contemporary carbon contains about 5×10^{22} atoms, 6.5×10^{10} of which are C-14 atoms, and has a beta disintegration rate of about 13.5 decays per minute.

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 food-borne 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).

With this knowledge, scientists 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 dating,** enables us to probe as much as 50,000 years into the past. Beyond this time span, there is too little carbon-14 remaining to permit accurate analysis.

Carbon-14 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 magnetic field as well as changes in the strength of Earth's magnetic field affect cosmic-ray intensities in Earth's atmosphere, which in turn produce fluctuations in the production of C-14. 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.

CHECK POINT

Suppose an archeologist extracts a gram of carbon from an ancient ax handle and finds it one-fourth as radioactive as a 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 two half-lives of C-14, or about 11,500 years, old.

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, whereas U-235 finally becomes the isotope Pb-207. Lead isotopes 206 and 207 that now exist were at one time uranium. The older the uranium-bearing 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.

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.

Rad Acronym (*r*adiation *a*bsorbed *d*ose) for a unit of absorbed energy. One rad is equal to 0.01 J of energy absorbed per kilogram of tissue.

Rem Acronym (*r*oentgen *e*quivalent *m*an) for a unit used to measure the effect of ionizing radiation on humans.

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

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

Strong force Force that attracts nucleons to each other within the atomic nucleus; a force that is very strong at close distances, and that greatly weakens as distance increases.

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.

Carbon dating Process of determining the time that has elapsed since death by measuring the radioactivity of the remaining carbon14 atoms.

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?

Environmental Radiation

7. Distinguish between a *rad* and a *rem*.
8. Do humans receive more radiation from artificial or from natural sources of radiation?
9. Is the human body radioactive? Explain.
10. What kinds of cells are in most danger when they are irradiated?
11. What is a radioactive tracer?

The Atomic Nucleus and the Strong Force

12. Name the two different nucleons.
13. Why doesn't the repulsive electric force of protons in the atomic nucleus cause the protons to fly apart?
14. Why is a larger nucleus generally less stable than a smaller nucleus?
15. What is the role of neutrons in the atomic nucleus?
16. Which contains the bigger percentage of neutrons, large nuclei or small nuclei?

Radioactive Half-Life

17. How does the rate of decay of a long-half-life material normally compare with the rate of decay of a short-half-life material?
18. What is the half-life of Ra-226?

Radiation Detectors

19. What kind of trail is left when an energetic particle shoots through matter?
20. Which two radiation detectors operate primarily by sensing the trails left by energetic particles that shoot through matter?
21. Which detector senses flashes of light produced by charged particles or gamma rays?

Transmutation of Elements

22. What is transmutation?

23. When thorium (atomic number 90) decays by emitting an alpha particle, what is the atomic number of the resulting nucleus?
24. When thorium decays by emitting a beta particle, what is the atomic number of the resulting nucleus?
25. What is the change in atomic mass for each of the above two reactions?
26. What change in atomic number occurs when a nucleus emits an alpha particle? A beta particle? A gamma ray?
27. What is the long-range fate of all the uranium that exists in the world?
28. When, and by whom, did the first successful intentional transmutation of an element occur?

Radiometric Dating

29. What occurs when a nitrogen nucleus captures an extra neutron?
30. Which are more prominent in the food we eat, carbon-12 or carbon-14?

RANKING

1. Rank these three types of radiation by their ability to penetrate this page of your book, from greatest penetration to least.
   a. Alpha particle.
   b. Beta particle.
   c. Gamma ray.
2. Consider these three nuclei: A. Th-233; B. U-235; C. U-238. From most to least, rank them by the number of
   a. protons in the nucleus.
   b. neutrons in the nucleus.
   c. electrons that normally surround the nucleus.
3. Consider the following reactions: A. uranium-238 emits an alpha particle; B. plutonium-239 emits an alpha particle; C. thorium-239 emits a beta particle.
   a. Rank the resulting nucleus by atomic number, from most to least.
   b. Rank the resulting nucleus by the number of neutrons, from most to least.

PROJECT

Write a letter to one of your favorite relatives that will help dispel any notion they may have about radioactivity being something new in the world. Briefly discuss the role of radioactivity in dating ancient objects. Also discuss how radioactivity is a major source of natural heat in Earth's interior, and cite its role in hot springs and volcanoes.

EXERCISES

1. In the 19th century, the famous physicist Lord Kelvin estimated the age of Earth to be 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 stated 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 33.22, 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? Does it matter which path is followed?
27. If an atom has 100 electrons, 157 neutrons, and 100 protons, what is its approximate atomic mass? What is the name of this element?
28. When a ${}^{226}_{88}\mathrm{Ra}$ 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 ${}^{218}_{84}\mathrm{Po}$ emits a beta particle, it transforms into the nucleus of a different element. What are the atomic number and the atomic mass of this "daughter" element?
30. When a nucleus of ${}^{218}_{84}\mathrm{Po}$ emits an alpha particle, what are 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: ${}^{2}_{1}\mathrm{H}$, ${}^{12}_{6}\mathrm{C}$, ${}^{56}_{26}\mathrm{Fe}$, ${}^{197}_{79}\mathrm{Au}$, ${}^{90}_{38}\mathrm{Sr}$, and ${}^{238}_{92}\mathrm{U}$.
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 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 at night on granite outcroppings. Comment on 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 60 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. Show that it will take 120 years for this isotope to decay to about one-sixteenth its original amount.
4. At 6:00 AM a hospital uses its cyclotron to make 1 milligram of the isotope fluorine-18 for use as a diagnostic tool with its PET scanner. The half-life of F-18 is 1.8 hours. How much F-18 is left at 3:00 PM? At midnight? Should the hospital plan to make more F-18 the next morning?
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. Show that the age of this artifact is 23,000 years old.
6. Suppose that you want to find out how much gasoline is in an underground storage tank. You pour in 1 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?

CHAPTER 33 ONLINE RESOURCES

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1 Lise Meitner, the discoverer of nuclear fission, 2 Otto Frisch, her physicist nephew who aided in her discovery, and 3 Otto Hahn, who took the credit for it. 4 Italian physicist Enrico Fermi received the 1938 Nobel Prize for work leading to nuclear fission. When he left Stockholm after receiving the prize to return to his native Italy, he said jokingly that he got lost and ended up in New York. In fact, he and his Jewish wife Laura carefully planned their escape from Fascist Italy. Four years later in Chicago, he was the first to initiate controlled fission, and he became an American citizen in 1945. 5 Robert J. Oppenheimer headed the Los Alamos labs for the Manhattan Project during World War II. He was considered a national hero—until he was professionally and personally devastated by political witch hunts in the 1950s.

Lise Meitner was born in 1878 in Vienna. Girls at that time had no public schooling after their early teen years. Lise received her school "completion certificate" while still 13. Since her parents could not afford to send her to Switzerland to a private boarding school, she enrolled in a "young ladies school" to prepare for teaching French. But her heart was in mathematics and physics, not French. At 19, she joined a group of other ambitious young women who studied on their own—with some help from private tutors—to prepare for the university. After just 2 years of intensive work, she passed the test for admission to the University of Vienna (1 of just 4 of 14 women who tried that year), and in 1906, at age 27, she earned a doctorate with highest honors.

With the encouragement and financial support of her father, Meitner went to Berlin to further her career. Max Planck departed from his policy of not letting women attend his lectures and allowed her into his class. After one year, she became his assistant. She then joined the chemist Otto Hahn in what was to be a fruitful 30-year collaboration. They soon discovered several new isotopes, and in 1909 she published two papers on beta radiation.

During World War I, both she and Hahn took some time off for war work—she to work as a nurse and X-ray technician—but they also found time to continue their research, and in 1918 they discovered element number 91, protactinium. In the 1920s she became the first woman in Berlin, perhaps the first in all of Germany, to be named a professor. Soon her work on radioactivity led to her scientific recognition worldwide.

When Adolf Hitler came to power in 1933, Meitner, although Jewish, was able to continue her work, at least for a time, protected by her Austrian citizenship. Most other Jewish scientists, including her nephew Otto Frisch, were dismissed or forced to resign from their posts, and most of them, including Albert Einstein, emigrated from Germany.

In 1934 came word of the work of Enrico Fermi and his colleagues in Rome, in which they had bombarded many elements, including uranium, with neutrons, and seemingly created new elements. Meitner and Hahn joined the international hunt for "transuranics," elements heavier than uranium—a hunt that unexpectedly led to nuclear fission.

In July 1938, when Meitner was threatened with dismissal, with the help of Dutch physicists she escaped to Holland. After a close call with German immigration officials, she reached safety, but without her possessions. She had hastily left Germany with only 10 marks in her purse, plus a ring that Otto Hahn had given her, one inherited from his mother, to be used to bribe the frontier guards if needed. Meitner then moved on to Stockholm, where she took up a post and established a working relationship with Niels Bohr, who traveled regularly between Copenhagen and Stockholm. She continued to correspond with Hahn and other German scientists.

In the fall of 1938, Hahn and Meitner met clandestinely in Copenhagen to plan a new round of experiments with uranium. In December of that year, Hahn wrote to Meitner that he and his associate Fritz Strassmann had discovered the element barium in samples of pure uranium that had been bombarded with neutrons. They were good chemists and sure of their result but were at a loss to explain the appearance of barium. During the Christmas holidays, Meitner and her visiting nephew Otto Frisch, on a walk in snowy woods in Sweden, came up with an explanation: The uranium nucleus was breaking apart into lighter nuclei, including nuclei of barium. Frisch rushed back to Copenhagen and performed an experiment that confirmed their hypothesis of nuclear breakup. Borrowing a term from biology, they called it *fission*.[1] When Niels Bohr boarded a boat for America on January 7, he carried the news of fission with him. (The possibility of nuclear fission had actually been suggested 5 years earlier by the German scientist Ida Noddack, based on hints from Fermi's work, but no one at the time took her suggestion seriously.)

Meitner and Frisch realized that based on the known masses of nuclei and Einstein's famous equation $E = mc^2$, the fission process should release a lot of energy. This energy release is what made it easy for Frisch, and later other scientists, to quickly verify the reality of fission in the laboratory.

In a letter to Hahn, Meitner explained the new idea. But it was politically impossible for the exiled Meitner to publish jointly with Hahn in 1939. So it was Hahn and Strassmann who published the now historic paper reporting the production of barium when uranium was bombarded with neutrons. And it was Hahn alone who, in 1944, received the Nobel Prize in Chemistry for the discovery of nuclear fission. Nowhere in his acceptance did he mention the role of Meitner and Frisch. He alone got the "limelight" of the prestigious award.

Scientists around the world realized, almost at once, that nuclear fission had potential to power a weapon. Émigré scientists in America jumped into action and urged Albert Einstein to write a letter of warning to President Roosevelt. But, instead, the Manhattan Project and the creation of the atomic bomb began under the direction of Robert J. Oppenheimer.

After the war was over, Meitner expressed outrage at the German scientists who helped Hitler (but who, fortunately, did not succeed in making an atomic bomb). She became a Swedish citizen in 1949 but moved to Britain in 1960 and died in Cambridge in 1968, shortly before her 90th birthday. Her nephew Otto composed the inscription on her headstone: "Lise Meitner: a physicist who never lost her humanity." A more recent memorial is found in the name of element number 109, meitnerium.

Nuclear Fission

Nuclear fission involves a delicate balance within the nucleus between nuclear attraction and the electrical repulsion between protons. In all nuclei of elements found in nature, 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

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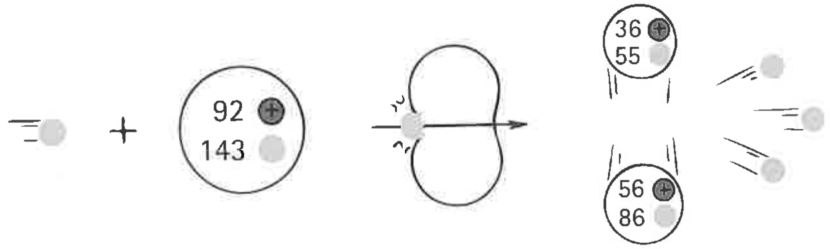
[1] Similarly, Ernest Rutherford used a biological term when he chose the word *nucleus* for the center of an atom.

nucleus separates. This is fission.[2] The absorption of a neutron by a uranium nucleus supplies enough energy to cause such an elongation. The resultant fission process may produce many different combinations of smaller nuclei. A typical example is



$$^{1}_{0}n + ^{235}_{92}\mathrm{U} \rightarrow ^{91}_{36}\mathrm{Kr} + ^{142}_{56}\mathrm{Ba} + 3(^{1}_{0}n)$$

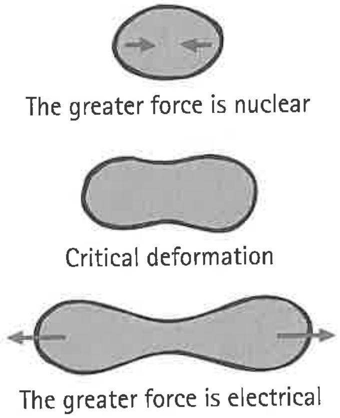


FIGURE 34.1

Nuclear deformation may continue all the way to fission when repulsive electrical forces overcome attractive nuclear forces.

In this reaction, note that one neutron starts the fission of the uranium nucleus and that the fission produces three neutrons (yellow).[3] Because neutrons have no charge and are not repelled by atomic nuclei, they make good "nuclear bullets" and can cause the fissioning of additional uranium atoms, releasing still more neutrons, which can cause still more fissions and release an avalanche of still more neutrons. Such a sequence is called a **chain reaction**—a self-sustaining reaction in which the products of one reaction event stimulate further reaction events (Figure 34.2).

A typical fission reaction releases energy of about 200,000,000 electron volts (eV).[4] (By comparison, the explosion of a TNT molecule releases only 30 eV.) The combined mass of the fission fragments and neutrons produced in fission is less than the mass of the original uranium nucleus. The tiny amount of missing mass converted to this awesome amount of energy is in accord with Einstein's equation $E = mc^2$. Quite remarkably, the energy of fission is mainly in the form of kinetic energy of the fission fragments that fly apart from one another and of the ejected neutrons. Interestingly, a smaller amount of energy is that of gamma radiation.

The scientific world was jolted by the news of nuclear fission—not only because of the enormous energy release but also because of the extra neutrons liberated in the process. A typical fission reaction releases two or three neutrons. These new neutrons can, in turn, cause the fissioning of two or three other atomic nuclei, releasing more energy and a total of from four to nine more neutrons. If each of these neutrons splits just one nucleus, the next step in the reaction will produce between 8 and 27 neutrons, and so on. Thus, a whole chain reaction can proceed at an exponential rate.

Why do chain reactions not occur in naturally occurring uranium ore deposits? They would if all uranium atoms fissioned so easily. Fission occurs mainly for the rare isotope U-235, which makes up only 0.7% of the uranium in pure uranium metal. When the more abundant isotope U-238 absorbs neutrons created by fission of U-235, the U-238 typically does not undergo fission. So any chain reaction is snuffed out by the neutron-absorbing U-238, as well as by the rock in which the ore

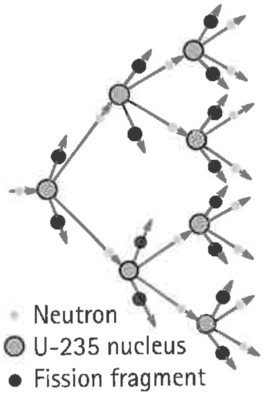


FIGURE 34.2

A chain reaction.

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[2] Fission resulting from neutron absorption is called *induced fission*. In rare instances, especially among the transuranics (elements heavier than uranium), nuclei can also undergo *spontaneous fission* without initial neutron absorption.

[3] In this reaction, three neutrons are ejected when fission occurs. In some other reactions, two neutrons may be ejected—or, occasionally, one or four. On average, fission produces 2.5 neutrons per reaction.

[4] The *electron volt* (eV) is defined as the amount of kinetic energy an electron acquires in accelerating through a potential difference of V.

is imbedded. In today's world, naturally occurring uranium is too "impure" to undergo a chain reaction spontaneously.[5]

If a chain reaction occurred in a baseball-size chunk of pure U-235, an enormous explosion would result. If the chain reaction were started in a smaller chunk of pure U-235, however, no explosion would occur. This is because of geometry: The ratio of surface area to mass is larger in a small piece than in a large one (just as there is more skin on six small potatoes having a combined mass of 1 kg than there is on a single 1-kg potato). So there is more surface area on a bunch of small pieces of uranium than on a large piece. In a small piece of U-235, neutrons leak through the surface before an explosion can occur. In a bigger piece, the chain reaction builds up to enormous energies before the neutrons get to the surface and escape (Figure 34.4). For masses greater than a certain amount, called the **critical mass,** an explosion of enormous magnitude may occur.

Consider a large quantity of U-235 divided into two pieces, each having a mass less than critical. The units are *subcritical.* Neutrons in either piece readily reach a surface and escape before a sizable chain reaction builds up. But if the pieces are suddenly driven together, the total surface area decreases. If the timing is right and the combined mass is greater than critical, called *supercritical,* the chain reaction builds up explosively. This is what can happen in a nuclear fission bomb (Figure 34.5). A bomb in which pieces of uranium are driven together is a so-called "gun-type" weapon, as opposed to the now more common "implosion weapon."

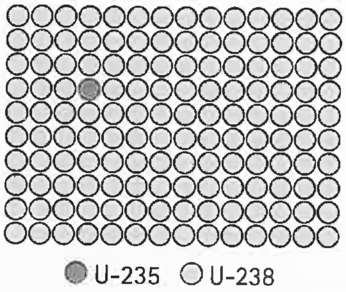

FIGURE 34.3

Only 1 part in 140 (0.7%) of naturally occurring uranium is U-235.

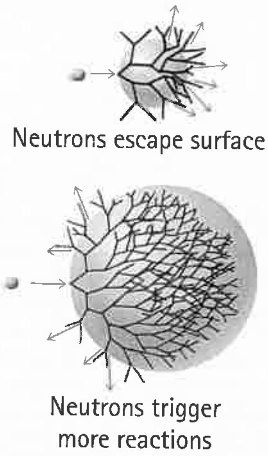

FIGURE 34.4

A chain reaction in a small piece of pure U-235 dies out because neutrons leak from the surface too readily. The small piece has a lot of surface area relative to its mass. In a larger piece, more uranium atoms and less surface area are presented to the neutrons.

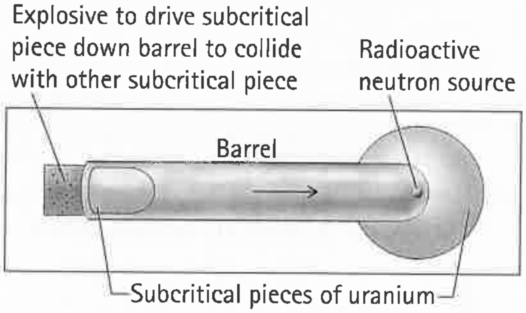

FIGURE 34.5

Simplified diagram of an idealized uranium fission bomb of the "gun type."

Constructing a fission bomb is a formidable task. The difficulty is separating enough U-235 from the more abundant U-238. Scientists took more than 2 years to extract enough U-235 from uranium ore to make the bomb that was detonated at Hiroshima in 1945. A chunk of U-235 probably a little larger than a softball was used in this historic blast. To this day, uranium isotope separation remains a difficult process, although advanced centrifuges have made it less formidable than it was in World War II. Project scientists at the secret Manhattan Project at that time used two methods of isotope separation. One method employed diffusion, where molecules of a gaseous compound (uranium hexafluoride) containing the lighter U-235 have a slightly greater average speed than molecules containing U-238 at the same temperature. The faster isotope has a higher rate of diffusion through a thin membrane or small opening, resulting in a slightly enriched gas containing U-235 on the other side (Figure 34.6). Diffusion through thousands of chambers ultimately produced a sufficiently enriched sample of U-235.

The other method, used only for partial enrichment, employed magnetic separation of uranium ions shot into a magnetic field. The smaller-mass U-235 ions

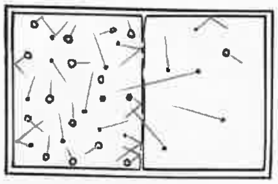

FIGURE 34.6

Lighter molecules move faster than heavier ones at the same temperature and diffuse more readily through a thin membrane.

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[5] Much earlier in Earth's history, the percentage of U-235 in natural uranium was greater than it is today. U-235 has a shorter half-life than U-238, so, over time, the percentage of U-235 declines. In 1972 the French physicist Francis Perrin turned up evidence that some 1.7 billion years ago, natural reactors existed in uranium deposits in what is now Gabon in West Africa.

CHECK POINT

What is the function of a *moderator* in a nuclear reactor? Of *control rods?*

Check Your Answers

A moderator slows down neutrons that are normally too fast to be absorbed readily by fissionable isotopes, such as U-235. Control rods absorb more neutrons when they are pushed into the reactor and fewer neutrons when they are pulled out of the reactor. They thereby control the number of neutrons that participate in the chain reaction.

Plutonium

Early in the 19th century, the farthermost planet known in the solar system was Uranus. The first planet to be discovered beyond Uranus was named Neptune. In 1930, what seemed to be a planet beyond Neptune was discovered and was named Pluto. During this time the heaviest element known was uranium. Appropriately enough, the first transuranic element to be discovered was named *neptunium* and the second transuranic element was named *plutonium.*

Neptunium is produced when a neutron is absorbed by a U-238 nucleus. Rather than undergoing fission, the nucleus emits a beta particle and becomes neptunium, the first synthetic element beyond uranium. The half-life of neptunium is only 2.3 days, so it isn't around very long. Neptunium is a beta emitter and very soon becomes plutonium. The half-life of plutonium is about 24,000 years, so it lasts a considerable time. The isotope plutonium-239, like U-235, will undergo fission when it captures a neutron. Whereas the separation of fissionable U-235 from uranium metal is a very difficult process (because U-235 and U-238 have the same chemistry), the separation of plutonium from uranium metal is relatively easy. This is because plutonium is an element distinct from uranium, with its own chemical properties.

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Video
Plutonium

The element plutonium is chemically poisonous in the same sense as are lead and arsenic. It attacks the nervous system and can cause paralysis. Death can follow if the dose is sufficiently large. Fortunately, plutonium does not remain in its elemental form for long because it rapidly combines with oxygen to form three compounds: PuO, PuO_2, and Pu_2O_3, all of which chemically are relatively benign. They will not dissolve in water or in biological systems. These plutonium compounds do not attack the nervous system and have been found to be chemically harmless.

Plutonium in any form, however, is radioactively toxic. It is more toxic than uranium, although less toxic than radium. Plutonium emits high-energy alpha particles, which kill cells rather than simply disrupting them and leading to mutations. Interestingly, damaged cells rather than dead cells contribute to cancer. This is why plutonium ranks relatively low as a cancer-producing substance. The greatest danger that plutonium presents to humans is its potential for use in nuclear fission bombs. Its usefulness is in fission reactors—particularly breeder reactors.

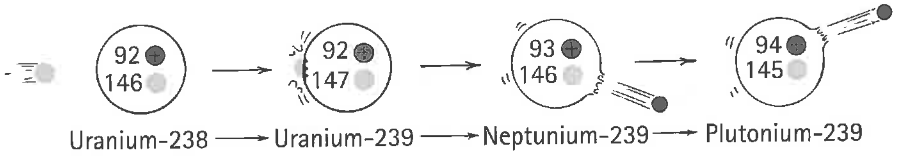

FIGURE 34.10

When a nucleus of U-238 absorbs a neutron, it becomes a nucleus of U-239. Within about half an hour, this nucleus emits a beta particle, resulting in a nucleus of about the same mass but with one more unit of charge. This is no longer uranium; it's a new element—*neptunium.* After the neptunium, in turn, emits a beta particle, it becomes plutonium. (In both events, an antineutrino, not shown, is also emitted.)

CHECK POINT

Why does plutonium not occur in appreciable amounts in natural ore deposits?

Check Your Answer

On a geological time scale, plutonium has a relatively short half-life, so any that exists is produced by very recent transmutations of uranium isotopes.

fyi

- Weapons-grade plutonium is 90% pure Pu-239.

The Breeder Reactor

A remarkable feature of fission power is the *breeding* of plutonium from nonfissionable U-238. Breeding occurs when small amounts of fissionable U-235 are mixed with U-238 in a reactor. Fissioning liberates neutrons that convert the relatively abundant nonfissionable U-238 to U-239, which beta-decays to become Np-239, which, in turn, beta-decays to fissionable plutonium—Pu-239. So, in addition to the abundant energy produced, fission fuel is bred from relatively abundant U-238 in the process.

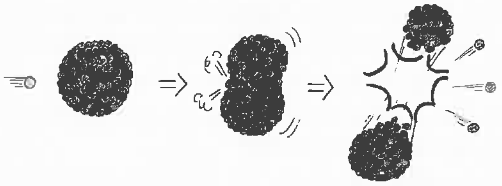

FIGURE 34.11

INTERACTIVE FIGURE

Pu-239 or U-233, like U-235, undergoes fission when it captures a neutron.

Some breeding occurs in all fission reactors, but a **breeder reactor** is specifically designed to breed more fissionable fuel than is put into it. Using a breeder reactor is analogous to filling your car's gas tank with water, adding some gasoline, then driving the car and having more gasoline at the end of the trip than at the beginning! The basic principle of the breeder reactor is very attractive: After a few years of operation, a breeder-reactor power plant can produce vast amounts of power while breeding twice as much fuel as it had in the beginning.

The downside of breeder reactors is the enormous complexity of successful and safe operation. The United States gave up on breeders in the 1980s, and only France, Germany, India, and China are still investing in them. Officials in these countries point out that supplies of naturally occurring U-235 are limited. At present rates of consumption, all natural sources of U-235 may be depleted within a century. Countries then deciding to use breeder reactors may well find themselves digging up radioactive wastes they once buried.[9]

Some public outcry is against nuclear power—"No Nukes!" The position of this book, in contrast, is "Know Nukes!"—first know something about the promises of, as well as the drawbacks to, nuclear power before saying *yes* or *no* to nukes.

CHECK POINT

Complete these reactions, which occur in a breeder reactor:

$^{239}_{92}\text{U} \rightarrow$ _____ $+ ^{0}_{-1}e$

$^{239}_{93}\text{NP} \rightarrow$ _____ $+ ^{0}_{-1}e$

Check Your Answers

$^{239}_{93}\text{NP}$; $^{239}_{92}\text{Pu}$. (Antineutrinos are also emitted in these beta-decay processes, and they escape unobserved.)

Fission Power

Energy available from nuclear fission was introduced to the world in the form of nuclear bombs. This violent image still impacts our thinking about nuclear power. Add to this the fearsome 1986 Chernobyl disaster in the Soviet Union, and we find many people viewing nuclear power as evil technology. Nevertheless, about 20%

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[9] Many nuclear scientists do not think that deep burial is a desirable solution to the problem of nuclear waste. Devices are presently being studied that could, in principle, convert long-lived radioactive atoms of spent reactor fuel into short-lived or nonradioactive atoms. Nuclear wastes may not plague future generations indefinitely, as has been commonly thought.

of electric energy in the United States is generated by nuclear-fission reactors. These reactors, sometimes called *nukes,* are simply nuclear furnaces. Like fossil-fuel furnaces, they do nothing more elegant than boil water to produce steam for a turbine. The greatest practical difference is the amount of fuel involved. One kilogram of uranium fuel, a chunk smaller than a baseball, yields more energy than 30 freight car loads of coal.

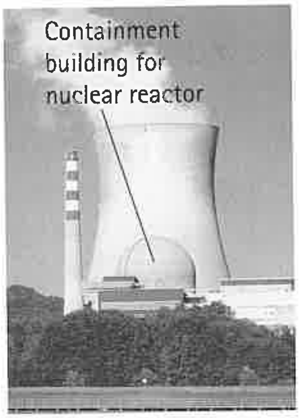

FIGURE 34.12

The nuclear reactor is housed within a dome-shaped containment building that is designed to prevent the release of radioactive isotopes in the event of an accident.

fyi

- Nuclear waste can be "burned" in special reactors that transmutes it into more benign elements, thus eliminating the objection that nuclear wastes are in the laps of future generations.

One disadvantage of fission power is the generation of radioactive waste products. Light atomic nuclei are most stable when composed of equal numbers of protons and neutrons, and it is mainly heavy nuclei that need more neutrons than protons for stability. For example, there are 143 neutrons but only 92 protons in U-235. When uranium fissions into two medium-weight elements, the extra neutrons in their nuclei make them unstable. These fragments are therefore radioactive, and most of them have very short half-lives. Some of them, however, have half-lives of thousands of years. Safely disposing of these waste products as well as materials made radioactive in the production of nuclear fuels requires special storage casks and procedures. Although fission power goes back a half century, the technology of radioactive waste disposal remains in the developmental stage.

The benefits of fission power are (1) plentiful electricity; (2) the conservation of the many billions of tons of coal, oil, and natural gas that every year are literally converted to heat and smoke and that in the long run may be far more precious as sources of organic molecules than as sources of heat; and (3) the elimination of the megatons of sulfur oxides and other poisons, as well as the greenhouse gas carbon dioxide, that are released into the air each year by the burning of these fuels.

The drawbacks include (1) the problem of storing radioactive wastes; (2) the production of plutonium and the danger of nuclear weapons proliferation; (3) the low-level release of radioactive materials into the air and groundwater; and, most importantly, (4) the risk of an accidental release of large amounts of radioactivity.

Reasoned judgment requires not only that we examine the benefits and drawbacks of fission power but also that we compare its benefits and drawbacks with those of other power sources.

The energy value of radioactive materials released in coal-burning power plants is some 1.5 times more than the energy provided by coal itself.

CHECK POINT

More environmental radiation surrounds a typical coal-fired power plant than surrounds a fission power plant. What does this indicate about the shielding typically surrounding the two types of power plants?

Check Your Answer

Coal-fired power plants are, seemingly, as American as apple pie, with (at this writing) no required shielding to restrict the emissions of radioactive particles. Fission power plants, on the other hand, are required to have shielding to ensure strictly low levels of radioactive emissions.

Mass–Energy Equivalence

In 1905, Albert Einstein discovered that mass is actually "congealed" energy. Mass and energy are two sides of the same coin, as stated in his celebrated equation $E = mc^2$. In this equation, E stands for the energy that any mass has at rest, m stands for mass, and c is the speed of light. The quantity c^2 is the proportionality constant of energy and mass. This relationship between energy and mass is the key to understanding why and how energy is released in nuclear reactions.

The more energy that is stored in a particle, the greater is the mass of the particle. Is the mass of a nucleon inside a nucleus the same as that of the same nucleon outside a nucleus? This question can be answered by considering the work that would be required to separate nucleons from a nucleus. From physics we know that work, which is expended energy, is equal to *force* × *distance*. Think of the amount of force required to pull a nucleon out of the nucleus through a sufficient distance to overcome the attractive strong nuclear force, comically indicated in Figure 34.13. Enormous work would be required. This work is energy added to the nucleon that is pulled out.

FIGURE 34.13

Work is required to pull a nucleon from an atomic nucleus. This work goes into mass energy.

The mass difference in a nucleon outside a nucleus and locked inside a nucleus is related to the "binding energy" of the nucleus. For uranium, the mass difference is about 0.8%, or 8 parts in 1000. The 0.8% reduction in the average nucleon mass within a uranium atom indicates the binding energy of the nucleus—how much work would be required to disassemble the nucleus.[10] That works out to be about 8 million eV per nucleon.

The experimental verification of this conclusion is one of the triumphs of modern physics. The average mass per nucleon within the nuclei of the isotopes of the various elements can be measured with an accuracy of 1 part per million or better. One means of doing this is with a *mass spectrometer* (Figure 34.14).

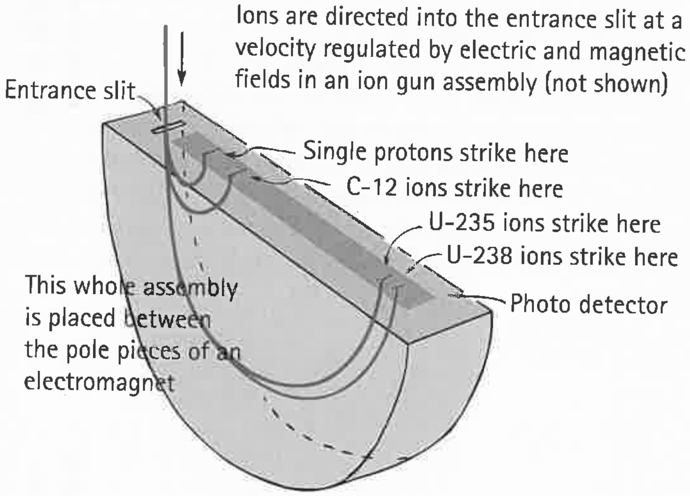

FIGURE 34.14

The mass spectrometer. Ions of a fixed speed are directed into the semicircular "drum," where they are swept into semicircular paths by a strong magnetic field. Which will be swept into smaller arcs, heavy nuclei or light nuclei?

In a mass spectrometer, charged ions with identical speeds are directed into a magnetic field, where they deflect into circular arcs. The greater the inertia of the ion, the more it resists deflection and the greater the radius of its curved path. The magnetic force sweeps the heavier ions into larger arcs and the lighter ions into smaller arcs. The ions pass through exit slits, where they may be collected, or they strike a detector, such as photographic film. An isotope is chosen as a standard, and its position on the film of the mass spectrometer is used as a reference point. The standard is the common isotope of carbon, C-12, the atomic mass of which is assigned the value of 12.00000 atomic mass units. Recall that the atomic mass unit (amu) is defined to be precisely one-twelfth the mass of the common carbon-12 atom. With this reference, the amu values of the other atoms are measured. You can see that in a C-12 atom, the average mass per nucleon is exactly 1.00000. This is less than the mass of either a hydrogen atom or a free neutron, which are, respectively, 1.007825 and 1.00867 amu.

A graph of nuclear mass as a function of atomic number is shown in Figure 34.15. The graph slopes upward with increasing atomic number, as expected, telling

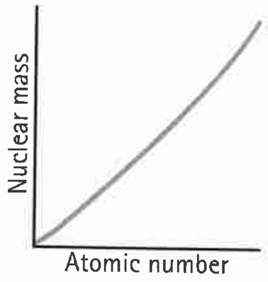

FIGURE 34.15

The plot shows how nuclear mass increases with increasing atomic number.

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[10] Strictly speaking, it isn't possible to measure the mass of an individual nucleon within a nucleus. We can only measure the total mass of the nucleus and divide by the number of nucleons therein to get the average mass per nucleon, which is what comes out to be about 0.8% less than the mass of a free nucleon.

TABLE 34.1

Masses and Masses per Nucleon of Some Isotopes

Isotope	*Symbol*	*Mass (amu)*	*Mass/Nucleon (amu)*
Neutron	n	1.008665	1.008665
Hydrogen	${}^{1}_{1}\text{H}$	1.007825	1.007825
Deuterium	${}^{2}_{1}\text{H}$	2.01410	1.00705
Tritium	${}^{3}_{1}\text{H}$	3.01605	1.00535
Helium-4	${}^{4}_{2}\text{He}$	4.00260	1.00065
Carbon-12	${}^{12}_{6}\text{C}$	12.00000	1.000000
Iron-58	${}^{58}_{26}\text{Fe}$	57.93328	0.99885
Copper-63	${}^{63}_{29}\text{Cu}$	62.92960	0.99888
Krypton-90	${}^{90}_{36}\text{Kr}$	89.91952	0.99911
Barium-143	${}^{143}_{56}\text{Ba}$	142.92063	0.99944
Uranium-235	${}^{235}_{92}\text{U}$	235.04393	1.00019

us that elements are more massive as atomic number increases. (The slope curves because there are proportionally more neutrons in the more massive atoms.)

A more important graph results from a plot of average mass *per nucleon* for the elements hydrogen through uranium (Figure 34.16). This is perhaps the most important graph in this book, for it is the key to understanding the energy associated with nuclear processes—fission as well as fusion. To obtain the average mass per nucleon, you divide the total mass of an atom by the number of nucleons in the nucleus. (Similarly, if you divide the total mass of a roomful of people by the number of people in the room, you get the average mass per person.) The major fact we learn from Figure 34.16 is that the average mass per nucleon varies from one nucleus to another.

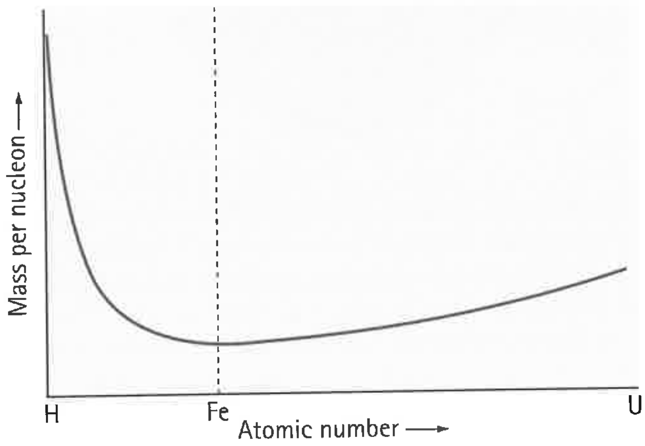


FIGURE 34.16

INTERACTIVE FIGURE

The graph shows that the average mass per nucleon in the nucleus varies from one end of the periodic table to the other. You can say that individual nucleons have the most mass in the lightest (hydrogen) nuclei, the least mass in iron nuclei, and intermediate mass in the heaviest (uranium) nuclei. (The vertical scale is exaggerated.)

The greatest mass per nucleon occurs for hydrogen, whose lone central proton has no binding energy to pull its mass down. As we progress to elements beyond hydrogen, Figure 34.16 tells us that the mass per nucleon decreases and is least for iron. The iron nucleus holds its nucleons more tightly than any other nucleus does. Beyond iron, the trend reverses itself as proton repulsion becomes more important and the binding energy per nucleon gradually decreases (meaning that the mass per nucleon gradually increases). This continues all the way through the list of elements.

From this graph, we can see why energy is released when a uranium nucleus is split into two nuclei of lower atomic number. When the uranium nucleus splits, the masses of the two fission fragments lie about halfway between the masses of uranium and hydrogen on the horizontal scale of the graph. It is most important to

The graph of Figure 34.16 reveals the energy of the atomic nucleus, likely the primary source of energy in the universe—which is why it can be considered the most important graph in this book.

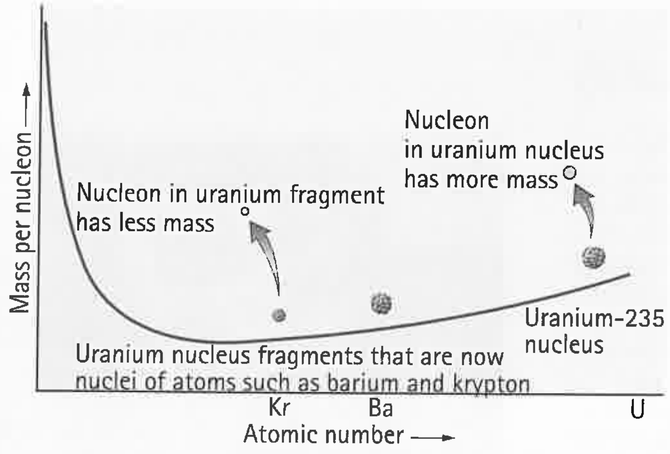
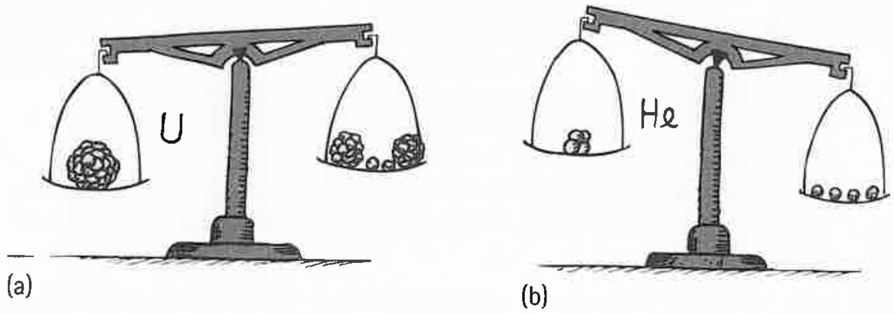


FIGURE 34.17

The average mass of each nucleon in a uranium nucleus is greater than the average mass of each nucleon in any one of its nuclear-fission fragments. This decrease in mass is transformed into energy. Hence, nuclear fission is an energy-releasing process.

note that the mass per nucleon in the fission fragments is *less than* the mass per nucleon when the same set of nucleons is combined in the uranium nucleus. When this decrease in mass is multiplied by the speed of light squared, it equals 200,000,000 eV, the energy yielded by each uranium nucleus that undergoes fission. As mentioned earlier, most of this enormous energy is the kinetic energy of the fission fragments.



(a)

(b)

FIGURE 34.18

INTERACTIVE FIGURE

The mass of a nucleus is *not* equal to the sum of the masses of its parts. (a) The fission fragments of a heavy nucleus like uranium are less massive than the uranium nucleus. (b) Two protons and two neutrons are more massive in their free states than when they are combined to form a helium nucleus.

We can think of the mass-per-nucleon curve as an energy valley that starts at the highest point (hydrogen), slopes steeply down to the lowest point (iron), and then slopes more gradually up to uranium. Iron is at the bottom of the energy valley and is the most stable nucleus. It is also the most tightly bound nucleus; more energy per nucleon is required to separate a nucleon from its nucleus than from any other nucleus.

All nuclear power today is by way of nuclear fission. A more promising long-range source of energy is to be found on the left side of the energy valley.

Binding energy reduces the mass of a nucleus by exactly the mass equivalence (E/c^2) of that binding energy. The more binding energy, the less mass. The iron nucleus has the greatest binding energy per nucleon and the least mass per nucleon.

TABLE 34.2

Energy Gain from Fission of Uranium

Reaction:	$^{235}U + n \rightarrow {}^{143}Ba + {}^{90}Kr + 3n + \Delta m$
Mass balance:	$235.04393 + 1.008665 = 142.92063 + 89.91952 + 3(1.008665) + \Delta m$
Loss of mass:	$\Delta m = 0.186$ amu
Gain of energy:	$\Delta E = \Delta mc^2 = 0.186 \times 931$ MeV $= 173$ MeV
Energy gain/nucleon:	$\Delta E/236 = 173$ MeV$/236 = 0.73$ MeV/nucleon

(1 amu × c^2 = 931 MeV, the energy equivalent of 1 amu. In addition to the above, there is an additional delayed energy release of about 25 MeV from the radioactive fission fragments, for a total energy release per fission event of close to 200 MeV.)

Physics at Airport Security

A version of the mass spectrometer shown in Figure 34.14 is employed in airport security. Ion mobility rather than electromagnetic separation is used to sniff out certain molecules, mainly the few nitrogen-rich ones characteristic of explosives. Security personnel swab your luggage or other belongings with a small disk of paper, which they place in a device that heats it to expel vapors from it. Molecules in the vapor are ionized by exposure to beta radiation from a radioactive source. Most molecules become positive ions, whereas nitrogen-rich molecules become negative, which drift against a flow of air to a positively charged detector. The time for a negative ion to reach the detector indicates the ion's mass—the heavier the ion, the slower it will be to reach the detector.

The same process occurs in body scans, in which a person stands momentarily in an enclosed region the size of a telephone booth where upward puffs of air impinge on the body. The air is then "sniffed" by the same technique, searching for some 40 types of explosives and 60 types of drug residues. Presto, green light means none were detected, and red light means—uh-oh!

CHECK POINT

1. Wait a minute! If isolated protons and neutrons have masses greater than 1.0000 amu, why don't 12 of them in a carbon nucleus have a combined mass greater than 12.0000 amu?
2. Correct the following incorrect statement: When a heavy element, such as uranium, undergoes fission, there are fewer nucleons after the reaction than before.

Check Your Answers

1. When you pull a nucleon from the nucleus, you do work on it and it gains energy. When that nucleon falls back into the nucleus, it does work on its surroundings and *loses* energy. Losing energy means losing mass. It's as if each nucleon, on average, slims down to a mass of exactly 1.0000 amu when it joins with 11 other nucleons to form C-12. If you pull them back out, you'll get back the original mass. Indeed, $E = mc^2$.
2. When a heavy element, such as uranium, undergoes fission, there aren't fewer nucleons after the reaction. Instead, there's *less mass* in the same number of nucleons.

Nuclear Fusion

Inspection of the mass-per-nucleon versus atomic-number graph will show that the steepest part of the energy hill is from hydrogen to iron. Energy is gained as light nuclei *fuse* (which means that they combine). This combining of nuclei is **nuclear fusion**—the opposite of nuclear fission. We can see from Figure 34.19 that as we move along the list of elements from hydrogen to iron (left side of the energy valley), the average mass per nucleon decreases. Thus, if two small nuclei were to

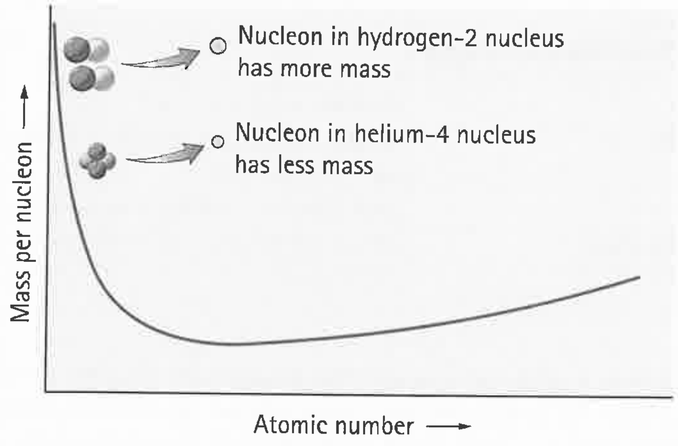


FIGURE 34.19
The average mass of a nucleon in hydrogen is greater than its average mass when fused with another to become helium. The decreased mass is mass that is converted to energy, which is why nuclear fusion of light elements is an energy-releasing process.

fuse, the mass of the fused nucleus would be less than the mass of the two single nuclei before fusion. Energy is released as light nuclei fuse.

Consider hydrogen fusion. For a fusion reaction to occur, the nuclei must collide at a very high speed in order to overcome their mutual electric repulsion. The required speeds correspond to the extremely high temperatures that are found in the Sun and other stars. Fusion brought about by high temperatures is called **thermonuclear fusion.** In the high temperatures of the Sun, approximately 657 million tons of hydrogen are fused to 653 million tons of helium each second. The "missing" 4 million tons of mass convert to energy. Such reactions are, quite literally, nuclear burning.

In a sense, nucleons in the heavy elements wish to lose mass and be like nucleons in iron. And nucleons in the light elements also wish to lose mass and become more like those in iron.

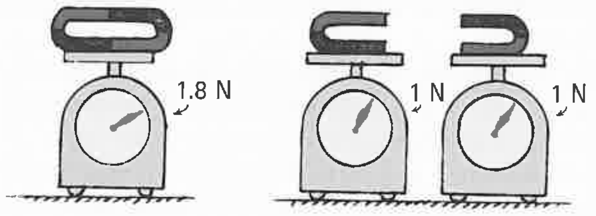
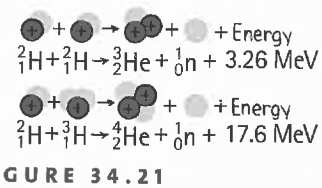


FIGURE 34.20
Fictitious example: The "hydrogen magnets" weigh more when they are apart than they do when they are together.

Interestingly, most of the energy of nuclear fusion is in the kinetic energy of fragments. When the fragments are stopped and captured, the energy of fusion turns into heat. In the Sun, this heat ends up as photons radiated from the surface. In fusion reactions of the future, part of this heat will be transformed to electricity.

Thermonuclear fusion is analogous to ordinary chemical combustion. In both chemical and nuclear burning, a high temperature starts the reaction; the release of energy by the reaction maintains a sufficient temperature to spread the fire. The net result of the chemical reaction is a combination of atoms into more tightly bound molecules. In nuclear reactions, the net result is nuclei that are more tightly bound. In both cases, mass decreases as energy is released. The difference between chemical and nuclear burning is essentially one of scale.

In fission reactions, the amount of matter that is converted to energy is about 0.1%; in fusion, it can be as much as 0.7%. These numbers apply whether the process takes place in bombs, in reactors, or in stars. Some typical fusion reactions are shown in Figure 34.21. Most reactions produce at least a pair of particles—for example, a pair of deuterium nuclei that fuse produce a tritium nucleus and a neutron rather than a lone helium nucleus. Either reaction is okay as far as adding the nucleons and charges is concerned, but the lone-nucleus case is not in accord with conservation of momentum and energy. If a lone helium nucleus flies away



$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3.26\ \text{MeV}$$

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\ \text{MeV}$$

FIGURE 34.21
Two of many fusion reactions.

TABLE 34.3

Energy Gain from Fusion of Hydrogen

Reaction:	$^{2}H + {}^{3}H \rightarrow {}^{4}_{2}H + n + \Delta m$
Mass balance:	$2.01410 + 3.01605 = 4.00260 + 1.008665 + \Delta m$
Mass defect:	$\Delta m = 0.01888$ amu
Energy gain:	$\Delta E = \Delta mc^2 = 0.018888 \times 931$ MeV $= 17.6$ MeV
Energy gain/nucleon:	$\Delta E\ 5 = 17.6$ MeV/5 $= 3.5$ MeV/nucleon

after the reaction, it adds momentum that wasn't there initially. Or if it remains motionless, there's no mechanism for energy release. So, because a single product particle can't move and it can't sit still, it isn't formed. Fusion normally requires the creation of at least two particles to share the released energy.[11]

Table 34.3 shows the energy gain from the fusion of hydrogen isotopes deuterium and tritium. This is the reaction proposed for plasma fusion power plants of the future. The high-energy neutrons, according to plan, will escape from the plasma in the reactor vessel and heat a surrounding blanket of material to provide useful energy. The helium nuclei remaining behind will help to keep the plasma hot. Another reaction, not described here, will provide the tritium, which is not found in nature on Earth.

Elements somewhat heavier than hydrogen release energy when fused. But they release much less energy per fusion reaction than hydrogen. The fusion of still heavier elements occurs in the advanced stages of a star's evolution. The energy released per gram during the various fusion stages from helium to iron amounts to only about one-fifth of the energy released in the fusion of hydrogen to helium.

Prior to the development of the atomic bomb, the temperatures required to initiate nuclear fusion on Earth were unattainable. When it was found that the temperatures inside an exploding atomic bomb are 4 to 5 times the temperature at the center of the Sun, the thermonuclear bomb was but a step away. This first hydrogen bomb was detonated in 1952. Whereas the critical mass of fissionable material limits the size of a fission bomb (atomic bomb), no such limit is imposed on a fusion bomb (thermonuclear, or hydrogen, bomb). Just as there is no limit to the size of an oil-storage depot, there is no theoretical limit to the size of a fusion bomb. Like the oil in a storage depot, any amount of fusion fuel can be stored with safety until it is ignited. Although a mere match can ignite an oil depot, nothing less energetic than a fission bomb can ignite a thermonuclear bomb. We can see that there is no such thing as a "baby" hydrogen bomb. It cannot be less energetic than its fuse, which is a fission bomb.

The hydrogen bomb is another example of a discovery applied to destructive rather than constructive purposes. The potential constructive side of the picture is the controlled release of vast amounts of clean energy.

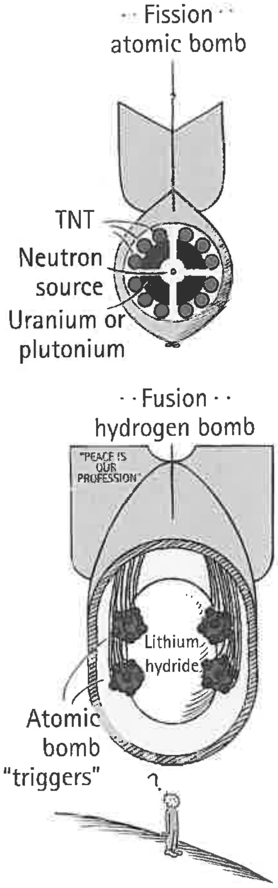


FIGURE 34.22

Fission and fusion bombs.

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[11] One of the reactions in the Sun's proton–proton fusion cycle does have a one-particle final state. It is proton + deuteron → He-3. This happens because the density in the center of the Sun is great enough that "spectator" particles share in the energy release. So, even in this case, the energy released goes to two or more particles. Fusion in the Sun involves more complicated (and slower!) reactions in which a small part of the energy also appears in the form of gamma rays and neutrinos. The neutrinos escape unhindered from the center of the Sun and bathe the solar system. Interestingly, the fusion of nuclei in the Sun is an occasional process, for the mean spacing between nuclei is vast, even at the high pressures in its center. That's why it takes some 10 billion years for the Sun to consume its hydrogen fuel.

CHECK POINT

1. First it was stated that nuclear energy is released when atoms split apart. Now it is stated that nuclear energy is released when atoms combine. Is this a contradiction? How can energy be released by opposite processes?
2. To obtain energy from the element iron, should iron nuclei be fissioned or fused?

Check Your Answers

1. Energy is released in any nuclear reaction in which the mass of the nuclei after the reaction is less than the mass of the nuclei before. When light nuclei, such as those of hydrogen, fuse to form heavier nuclei, total nuclear mass decreases. The fusion of light nuclei therefore releases energy. When heavy nuclei, such as those of uranium, split to become lighter nuclei, total nuclear mass also decreases. The splitting of heavy nuclei, therefore, releases energy. For energy release, "decrease mass" is the name of the game—any game, chemical or nuclear.
2. Neither, because iron is at the very bottom of the curve (energy valley). If you fuse two iron nuclei, the product lies somewhere on the upper right of iron on the curve, which means the product has a higher mass per nucleon. If you split an iron nucleus, the products lie on the upper left of iron on the curve, which again means a higher mass per nucleon. Because no mass decrease occurs in either reaction, no energy is ever released.

fyi

- The energy released in fusing a pair of hydrogen nuclei is less than that of fissioning a uranium nucleus. But because there are more atoms in a gram of hydrogen than in a gram of uranium, gram for gram, fusion of hydrogen releases several times as much energy as fission of uranium.

Controlling Fusion

The fuel for nuclear fusion is hydrogen, the most plentiful element in the universe. The reaction that works best at "moderate" temperature is the fusion of the hydrogen isotopes deuterium ($^{2}_{1}\text{H}$) and tritium ($^{3}_{1}\text{H}$). Deuterium is found in ordinary water. Deuterium in the world's oceans has the potential to release vastly more energy than all the world's fossil fuels and much more than the world's supply of uranium. Tritium, with a half-life of 12 years, is almost completely absent in nature, but it can be created by reacting deuterons (as in Figure 34.21) or in a reaction involving lithium.

Fusion, therefore, is a dream source of long-term energy needs. The outlook for fusion power in the foreseeable future, however, is bleak. Various fusion schemes have been tried. The earliest approach, still being pursued, involves confining a hot plasma with a magnetic field. Other approaches have harnessed high-energy lasers. One scheme is to drop hydrogen pellets into a crossfire of lasers that would ignite pulses of fusion power. The problems, after many years of effort, have been overwhelming. Implosion of a variety of particles, electrons, and many kinds of ions has also been unsuccessful. All scenarios have been in quest of an "energy breakeven," where energy output at least equals energy input. Except for brief spurts, it hasn't happened.

Will there be a breakthrough, where sustained energy output in a device will be greater than the energy input to initiate and sustain fusion? Will we find a way to tame the power of the Sun and stars? We don't know. If and when that comes to be, humans may synthesize their own elements and produce energy in the process, just as the stars have always done. At that point, fusion will likely be the primary energy source for generations to come. Keep tuned to the web.

SUMMARY OF TERMS

Nuclear fission The splitting of the nucleus of a heavy atom, such as uranium-235, into two smaller nuclei, accompanied by the release of much energy.

Chain reaction A self-sustaining reaction in which the products of one reaction event stimulate further reaction events.

Critical mass The minimum mass of fissionable material in a reactor or nuclear bomb that will sustain a chain reaction.

Breeder reactor A fission reactor that is designed to breed more fissionable fuel than is put into it by converting nonfissionable isotopes to fissionable isotopes.

Nuclear fusion The combination of light atomic nuclei to form heavier nuclei, with the release of much energy.

Thermonuclear fusion Nuclear fusion produced by high temperature.

REVIEW QUESTIONS

Nuclear Fission

1. Why does a chain reaction not occur in uranium mines?
2. Why is a chain reaction more likely in a big piece of uranium than it is in a small piece?
3. What is meant by the idea of a critical mass?
4. Which will leak more neutrons, two separate pieces of uranium or the same pieces stuck together?
5. What were the two methods used to separate U-235 from U-238 in the Manhattan Project during World War II?

Nuclear Fission Reactors

6. What are the three possible fates of neutrons in uranium metal?
7. What are the three main components of a fission reactor?
8. What are the safeguards to prevent a reactor exploding like a fission bomb?
9. What isotope is produced when U-238 absorbs a neutron?
10. What isotope is produced when U-239 emits a beta particle?
11. What isotope is produced when Np-239 emits a beta particle?
12. What do U-235 and Pu-239 have in common?

The Breeder Reactor

13. What is the effect of placing small amounts of fissionable isotopes with large amounts of U-238?
14. Name three isotopes that undergo nuclear fission.
15. How does a breeder reactor breed nuclear fuel?

Fission Power

16. How is a nuclear reactor similar to a conventional fossil-fuel plant? How is it different?
17. Cite a main advantage of fission power. Cite a main drawback.

Mass–Energy Equivalence

18. What celebrated equation shows the equivalence of mass and energy?
19. Is work required to pull a nucleon out of an atomic nucleus? Does the nucleon, once outside, have more energy than it did when it was inside the nucleus? In what form is this energy?
20. Which ions are least deflected in a mass spectrometer?
21. What is the basic difference between the graphs of Figure 34.15 and Figure 34.16?
22. In which atomic nucleus do nucleons have the greatest average mass? In which nucleus do they have the least average mass?
23. If the graph in Figure 34.16 is seen as an energy valley, what can be said about the energy of nuclear transformations that progress toward iron?

Nuclear Fusion

24. When two hydrogen nuclei are fused, is the mass of the product nucleus more or less than the sum of the masses of the two hydrogen nuclei?
25. For helium to release energy, should it be fissioned or fused?

Controlling Fusion

26. Where are isotopes of deuterium and tritium to be found?

RANKING

1. Assume that all of the following nuclei undergo fission into a pair of equal or nearly equal mass fragments. Using Figure 34.16 as your guide, rank from greatest to least the *reduction* in mass for these nuclei after fission.
   a. Uranium
   b. Silver
   c. Titanium
   d. Iron
2. Rank from greatest to least the *reduction* of mass per nucleon that accompanies the fusion of the following pairs of nuclei.
   a. Two hydrogen nuclei
   b. Two carbon nuclei
   c. Two aluminum nuclei
   d. Two iron nuclei

PROJECT

Write a letter to Grandpa or Grandma discussing nuclear power. Cite why uranium mines can be closed if plutonium from present nuclear warheads worldwide can be dismantled and used as fission fuel for power reactors. Cite both the ups and downs of nuclear fission power plants and explain how the comparison affects your personal view of nukes. Also explain to him or her how nuclear fission and nuclear fusion differ.

EXERCISES

1. Do today's nuclear power plants use fission, fusion, or both?
2. Why doesn't uranium ore spontaneously undergo a chain reaction?
3. Some heavy nuclei, containing even more protons than the uranium nucleus, undergo "spontaneous fission," splitting apart without absorbing a neutron. Why is spontaneous fission observed only in the heaviest nuclei?
4. Why will nuclear fission probably not be used directly for powering automobiles? How could it be used indirectly to power automobiles?
5. Why does a neutron make a better nuclear bullet than a proton?
6. Why will the escape of neutrons be proportionally less in a large piece of fissionable material than in a smaller piece?
7. A 56-kg sphere of U-235 constitutes a critical mass. If the sphere were flattened into a pancake shape, would it still be critical? Explain.
8. Which shape is likely to need more material for a critical mass, a cube or a sphere? Explain.
9. Does the average distance that a neutron travels through fissionable material before escaping increase or decrease when two pieces of fissionable material are assembled into one piece? Does this assembly increase or decrease the probability of an explosion?
10. U-235 releases an average of 2.5 neutrons per fission, while Pu-239 releases an average of 2.7 neutrons per fission. Which of these elements might you therefore expect to have the smaller critical mass?
11. Uranium and thorium occur abundantly in various ore deposits. However, plutonium could occur only in exceedingly tiny amounts in such deposits. What is your explanation?
12. Why, after a uranium fuel rod reaches the end of its fuel cycle (typically 3 years), does most of its energy come from the fissioning of plutonium?
13. If a nucleus of $^{232}_{90}\text{Th}$ absorbs a neutron and the resulting nucleus undergoes two successive beta decays (emitting electrons), what nucleus results?
14. The water that passes through the reactor core of a water-moderated fission reactor does not pass into the turbine. Instead, heat is transferred to a separate water cycle that is entirely outside the reactor. Why is this done?
15. Why is carbon better than lead as a moderator in nuclear reactors?
16. Is the mass of an atomic nucleus greater or less than the sum of the masses of the nucleons composing it? Why don't the nucleon masses add up to the total nuclear mass?
17. The energy release of nuclear fission is tied to the fact that the heaviest nuclei have about 0.1% more mass per nucleon than nuclei near the middle of the periodic table of the elements. What would be the effect on energy release if the 0.1% figure were instead 1%?
18. In what way are fission and fusion reactions similar? What are the main differences in these reactions?
19. How is chemical burning similar to nuclear fusion?
20. To predict the approximate energy release of either a fission reaction or a fusion reaction, explain how a physicist makes use of the curve in Figure 34.16 or a table of nuclear masses and the equation $E = mc^2$.
21. What nuclei will result if a U-235 nucleus, after absorbing a neutron and becoming U-236, splits into two identical fragments?
22. Heavy nuclei can be made to fuse—for instance, by firing one gold nucleus at another one. Does such a process yield energy or cost energy? Explain.
23. Light nuclei can be split. For example, a deuteron, which is a proton–neutron combination, can split into a separate proton and separate neutron. Does such a process yield energy or cost energy? Explain.
24. Which process would release energy from gold, fission or fusion? Which would release energy from carbon? From iron?
25. If uranium were to split into three segments of equal size instead of two, would more energy or less energy be released? Defend your answer in terms of Figure 34.16.
26. Mixing copper and zinc atoms produces the alloy brass. What would be produced with the fusion of copper and zinc nuclei?
27. Oxygen and hydrogen atoms combine to form water. If the nuclei in a water molecule were fused, what element would be produced?
28. If a pair of carbon atoms were fused, and the product were to emit a beta particle, what element would be produced?
29. Suppose the curve in Figure 34.16 for mass per nucleon versus atomic number had the shape of the curve in Figure 34.15. Then would nuclear fission reactions produce energy? Would nuclear fusion reactions produce energy? Defend your answers.
30. The "hydrogen magnets" in Figure 34.20 weigh more when apart than when combined. What would be the basic difference if the fictitious example instead consisted of "nuclear magnets" half as heavy as uranium?
31. In a nuclear fission reaction, which has more mass, the initial uranium or its products?
32. In a nuclear fusion reaction, which has more mass, the initial hydrogen isotopes or the fusion products?
33. Which produces more energy, the fissioning of a single uranium nucleus or the fusing of a pair of deuterium nuclei? The fissioning of a gram of uranium or the

fusing of a gram of deuterium? (Why do your answers differ?)

34. Why is there, unlike fission fuel, no limit to the amount of fusion fuel that can be safely stored in one locality?
35. If a fusion reaction produces no appreciable radioactive isotopes, why does a hydrogen bomb produce significant radioactive fallout?
36. List at least two major potential advantages of power production by fusion rather than by fission.
37. Sustained nuclear fusion has yet to be achieved and remains a hope for abundant future energy. Yet the energy that has always sustained us has been the energy of nuclear fusion. Explain.
38. Explain how radioactive decay has always warmed Earth from the inside and how nuclear fusion has always warmed Earth from the outside.
39. The world has never been the same since the discovery of electromagnetic induction and its applications to electric motors and generators. Speculate and list some of the worldwide changes that are likely to follow the advent of successful fusion reactors.
40. Discuss, and make a comparison of, pollution by conventional fossil-fuel power plants and nuclear-fission power plants. Consider thermal pollution, chemical pollution, and radioactive pollution.
41. Ordinary hydrogen is sometimes called a perfect fuel, both because of its almost unlimited supply on Earth and because, when it burns, harmless water is the product of the combustion. So why don't we abandon fission and fusion energies, not to mention fossil-fuel energy, and just use hydrogen?
42. If U-238 splits into two even pieces, and each piece emits an alpha particle, what elements are produced?
43. The energy of fission is mainly in the kinetic energy of its products. What becomes of this energy in a commercial power reactor?
44. Fermi's original reactor was just "barely" critical because the natural uranium that he used contained less than 1% of the fissionable isotope U-235 (half-life 713 million years). What if, in 1942, Earth had been 9 billion years old instead of 4.5 billion years old. Would Fermi have been able to make a reactor go critical with natural uranium?
45. U-235 has a half-life of about 700 million years. What does this say about the likelihood of fission power on Earth 1 billion years from now?

PROBLEMS

1. The kiloton, which is used to measure the energy released in an atomic explosion, is equal to 4.2×10^{12} J (approximately the energy released in the explosion of 1000 tons of TNT). Recalling that 1 kilocalorie of energy raises the temperature of 1 kg of water by 1°C and that 4184 joules is equal to 1 kilocalorie, show that 4.0×10^{8} kilograms of water (nearly half a million tons) can be heated through 50°C by a 20-kiloton atomic bomb.
2. The isotope of lithium used in a hydrogen bomb is Li-6, whose nucleus contains three protons and three neutrons. When a Li-6 nucleus absorbs a neutron, a nucleus of the heaviest hydrogen isotope, tritium, is produced. What is the other product of this reaction? Which of these two products fuels the explosive reaction?
3. An important fusion reaction in both hydrogen bombs and controlled-fusion reactors is the "DT reaction," in which a deuteron and a triton (nuclei of heavy hydrogen isotopes) combine to form an alpha particle and a neutron with the release of much energy. Use momentum conservation to explain why the neutron resulting from this reaction receives about 80% of the energy, while the alpha particle gets only about 20%.

CHAPTER 34 ONLINE RESOURCES

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Interactive Figures

- 34.11, 34.16, 34.18

Tutorial

- Nuclear Physics

Video

- Plutonium

Quizzes

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PART SEVEN MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following.

1. The neutrons in an atom are normally found
   (a) inside the nucleus. (c) Either of these.
   (b) outside the nucleus. (d) Neither of these.
2. Spectral lines of the elements are
   (a) chaotic. (c) positioned by amplitude.
   (b) ordered. (d) in phase.
3. The energy of an emitted photon is related to its
   (a) frequency. (c) amplitude.
   (b) polarization. (d) direction.
4. The discrete orbits of electrons is best understood when modeled by
   (a) high-speed particles. (c) waves.
   (b) particles on springs. (d) photons.
5. From quantum mechanics we learn that a radioactive nucleus is governed by
   (a) Newton's laws. (c) certainty.
   (b) probability. (d) no laws at all.
6. Radioactivity has been around on Earth since the
   (a) middle of the 1900s.
   (b) Industrial Revolution.
   (c) advent of medical technology.
   (d) Earth formed.
7. Which of these can NOT be deflected by electrical or magnetic means?
   (a) Alpha rays. (c) Gamma rays.
   (b) Beta rays. (d) All can.
8. Which type of radiation from cosmic sources predominates on the inside of high-flying commercial airplanes?
   (a) Alpha. (c) Gamma.
   (b) Beta. (d) None of these.
9. In the atomic nucleus, electrical forces tend to
   (a) hold particles together. (c) produce orbital motion.
   (b) push particles apart. (d) charge particles.
10. When food is exposed to gamma radiation, the food
    (a) becomes slightly radioactive.
    (b) doesn't become radioactive.
    (c) will spoil faster.
    (d) should be avoided.
11. Most of the radiation in Earth's biosphere is
    (a) natural background radiation.
    (b) the result of military activities.
    (c) from nuclear power plants.
    (d) in the form of cosmic rays.
12. Carbon-14 is primarily produced by cosmic radiation in the
    (a) atmosphere.
    (b) food we eat.
    (c) Earth's interior.
    (d) fallout of nuclear bomb tests.
13. A radioactive sample has a half-life of 1 hour. Starting with 1.000 gram of it at noon, how much remains at 3:00 PM?
    (a) 0.50 g. (c) 0.125 g.
    (b) 0.25 g. (d) 0.0625 g.
14. When an element ejects an alpha particle, the mass number of the resulting element
    (a) reduces by 2. (c) increases by 2.
    (b) reduces by 4. (d) increases by 4.
15. When an element ejects an alpha particle, the atomic number of the resulting element
    (a) reduces by 2. (c) increases by 2.
    (b) reduces by 4. (d) increases by 4.
16. When an element ejects a beta particle, the atomic number of that element
    (a) reduces by 1. (c) reduces by 2.
    (b) increases by 1. (d) increases by 2.
17. A certain element emits 1 alpha particle, and its products then emit 2 beta particles in succession. The atomic number of the resulting element is changed by
    (a) zero. (c) minus 2.
    (b) minus 1. (d) plus 1.
18. When a nucleus of uranium-238 emits an alpha particle, left behind is
    (a) thorium-242. (c) thorium-234.
    (b) thorium-238. (d) radium-214.
19. When a proton is plucked from an atomic nucleus, there is a decrease in
    (a) charge. (c) mass.
    (b) energy. (d) None of these.
20. When small pieces of material are assembled into a larger piece, the combined surface area
    (a) greatly increases. (c) decreases.
    (b) slightly increases. (d) is unchanged.
21. Chain reactions in a fission reactor are caused by
    (a) kinetic energy. (c) mass conversion.
    (b) energy conversion. (d) ejected neutrons.
22. A common nuclear fission reactor
    (a) heats water.
    (b) generates electricity directly.
    (c) gets energy from nothing.
    (d) is a major polluter of the atmosphere.
23. Compared with the mass of a uranium atom undergoing fission, the combined masses of the products after fission are
    (a) less. (c) the same.
    (b) more. (d) zero.
24. When energy is released by the process of fusion, the total mass of the material after the event is
    (a) less. (c) more.
    (b) the same. (d) zero.
25. Which process would release energy from gold, fission or fusion? From carbon?
    (a) Gold: fission; carbon: fusion
    (b) Gold: fusion; carbon: fission
    (c) Gold: fission; carbon: fission
    (d) Gold: fusion; carbon: fusion
26. If an iron nucleus split in two, its fission fragments would have
    (a) less mass per nucleon.
    (b) more mass per nucleon.
    (c) the same mass per nucleon.
    (d) either more or less mass per nucleon.
27. Which of these three elements has the most mass *per* nucleon?
    (a) Hydrogen. (c) Uranium.
    (b) Iron. (d) Same in each.
28. In both fission and fusion, energy is released while mass
    (a) decreases.
    (b) remains unchanged; is conserved.
    (c) increases.
    (d) may decrease or increase.
29. In either a fission event or a fusion event, a quantity that remains unchanged is the
    (a) kinetic energy. (c) number of nucleons.
    (b) mass. (d) binding of nucleons.
30. The equation that most underlies energy release in nuclear events is
    (a) $E = hf$. (c) $E = Fd$.
    (b) $E = 1/2\, mv^2$. (d) $E = mc^2$.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.