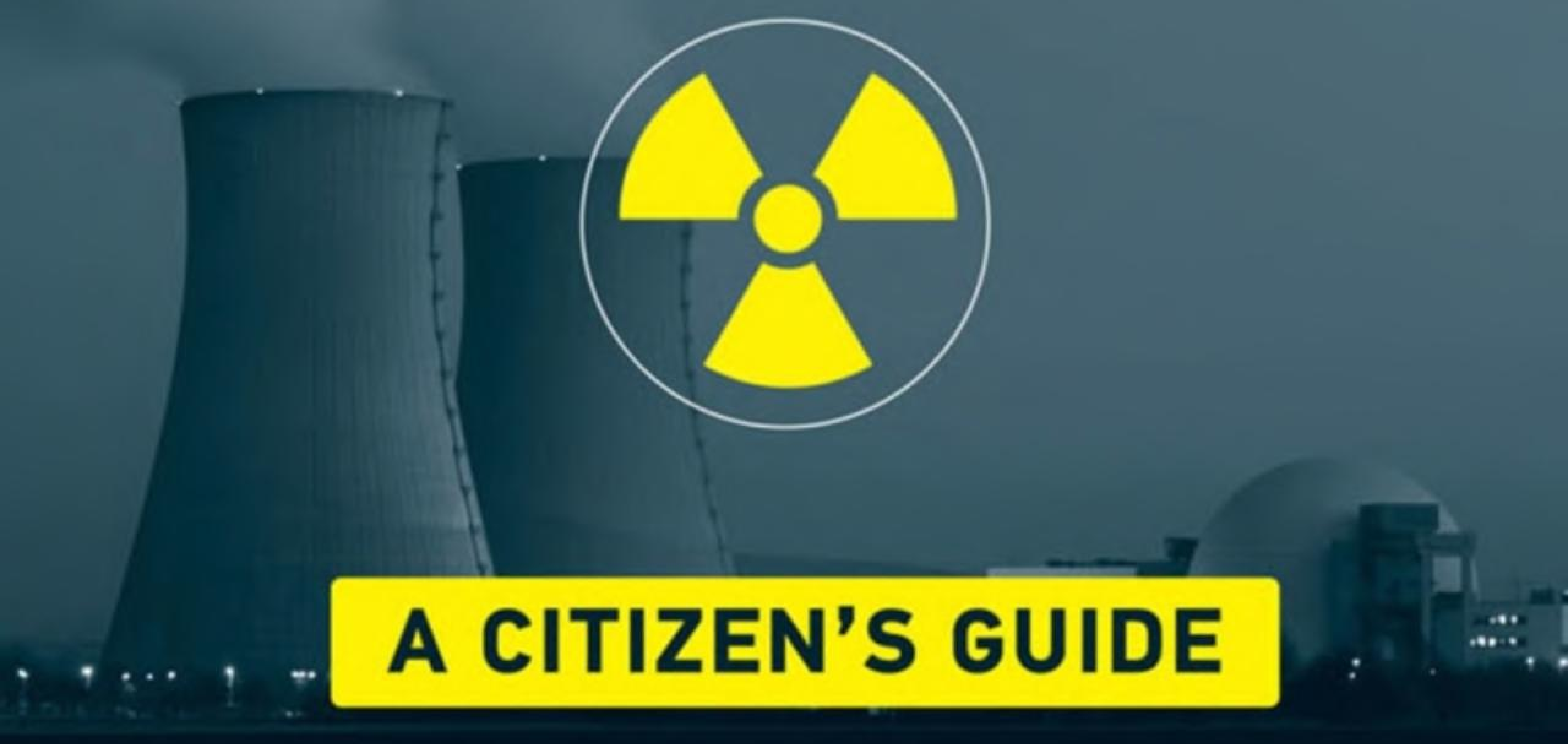
NUCLEAR CHOICES FOR THE TWENTY-FIRST CENTURY



A CITIZEN'S GUIDE

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Preface

Nuclear technology is an inescapable part of our lives. Nuclear reactors provide a significant share of our electrical energy. Techniques of nuclear medicine diagnose and treat our diseases. Nuclear processes help industry produce better and safer products, preserve our food and protect it from pests, and help archaeologists understand our past. And since the mid-twentieth century, nuclear weapons have purportedly kept the peace by threatening the annihilation of civilization.

With nuclear technology come dangers. Nuclear war is an obvious one. So are reactor accidents like those at Three Mile Island, Chernobyl, and Fukushima. Mining uranium, manufacturing nuclear weapons, and normal operation of nuclear power plants all release radioactivity to the environment. Nuclear medicine carries risks that must be weighed against its potential benefits. Even such non-nuclear technologies as aviation and house construction have nuclear dangers associated with them.

The news media regularly bring nuclear technology and its dangers to our attention. Nuclear technology provokes vigorous debates at the local, national, and global levels. Nuclear issues force us to make nuclear choices—individually in the voting booth, in citizens' forums, through our elected representatives, and through our leaders as they pursue international negotiations.

We've written this book on the premise that nuclear choices are best made by citizens who know something about the underlying issues, who understand the basics of nuclear technology, and who can judge for themselves statements advocating particular positions. In that spirit, the book demands no prior knowledge of nuclear matters. It does ask that readers be open to a range of opinions, be willing to grasp some basic science and technology, and be willing to bring informed judgment to their own nuclear choices.

We emphasize that *Nuclear Choices* does not expect of our readers any particular scientific or technological background. We'll supply the needed science and technology at levels appropriate for a general readership. Also, we don't expect our readers to toe a particular political line when it comes to nuclear issues, and we aren't going to push one on them. Although the book is written for individual citizens, it may also find use in college courses—although it's not designed as a textbook because it lacks problem sets, discussion questions, and other hallmarks of a textbook. We've written *Nuclear Choices* on the premise that citizens of today's industrialized societies cannot avoid nuclear technology, and whatever the context, the book should help citizens from all walks of life become familiar with nuclear technologies and the issues surrounding them and gain confidence in making nuclear choices.

Our specific goal is to introduce readers to ideas they'll need to understand nuclear issues as they're presented in contemporary news media and civic debate. By covering essentially all nuclear technologies in one book, we've been able to stress the connections among them—especially the multifaceted relation between nuclear power and nuclear weapons. Readers seeking a deeper understanding of individual nuclear technologies are referred to more thorough works listed at the end of each chapter.

Readers of a certain age may note a similarity between this book and RW's 1991 book *Nuclear Choices*, which was revised in 1993 to reflect the collapse of the Soviet Union but saw no further revisions. Yet the original *Nuclear Choices* remained in print, hopelessly dated, until we made the decision to create this new title in the spirit of the original book. So much has happened since that first *Nuclear Choices*! We've had new arms-control agreements that brought an order-of-magnitude drop in the world's nuclear arsenals; disturbing nuclear incidents including the Fukushima disaster; the September 11, 2001, attacks that heightened concern over nuclear terrorism; declassification of nuclear policy documents from the Cold War that give new insights into governmental thinking; a nuclear-armed Pakistan and the resulting India-Pakistan nuclear standoff; the astonishing rise of North Korea as a nuclear-armed state capable of threatening the United States with intercontinental ballistic missiles and thermonuclear weapons; the increasing recognition that Earth faces a global climate crisis with direct implications for our energy sources, including nuclear energy; a huge international effort to develop energy from nuclear fusion; a doubling of the background radiation dose in the United States; growth and then substantial decline in nuclear power's contribution to the world's electrical energy supply; and much, much more.

That vast scope of nuclear happenings challenges an author seeking comprehensive coverage of so broad and important a field. So RW invited FDV to join as coauthor on the new book and was delighted when the latter accepted. By bringing in FDV as coauthor, the book gains the expertise of a nuclear physicist who brings the unique perspective of a scientist working in what is largely a policy think tank (the Center for Nonproliferation Studies) devoted to issues around nuclear weapons proliferation as well as connections between nuclear power and nuclear weapons.

Many people and institutions contributed to the making of this book. We're particularly grateful to the Alfred P. Sloan Foundation's Books Program for a grant that helped support the project. (The original *Nuclear Choices* also received support from the Sloan Foundation, under its New Liberal Arts Program, which was intended to cultivate technological literacy in liberal arts environments.) We also received support from the One Middlebury Fund, whose purpose is to foster collaboration between Middlebury College in Vermont, where RW is based, and the college's graduate school, the Middlebury Institute of International Studies in Monterey, California, FDV's professional home. *Nuclear Choices* is probably the first book published jointly by scholars from Middlebury's two campuses on the East and West Coasts. In addition to these two generous grants, countless corporations, government agencies, national laboratories, universities, and individuals supplied factual information, photographs, and drawings. They're acknowledged individually where appropriate, and here we thank them all collectively. We're also grateful to our colleagues for their patience as this project drew us away from other obligations and, finally, to our families for their support.

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Middlebury, Vermont
March 2020

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Nuclear Questions, Nuclear Choices

In 2017, 58 percent of Swiss voters supported a government-proposed ban on new nuclear power plants. A year later, Taiwanese citizens voted overwhelmingly to overturn a government policy that would have eliminated nuclear power on the island. So the Swiss voted against nuclear power and the Taiwanese voted for it. If you were a Swiss or Taiwanese citizen, how would you have voted? On what would you have based your vote? Concern for safety? For the environment? Economics?

You've hit your head in a fall and your doctor is worried about a possible concussion. She recommends a CT scan. This, you discover, will give you some 2 millisieverts of radiation—about 30 percent of your yearly background radiation dose. Should you have the scan, or is the radiation a greater risk than the possible concussion? And what's a millisievert, and what's background radiation, and why should you be subject to radiation at all?

In January 2018, amid rising tensions between the United States and North Korea over the latter's long-range ballistic missile tests, residents of Hawaii received texts reading "BALLISTIC MISSILE THREAT INBOUND TO HAWAII. SEEK IMMEDIATE SHELTER. THIS IS NOT A DRILL." Panic ensued until, more than half an hour later, a second announcement declared a false alarm. An employee of the Hawaii Emergency Management Agency had inadvertently sent the text, confusing what was to be a test message with the real thing. How would you, as a resident of Hawaii, have reacted to the message? Where could you have found shelter from a nuclear attack? And what of the rest of the United States' population, almost all now within range of North Korea's ballistic missiles? How serious is this threat, and how should the United States respond?

Since the late 2010s, the state of South Australia has seen controversy over whether to build nuclear waste facilities in the state's arid outback—including the possibility of importing waste from outside Australia. A

Royal Commission produced a report favoring nuclear waste storage in South Australia, citing economic benefits. Then a 300-member citizens jury voted two-to-one against the nuclear waste proposals. If you had been a member of that jury, how would you have voted? On what knowledge or instincts would you have based your vote? What is nuclear waste? How is it formed? How dangerous is it? How long will it remain hazardous? What if terrorists got their hands on it?

Your local natural-foods store is considering a ban on irradiated foods. Should you support the ban? Does irradiation make foods safer or less safe? Do the foods become radioactive? Is there a connection between food irradiation and the nuclear power industry or the nuclear weapons establishment?

In 2019, President Donald Trump withdrew the U.S. from the Intermediate-Range Nuclear Forces (INF) Treaty, a 1987 agreement between the United States and the countries of the former Soviet Union, including Russia. Under the agreement, the U.S. destroyed nearly 1,000 missiles while the other side destroyed nearly 2,000. The treaty is credited with reducing the risk of nuclear war, especially in late twentieth-century Europe. But had the INF Treaty become obsolete in today's world, where nuclear powers such as China aren't subject to the ban on intermediate-range missiles? Or has withdrawal from the INF sparked a new nuclear arms race? How would you, as a citizen or political leader, have decided whether or not to stick with the treaty?

Getting Informed

The questions in the preceding paragraphs are *nuclear* questions, and they call for *nuclear choices*—choices that need to be made by you, as a citizen, or by your elected leaders. As the multitude of questions suggests, nuclear issues are complex. They raise technical, political, moral, and practical questions. Those questions are far from academic; they demand answers and action from citizens, legislators, political activists, scientists, businesspeople, and national leaders. The answers we give and the choices we make have potentially major roles in shaping the future of civilization and of our planet itself.

We're called on to answer nuclear questions and to make nuclear choices, often without a clear sense of the relevant technical and political realities. How many voters really know what plutonium is, where it comes from, and why it's a crucial material in the nuclear age? How many people flipping on a light switch really understand what's going on at the (possibly nuclear) power plant that provides their electricity? How many people alive today because nuclear medicine techniques detected or even cured their cancers know that they owe their lives to radiation? We dread the reality of a nuclear-armed North Korea or the growing prospect of a nuclear-armed Iran, but how many of us understand how our country's own decisions might aid or hinder others' efforts to acquire nuclear weapons? Most of us harbor a deep fear of nuclear radiation, but do we know how its dangers compare with risks we willingly take, such as smoking, neglecting to use seat belts, or living with pollution from coal-fired power plants? Many of us yearn for a world free of nuclear weapons, but what about the political, strategic, and technical challenges on the path to that goal? And, ultimately, do we understand what it is that makes our nuclear technologies so fundamentally different from anything humanity has known before?

You might try to get answers to these and other questions from news media, from your peers, or from the Internet. But type "nuclear power" into a search engine and you'll get over 300 million hits. "Nuclear weapons" gets nearly 200 million. Even "plutonium" garners 10 million hits. Which of these are authoritative and which are propaganda for one side or the other of a particular nuclear issue?

This book is designed to provide citizens with a basic understanding of nuclear technology and of the controversies surrounding its use. The book is divided into three parts. Part I deals with the nature of the atom and its nucleus, with nuclear radiation, and with the fundamentals of nuclear energy. Part II examines nuclear power, including our use of energy, the operation of nuclear power plants, nuclear accidents, nuclear waste, and alternatives to nuclear power. Part III describes nuclear weapons, including their operation, their destructive effects, delivery systems for getting them to their targets, strategies for their use or nonuse, the feasibility of defense against them, the prospects for controlling the spread of these weapons to other countries and to terrorist groups, and ultimately how we might prevent nuclear war. But this division into three parts is in some respects only a convenience. Nuclear power and nuclear weapons share the same fundamental physics, and many of their technologies overlap. So do their histories: today's nuclear power plants are descendants of reactors originally developed for military purposes, and the 1950s "Atoms for Peace" slogan aimed to calm a public alarmed by the development of nuclear bombs—and perhaps to distract from the ongoing race to develop ever more destructive weapons. Some of the thorniest nuclear issues center on connections between nuclear power and nuclear weapons, and these issues will arise repeatedly throughout the book. So expect to find nuclear weapons in the section on nuclear power and vice versa.

This book is for citizens, not scientists or nuclear specialists. It assumes no particular background in science or in nuclear issues. It provides a simplified introduction to nuclear science and technology and the controversies that surround them. The book's goals are to instill a level of nuclear literacy that gives you an understanding of the nuclear issues you'll continually encounter and to help you make intelligent choices based on that understanding.

This is not an antinuclear book, nor is it a pronuclear book. It aims to provide you with an unbiased view of nuclear technology and the issues that surround it. That's easy where scientific and technological facts are concerned but harder when things get controversial. Engaging those controversies is as important as understanding the underlying technology, and therefore we'll make every attempt to present arguments on all sides. Your authors do have strong feelings on some of the issues and are quite open on others. Where a display of personal opinion is unavoidable, we'll clearly designate it as such; otherwise, any arguments presented or questions asked don't necessarily reflect the authors' own views.

Reading this book isn't an academic exercise. Nuclear technology is an unavoidable part of our world, with the potential to bring us substantial benefit or unimaginable disaster. You'll be called to make choices about nuclear issues, and this book should help you make them informed choices.

Will this book give you all the answers? Will it tell you what nuclear choices to make? No. You may, in fact, find it frustrating that you might come away from your reading less certain of your opinion on complex nuclear issues. That shouldn't be surprising—the questions presented at the beginning of this chapter suggest that even nuclear experts often disagree. So one thing you should take from this book is a healthy, critical skepticism about experts' or activists' nuclear opinions. If the experts agreed, resolving nuclear questions would be easy. But they don't agree. Yet the nuclear issues need resolution—and you're someone who has to help resolve them. This book is written on the premise that those issues are best resolved by citizens who understand the basis of nuclear technology.

I

The Nuclear Difference

2

Atoms and Nuclei

After the 1945 nuclear bombings of Japan, Albert Einstein remarked that "the unleashed power of the atom has changed everything save our modes of thinking."[1] What is it that makes nuclear technology—"the unleashed power of the atom"—extraordinary? Why is the nuclear age unlike any previous age? The answer, in a nutshell, is that nuclear processes release over a million times as much energy as the more familiar happenings of our everyday world. That's the **nuclear difference.** Whereas a coal-burning power plant consumes many 110-car trainloads of coal each week (figure 2.1a), a comparable nuclear plant requires only a few truckloads of uranium fuel a year (figure 2.1b). A single nuclear bomb can destroy a city, a job that thousands of conventional bombs can't accomplish. But why this nuclear difference? Where does the millionfold energy increase come from? And why, with nuclear processes, do we encounter the new phenomenon of radiation? The answers to these questions lie in the atom and its nucleus.

A World Made from Three Particles

The matter of our world exhibits tremendous variety, from the tenuousness of air to the solidity of steel, from the rugged density of rock to the delicacy of a snowflake, from the green slipperiness of a frog to the savory crunch of an apple. It's remarkable that all these things—and all other things on Earth and throughout the visible universe—are made from combinations of just three simple building blocks: the **neutron**, the **proton**, and the **electron**. In this chapter you'll see how neutrons, protons, and electrons join to form the atomic nuclei and then the atoms from which the matter of our world is made.

Physicists have identified scores of so-called subatomic particles, and experiments with ever larger, more energetic, and more expensive machines

Figure 2.1
(a) A truckload of uranium fuel arrives at the Vermont Yankee nuclear power plant. Four such truckloads supplied all the fuel needed for the now-closed plant's once-in-18-months refueling (Entergy Nuclear). (b) A 110-car trainload of coal arrives at a Kansas power plant. Fourteen such trainloads fuel the plant each week (Earl Richardson, *Topeka Capital-Journal*). The contrast between figures 2.1a and 2.1b is a manifestation of the nuclear difference.

continue in an effort to understand how these fundamental bits of matter are related. Yet most subatomic particles appear to be of little importance in the day-to-day interactions of matter. They do arise in the physicists' giant accelerators and in interactions of cosmic rays with Earth's atmosphere, and many played important roles in the early universe. But it's only a slight simplification to say that the composition and the behavior of ordinary matter—from a human heart to a nuclear bomb—involve only the interactions of neutrons, protons, and electrons.

Neutrons and protons are so tiny that it would take 13 trillion of them, lined up, to span an inch. Neutrons and protons have very nearly the same mass (for our purposes, the same thing as weight), and that mass is so small that a pound of either would contain 270 trillion trillion particles. You can envision these particles as small spheres, although a physicist might caution that concepts from your everyday world aren't entirely appropriate in the subatomic realm.

Neutrons and protons differ in an important respect: the neutron carries no **electric charge**, whereas the proton carries one unit of positive electric charge. Charge is a fundamental property of matter, and a subatomic particle either has it or doesn't. A particle with charge has either one unit of positive charge or one unit of negative charge; no other amount seems possible.[2] There's nothing missing or deficient about negative charge; positive and negative are just names we use to distinguish the two different kinds of charge.

So we have the neutron and the proton: particles of essentially the same size and mass, differing in that the proton carries one unit of positive electric charge, whereas the neutron, as its name implies, is electrically neutral. Together, neutrons and protons are called **nucleons**.

The third particle, the electron, is much less massive than the others—it would take about 2,000 electrons to equal the mass of a neutron or proton. The electron carries one unit of negative electric charge. Even though the electron is much less massive than the proton, its charge is exactly equal but opposite to that of the proton.

Combining Particles

To see how our complex world is made from neutrons, protons, and electrons, we need to understand how these particles join to make larger entities. Nature provides what appear as three fundamental **forces** by which particles can interact and stick together: the **gravitational force**, the **electric force**,[3] and the **nuclear force**. (One grand goal of physics is to learn whether these three "fundamental" forces are really aspects of a single interaction governing all that happens in the universe.)

The gravitational force is familiar: it keeps you rooted to Earth, makes you fall, and holds the Moon in its orbit around Earth and Earth in its orbit around the Sun. But gravity is the weakest of the forces, significant only for larger objects—things the size of people, missiles, mountains, planets, and stars. Gravity plays essentially no role in the subatomic world of nuclear interactions, and we'll neglect gravity as we explore basic nuclear phenomena. Gravity will become important again when we consider the trajectory of a missile or the meltdown of a reactor.

With gravity out of the picture, we have only the electric force and the nuclear force. For our purposes, the electric force manifests itself as an interaction between electrically charged particles. Particles with no charge—neutrons—don't experience the electric force. Two particles with the same charge, either positive or negative, experience a repulsive electric force. Two particles with opposite charges attract each other via the electric force. The strength of the attractive or repulsive force depends on the distance between the particles; move them farther apart and the force

What the world is made of . . .

neutrons (n)	No electric charge. Mass = 1. Feels nuclear force only.
+	protons (p)	Electric charge: +1. Mass = 1. Feels both electric and nuclear force
−	electrons (e)	Electric charge: –1. Mass = 1/2,000. Feels electric force only.

. . . and how it's stuck together

nuclear force	Acts between nucleons (n, p), (n, n), (p, p). Always attractive. Strong, but short range.
electric force	Acts between charged particles (e, p), (e, e), (p, p). Opposites attract; likes repel. Weak, but long range.

Figure 2.2
Three particles and the forces by which they interact.

weakens. However, it doesn't weaken all that rapidly with increasing distance, so the electric force is a **long-range force**.

The nuclear force acts only between nucleons—between protons and protons, between neutrons and neutrons, or between protons and neutrons. It's always attractive. When the particles are very close—roughly their own diameter apart—the nuclear force is extremely strong, but it falls off rapidly with distance, quickly becoming insignificant. The nuclear force is thus a strong but **short-range force.**

Figure 2.2 summarizes the three particles and the two forces by which they interact. The forces are characterized by their strength and range, and by the particles between which they act. Here we have everything we need to build the nuclei, atoms, and molecules from which all substances are made. We'll start with nuclei.

Building Nuclei

An **atomic nucleus** is a group of nucleons—neutrons and protons—bound together by the nuclear force. The simplest nucleus—that of hydrogen—is a single proton; every other nucleus contains a mixture of protons and neutrons. The next simplest nucleus is a combination of a proton

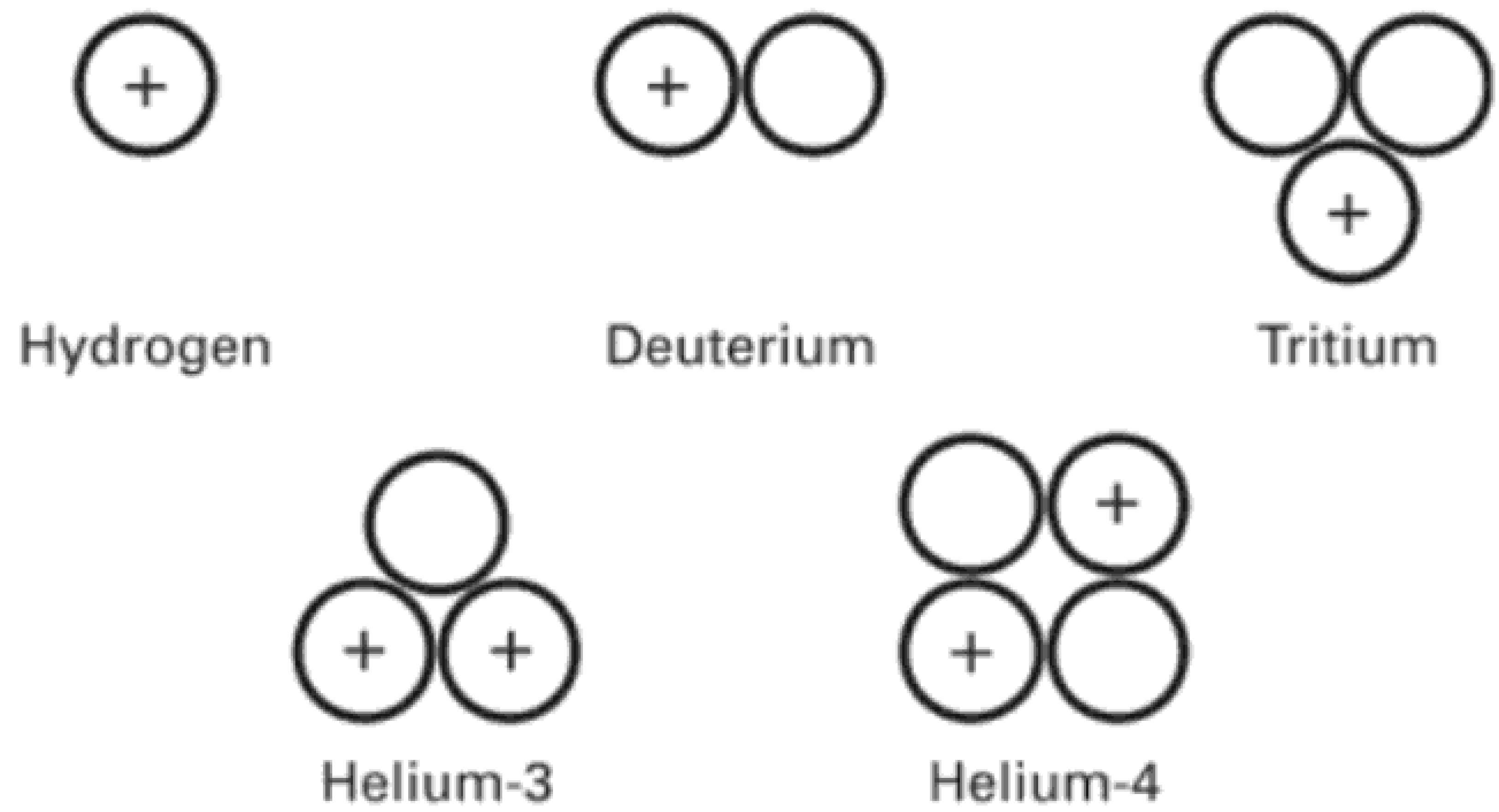

Figure 2.3
The hydrogen nucleus is a single proton. Other simple nuclei are deuterium (one proton and one neutron, also called a *deuteron*), tritium (one proton, two neutrons), helium-3 (two protons, one neutron), and helium-4 (two protons, two neutrons).

and a neutron, which constitutes a deuterium nucleus. A combination of one proton and two neutrons is tritium, a nucleus that can't last very long. Two other simple nuclei are helium-3, formed of two protons and one neutron, and helium-4, containing two protons and two neutrons. Figure 2.3 shows the five nuclei we've introduced so far, using the pictorial symbolism of figure 2.2 to represent protons and neutrons. We'll explore other nuclei shortly, but first we need to distinguish nuclei from atoms.

Building Atoms

A nucleus contains protons, which carry positive electric charge, and neutrons, which carry no electric charge. Therefore all nuclei are positively charged, and that means they attract negatively charged electrons. Normally, a nucleus surrounds itself with electrons equal in number to the protons in the nucleus. The resulting object is an **atom**. You can visualize an atom as a miniature solar system, with the nucleus surrounded by orbiting electrons, like the Sun by its planets. Gravity keeps the planets in orbit, while the electrical attraction of the nucleus plays the same role for the atomic electrons. Although a gross oversimplification, this picture contains the essence of what you'll need in order to understand the difference between nuclear and conventional energy sources. Figure 2.4 depicts atoms of hydrogen and helium, each consisting of a nucleus surrounded by the appropriate number of electrons.

Although figure 2.4 shows the essential configurations of atoms, it's misleading in its scale. In a real atom, the distance between the nucleus

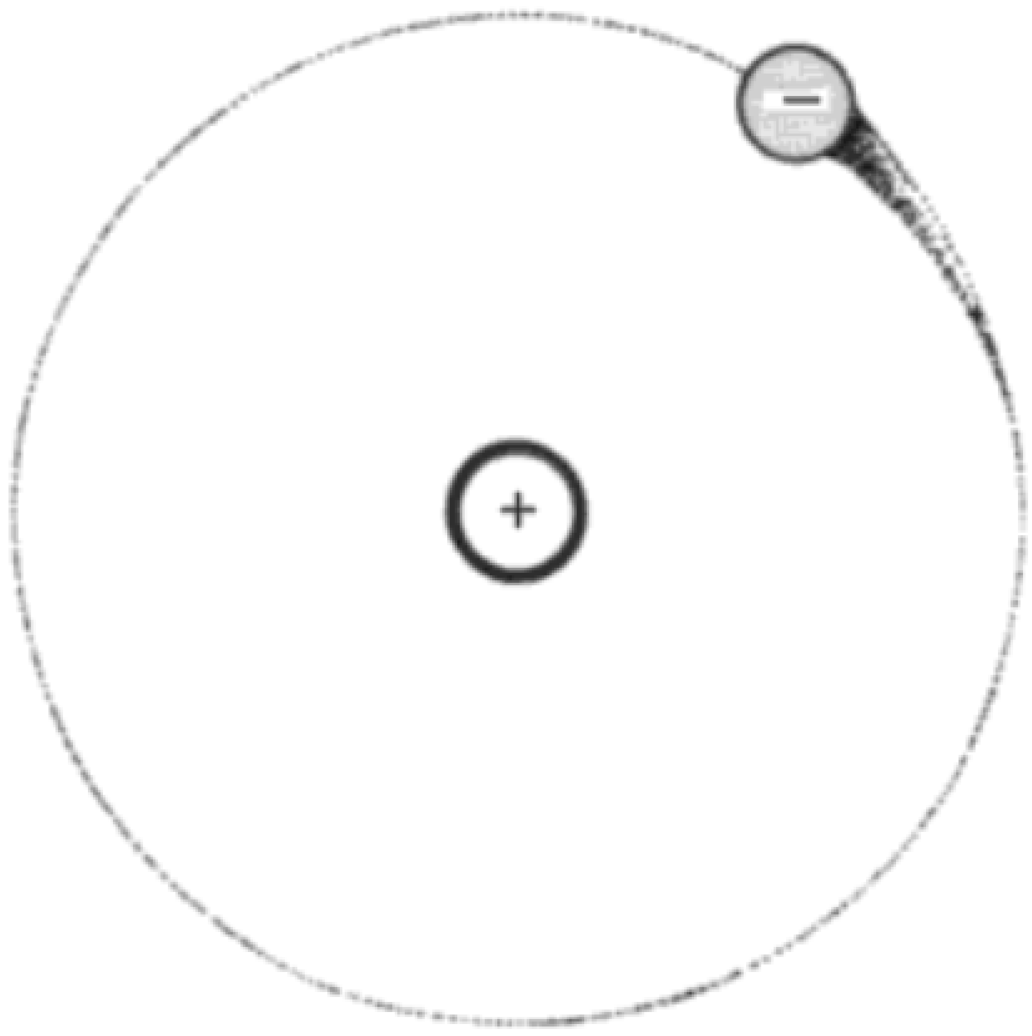

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Figure 2.4
Atoms of hydrogen and helium. Note that in each case the number of orbiting electrons is the same as the number of protons in the nucleus.

and the surrounding electrons is far larger than our figure suggests—more than 10,000 times the diameter of the nucleus. If figure 2.4 were drawn to scale, the nucleus would be an invisible dot. If the nucleus of an atom were the size of a basketball, the electrons would be a mile away. Between the nucleus and its electrons would be a mile of emptiness. Atoms—and therefore everything that's made from atoms—are mostly empty space.

Building Molecules

Two or more atoms can join to form a **molecule**. The water molecule, for example, consists of two hydrogen atoms and an oxygen atom; its composition is reflected in its chemical formula, H_2O. This bonding of atoms to form molecules is what chemistry is all about, and the rearrangement of atoms into a new molecular configuration is a **chemical reaction**. Many conventional energy sources involve chemical reactions. Burning coal combines carbon atoms in the coal with oxygen from the atmosphere, producing carbon dioxide gas and in the process releasing energy (figure 2.5). Burning gasoline in your car's engine breaks up complicated molecules containing hydrogen and carbon, producing mostly carbon dioxide and water, along with energy. The high explosives used in conventional weapons undergo rapid chemical reactions, releasing their energy in a burst. The atoms in the food you eat are rearranged through chemical reactions in your body, supplying the energy that keeps you alive. Chemical reactions are important and commonplace in our lives.

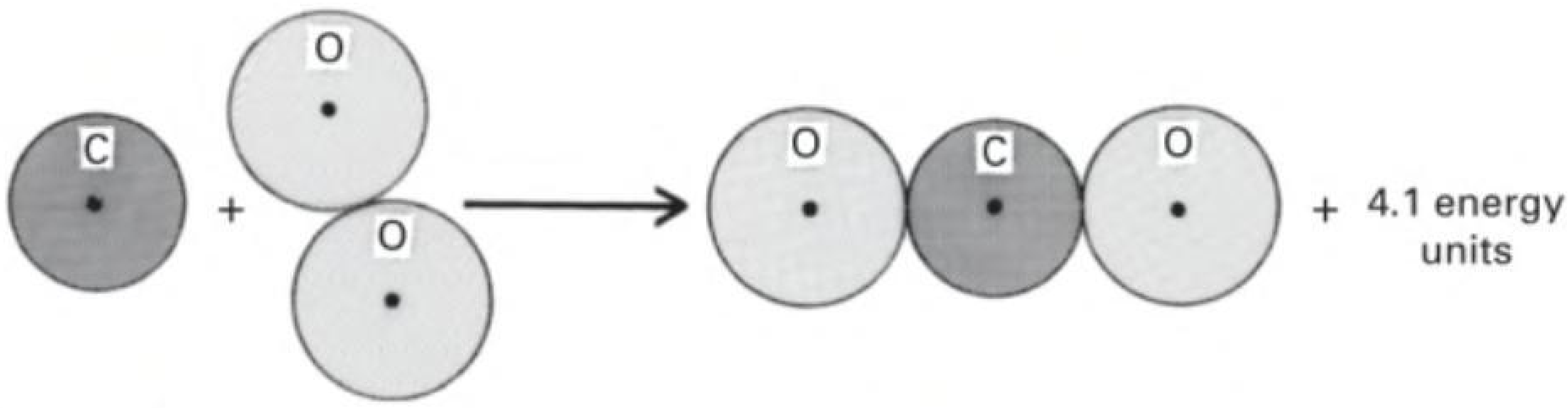


Figure 2.5
A chemical reaction. Here one atom of carbon joins two atoms of oxygen to form carbon dioxide. This is the basic reaction involved in burning coal. The energy released is 4.1 in units used by physicists working with atomic and nuclear processes. The black dots represent atomic nuclei, which aren't affected by the rearrangement of the atoms.

Chemical reactions involve electrons at the outer fringes of atoms. Those electrons interact through the relatively weak electric force, and therefore the energy involved in taking apart or putting together molecules is relatively small—so chemical reactions aren't highly energetic. Because atomic electrons are so far from the nucleus, the nuclei of interacting atoms remain widely separated. The nuclear force, which acts only at short distances, therefore plays no role in chemical reactions.

The Nuclear Difference

Nuclear reactions, in contrast, occur when the nucleus itself changes. This can happen if two nuclei join, if a nucleus ejects some of its nucleons, or if a nucleus is struck by another particle. Because the nuclear force is so strong at distances the size of a nucleus, nuclear reactions involve a lot of energy. Here, then, is the nuclear difference: it's the difference between the weaker but long-range electric force that governs the interactions of everyday chemical reactions, and the much stronger but short-range nuclear force that comes into play only in reactions involving the nucleus. Because of the relative strengths of the forces, that difference makes a typical nuclear reaction release several million times the energy of a chemical reaction (figure 2.6). That difference—based ultimately on the difference between the electric and nuclear forces—is, in turn, responsible for the dramatic differences between nuclear and conventional weapons, and between the fuel requirements of nuclear and fossil-fueled power plants (recall figure 2.1).

Whereas chemical reactions—burning coal or gasoline, metabolizing food, synthesizing plastics, and so on—are commonplace, nuclear reactions are rare under the conditions that prevail on Earth today. Our species

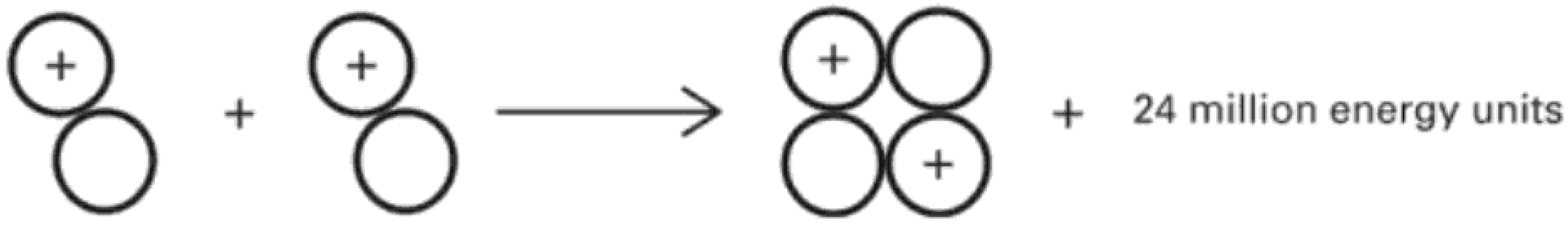


Figure 2.6
A nuclear reaction. Here two deuterium nuclei join to form a helium-4 nucleus. The nuclei are less than 1/10,000 the size of the atoms in figure 2.5, but the energy released is some 6 million times that of the chemical reaction shown in the preceding figure.

harnessed fire—a chemical reaction—in prehistoric times, but it wasn't until the mid-twentieth century that we learned to tend nuclear "fires" and their violent cousins, nuclear explosions. Nuclear reactions are common, though, elsewhere in the universe; in particular, the Sun and other stars shine because of nuclear reactions in their interiors.

You'll notice that this book never speaks of "atomic energy," "atomic bombs," "atomic power plants," or "atomic warfare," nor of "splitting the atom." The adjective *atomic* is ambiguous; since the interaction of atoms is involved in everyday chemical reactions, the energy they release might as well be called "atomic." Even Einstein's "unleashed power of the atom" suffers the same ambiguity. The reactions, the reactors, the bombs, the wars, the technologies that we're interested in here are distinctly *nuclear*, since their essence involves rearrangement of the atomic nucleus. And if we split anything, it will be a nucleus. We use the adjective *nuclear* to make all this absolutely clear.

Elements and Isotopes

An **element** is a substance that behaves chemically in a unique and identifiable way and whose most basic particle is a single atom. Oxygen is an element; so is hydrogen. Even a single oxygen atom exhibits the properties of elemental oxygen, but if you break that atom further it no longer behaves as oxygen. Water, H_2O, isn't an element; the smallest piece of water you can have is a single molecule, consisting of two hydrogen atoms and one oxygen atom. If you take the molecule apart, you have hydrogen and oxygen but no longer water.

What gives the atoms of a particular element their unique chemical behavior? "Chemical behavior" means how they interact with other atoms, forming the multitude of different substances that make up our world. You've seen that chemical reactions involve only the electrons that swarm in a distant cloud around the nucleus. So what determines the chemical behavior of an atom? Simply this: the number of electrons it contains. And what determines that? Since an atom forms when a nucleus attracts to itself as many electrons as it has protons, it's the number of protons in its nucleus that ultimately determines the chemical species to which an atom belongs.

The number of protons in a nucleus is the **atomic number**. Hydrogen, as figure 2.7 shows, has atomic number 1, helium has atomic number 2, and carbon has 6. Although figure 2.7 doesn't show all the individual particles, iron has 26 protons, gold has 79, and uranium has 92. An element's name and its atomic number are synonymous; to be oxygen is to have eight protons in your nucleus. In addition to its name and its atomic number, each element also has a unique one- or two-letter symbol; hydrogen is H, helium He, oxygen O, iron Fe, and uranium U. Table 2.1 gives the names, atomic numbers, and symbols of selected elements.

If we were chemists, we would be content with the atomic number of a nucleus—the number of protons—since that determines the species of chemical element. But here we're concerned with nuclear matters, so we need to characterize nuclei further. Figure 2.3 introduced the nuclei of hydrogen, deuterium, tritium, helium-3, and helium-4. Why the similar

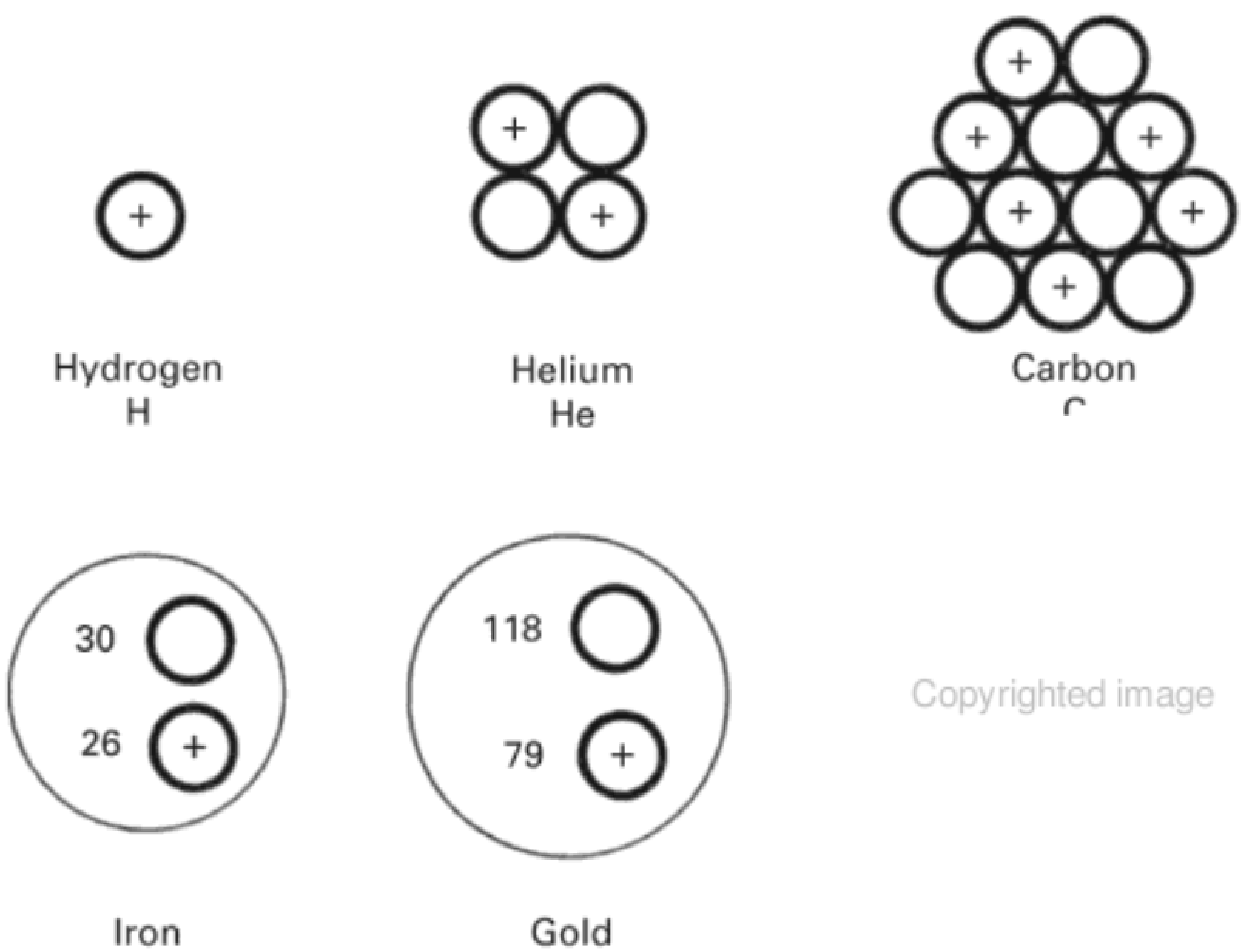


Figure 2.7
Some nuclei with element names and symbols. Figures are only suggestive; nucleons aren't locked into the fixed patterns shown here.

Table 2.1
Selected elements

Atomic number	Element name	Symbol
1	hydrogen	H
2	helium	He
6	carbon	C
7	nitrogen	N
8	oxygen	O
13	aluminum	Al
26	iron	Fe
38	strontium	Sr
79	gold	Au
86	radon	Rn
88	radium	Ra
92	uranium	U
94	plutonium	Pu

names for the last two? Because they're both nuclei of the same chemical element, helium. You can see in figure 2.3, and again in figure 2.8, why this is. Both contain two protons, and therefore both would form atoms with two electrons. Those atoms would exhibit similar chemical behavior, even though they have different numbers of neutrons. As far as the chemist is concerned, both are atoms of the same substance: helium. The names helium-3 and helium-4 reflect the total numbers of nucleons: two protons and one neutron in helium-3, two protons and two neutrons in helium-4. The total number of nucleons—protons and neutrons—is the **mass number** of a nucleus. Since protons and neutrons have nearly the same mass, the mass number gives approximately the total mass of a nucleus.

So helium-3 and helium-4 are both nuclei of helium, since the atoms they form have similar chemical behavior. But they *are* different, and that difference manifests itself in nuclear reactions. That's why we need to distinguish nuclei of the same element that have different numbers of neutrons and therefore different mass numbers. Such nuclei are called **isotopes**. Helium-3 and helium-4 are two isotopes of helium. And, as figure 2.8 shows, nuclei of hydrogen, deuterium, and tritium each have only one proton. So they're isotopes of the same element, namely hydrogen. Ordinary hydrogen could be called hydrogen-1; deuterium, hydrogen-2; and tritium, hydrogen-3. The use of separate isotope names is a confusion that, fortunately, is limited to hydrogen.

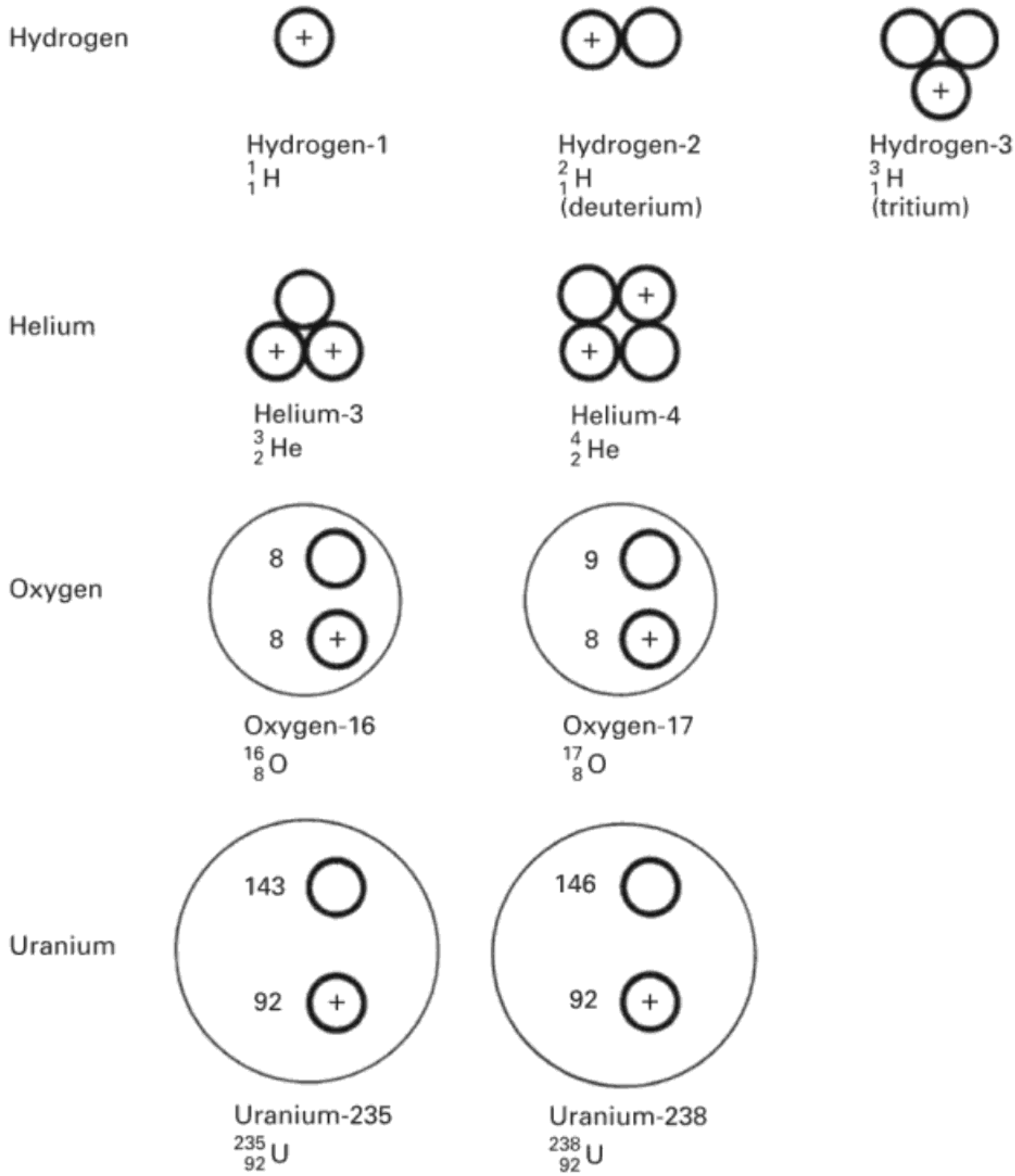


Figure 2.8
Isotopes of a given element have the same number of protons but different numbers of neutrons. Shown are three isotopes of hydrogen and two each of helium, oxygen, and uranium. Although isotopes have similar chemical behavior, their nuclear behavior can be very different. For example, only the rare isotope uranium-235 can serve directly as fuel for nuclear reactors and weapons.

To a chemist, He is the symbol for helium. But for nuclear purposes that doesn't tell us enough, so we elaborate by adding the atomic and mass numbers. The atomic number goes in front of the element symbol, at the bottom; the mass number goes in front at the top. Thus the helium isotopes helium-3 and helium-4 are written ${}^{3}_{2}He$ and ${}^{4}_{2}He$, respectively. Ordinary hydrogen is ${}^{1}_{1}H$, deuterium is ${}^{2}_{1}H$, and tritium is ${}^{3}_{1}H$. Soon we'll be very much concerned with two important isotopes of uranium, uranium-235 and uranium-238; since uranium has atomic number 92, their symbols are ${}^{235}_{92}U$ and ${}^{238}_{92}U$. Strictly speaking, the letter(s) and the atomic number in a symbol are redundant; atomic number 92 and the symbol U mean the same thing, namely uranium. Sometimes you'll see a nuclear symbol written with just the mass number, for example, ${}^{235}U$ or U-235; that's enough to tell the element (uranium) and the particular isotope (the one with a total of 235 nucleons). If you need the number of neutrons, you can get it by subtracting: since ${}^{235}_{92}U$ has 235 total nucleons and 92 protons, it has $235 - 92$ or 143 neutrons. Figure 2.9 shows the meaning of a nuclear symbol.

By now you've encountered a number of elements and some of their isotopes. Each isotope represents a unique combination of protons and neutrons, bound by the nuclear force to form a nucleus. How many different nuclei can we make? Is any combination of protons and neutrons a viable nucleus? No. The range of possible nuclei is distinctly limited.

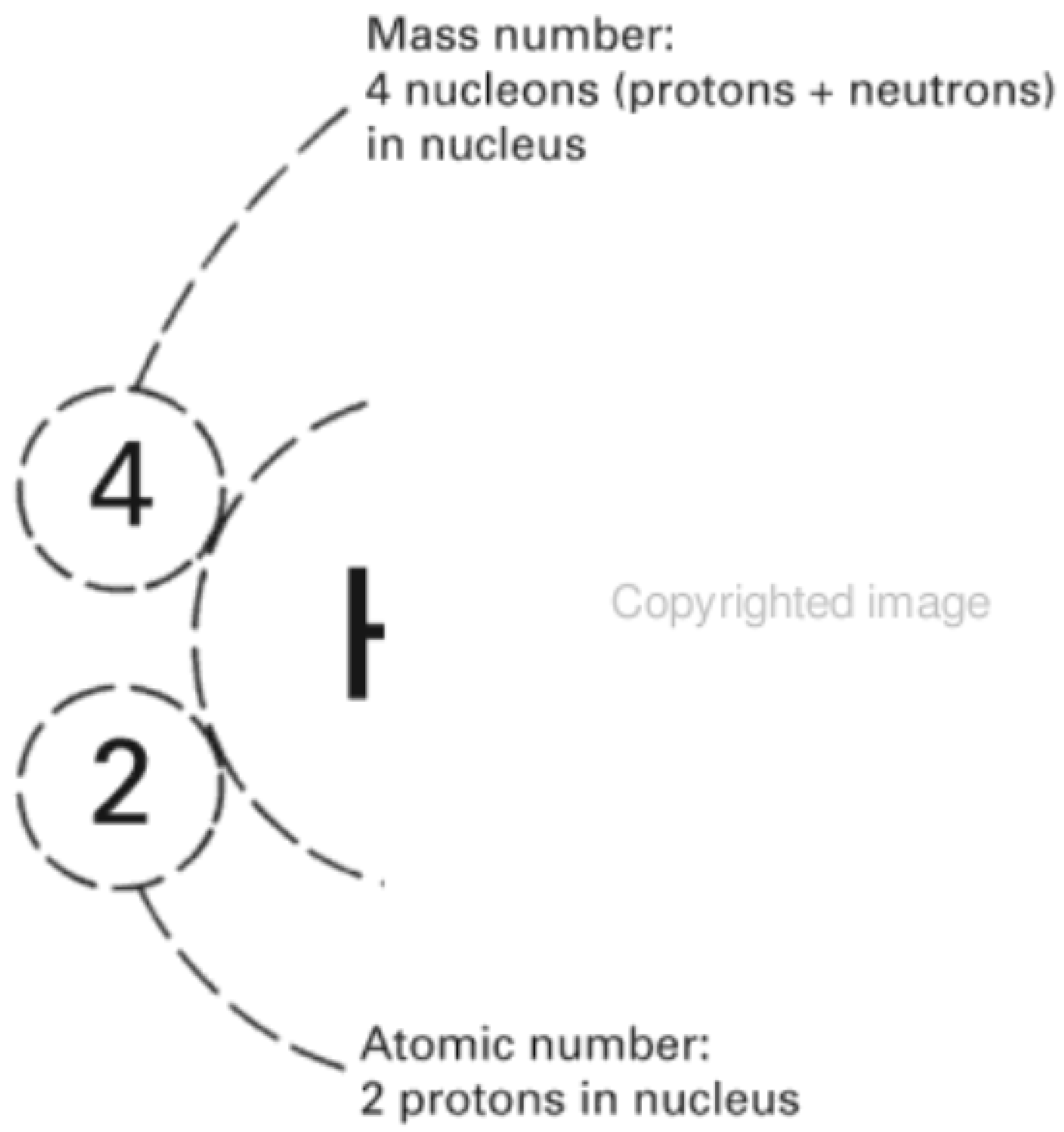


Figure 2.9
Anatomy of a nuclear symbol.

Nuclei consist of protons and neutrons held together by the nuclear force—a strong but short-range force. But the electric force is also present and acts to repel the protons in a nucleus. A combination of protons alone isn't possible; neutrons are needed to "dilute" the repulsive effect of the electric force. The lighter nuclei generally contain nearly equal numbers of protons and neutrons, and in the most common isotopes of helium ($^{4}_{2}$He), carbon ($^{12}_{6}$C), and oxygen ($^{16}_{8}$O), the numbers of protons and neutrons are exactly equal. Less common isotopes of these elements include helium-3 ($^{3}_{2}$He), carbon-13 ($^{13}_{6}$C), oxygen-17 ($^{17}_{8}$O), and oxygen-18 ($^{18}_{8}$O). In fact, these are the only nuclei of helium, carbon, and oxygen you can make and have stick together forever. (Nuclei that stick together indefinitely are **stable nuclei**.) If, for these and other light elements, you deviate too much from equal neutron and proton numbers, the resulting nucleus is **unstable**, meaning it won't stick together indefinitely. Try to make oxygen-19 ($^{19}_{8}$O), for example. It just won't stick. There are too many neutrons, and the nucleus will soon fly apart; you'll see just how in the next chapter. Try to make oxygen-14 ($^{14}_{8}$O), and again the nucleus comes apart, because now it has too few neutrons in relation to its eight protons.

You can see why a nucleus with too few neutrons might tend to come apart: there's less attractive nuclear force to counter the repulsive electric force between protons. With larger nuclei, this effect becomes more important. That's because protons at opposite sides of a large nucleus are so far apart that they don't feel the attractive but short-range nuclear force. But the long-range electric force still tends to repel them (figure 2.10). To counter this electric repulsion, the nucleus needs more nuclear "glue" in the form of neutrons that feel only the nuclear attraction. Therefore larger nuclei tend to have more neutrons than protons. Figure 2.11 plots number of neutrons versus number of protons for stable nuclei. Each little square represents a stable nucleus, specified by its neutron and proton numbers. For lighter nuclei (those with fewer nucleons, near the lower left of figure 2.11), the stable isotopes lie very close to the line representing equal numbers of protons and neutrons. But heavier nuclei deviate from this line as they require ever more neutrons to counter the electric repulsion of their widely separated protons. Thus the stable nuclei lie in a curved band that bends increasingly upward. You'll soon see how the shape of this band explains why the waste products of nuclear reactors and weapons are so dangerous. Above atomic number 83 (bismuth, with 83 protons) there are no stable isotopes. For these large nuclei, the repulsive electric force ultimately wins. Nuclei with more than 83 protons are all unstable, and, sooner or later, they come apart in one way or another.

Figure 2.10
Two widely separated protons in a large nucleus experience mutual repulsion due to the long-range electric force. But because of its short range, the attractive nuclear force between them is insignificant. An excess of neutrons is therefore necessary to hold the nucleus together.

Summary

You've now met the few simple ingredients that make up our world: protons, neutrons, electrons, and the electric and nuclear forces that bind them into the nuclei, atoms, and molecules from which all else is made. You've seen how the relatively weak electric force is responsible for ordinary chemical reactions—interactions that involve only the electrons in distant orbits around their nuclei and that leave the nuclei unchanged. These chemical reactions are responsible for the energy released in burning coal or gasoline, in exploding TNT, and in metabolizing food.

Nuclear reactions, in contrast, involve rearrangement of the protons and neutrons that make up the atomic nucleus. Because these particles are so tightly bound by the strong nuclear force, the energy involved in nuclear reactions is millions of times that of chemical reactions. This single fact constitutes the nuclear difference, which explains why a coal-burning power plant consumes trainloads of coal each week whereas a few truckloads of uranium will fuel its nuclear counterpart for a year, and why a nuclear bomb can destroy a city whereas a conventional one takes

Figure 2.11
Neutron number versus proton number for stable nuclei, represented by small black squares. Most smaller nuclei have equal or nearly equal numbers of protons and neutrons, but larger nuclei have many more neutrons, for the reason explained in figure 2.10. Inset is a magnification showing the first four stable isotopes.

out only a few buildings. And it's this nuclear difference that makes warfare in the nuclear age a serious threat to human civilization.

Although we haven't yet explored nuclear reactions in detail, you've seen how protons and neutrons join together to form nuclei. Not all combinations result in stable nuclei that stick together indefinitely. So far we've considered stable nuclei, but you'll see in the next chapter that unstable nuclei also exist, although not forever. Those unstable nuclei are important factors—sometimes desirable, sometimes not—in most of today's nuclear technologies.

Superheavy Nuclei

The heaviest element naturally occurring in significant quantities is uranium, with atomic number 92. Starting in the 1930s, still heavier nuclei have been created artificially by bombarding heavy nuclei with other particles. The best known of these *transuranic elements* is plutonium (atomic number 94), which is produced in nuclear reactors and used in nuclear weapons. From the 1940s through early 1970s, elements 93 through 103 and element 106 were synthesized at the Lawrence Berkeley Laboratory in California; appropriately, elements 97 and 98 are, respectively, berkelium and californium. A group in the Soviet Union produced elements 104 and 105 in the 1960s. The 1980s and 1990s added elements 107 through 112, and the early twenty-first century extended the list through element 118. Laboratories in Russia, the United States, Germany, and Japan all contributed to the synthesis of these new elements. All the superheavy elements are unstable, with those numbered 115 and beyond having lifetimes well under one second. However, nuclear physicists anticipate an *island of stability*, with longer-lived isotopes appearing at atomic numbers around 120 and beyond.

Glossary

atom A nucleus surrounded by a number of electrons equal to the number of protons in the nucleus. An atom is the smallest particle of a chemical element.

atomic nucleus A cluster of protons and neutrons bound together by the nuclear force. Except for hydrogen (a single proton), all nuclei contain both protons and neutrons.

atomic number The number of protons in a nucleus. The atomic number determines the element; for example, hydrogen has atomic number 1, helium 2, oxygen 8, and uranium 92.

chemical reaction An event in which atoms are rearranged into a new molecular configuration, as in the joining of two hydrogen atoms and one oxygen to make a water molecule, H_2O. The nuclei of the interacting atoms are essentially unaffected in a chemical reaction, and an individual chemical reaction involves far less energy than a nuclear reaction.

electric charge A fundamental property of matter possessed by electrons and protons. Electric charge comes in two kinds, positive and negative.

electric force A force that acts between electrically charged particles. The electric force between oppositely charged particles is attractive; between particles of like charge, it's repulsive. At close range—roughly the size of a nucleon—the electric force is much weaker than the nuclear force, but with increasing distance it falls off less rapidly than the nuclear force. The electric force holds atoms together and is responsible for joining atoms to form molecules.

3

Radioactivity

The preceding chapter showed how atomic nuclei are made of protons and neutrons. But not all combinations of these nucleons stick together indefinitely. Those that do are the stable nuclei of figure 2.11; those that don't are unstable. Sooner or later, an unstable nucleus comes apart. The coming-apart process is **radioactive decay**, and unstable nuclei or materials containing them are **radioactive**. Some elements have both stable and unstable isotopes; the latter are **radioisotopes**. The physicist Marie Curie coined the term *radioactivity*. She won Nobel prizes in both physics and chemistry for her pioneering work on radioactive decay (figure 3.1).

Radioactive Decay

How does a radioactive nucleus come apart? Although there are many ways, we'll focus on the three most common: alpha decay, beta decay, and gamma decay. In **alpha decay**, a nucleus spits out two protons and two neutrons, bundled together as a helium-4 nucleus. This He-4 nucleus is called an **alpha particle**, a name that dates to the early 1900s, when it wasn't yet known that the particles were in fact helium nuclei. Alpha decay is common among the larger unstable nuclei, which need to rid themselves of excess protons (recall figure 2.10 and related discussion). The alpha particle carries off two protons, dropping the atomic number of the remaining nucleus by 2. Since the alpha particle contains a total of four nucleons, the mass number drops by 4. In a typical alpha decay, uranium-238 ($^{238}_{92}U$) emits an alpha particle ($^{4}_{2}He$), leaving a nucleus of thorium-234 ($^{234}_{90}Th$). Figure 3.2 shows this decay, both pictorially and using nuclear symbols. Note how the sum of the atomic numbers on the left equals the atomic number on the right. The same is true for the mass numbers.

Copyrighted image

Figure 3.1
Marie and Pierre Curie in their Paris laboratory. (Science Source)

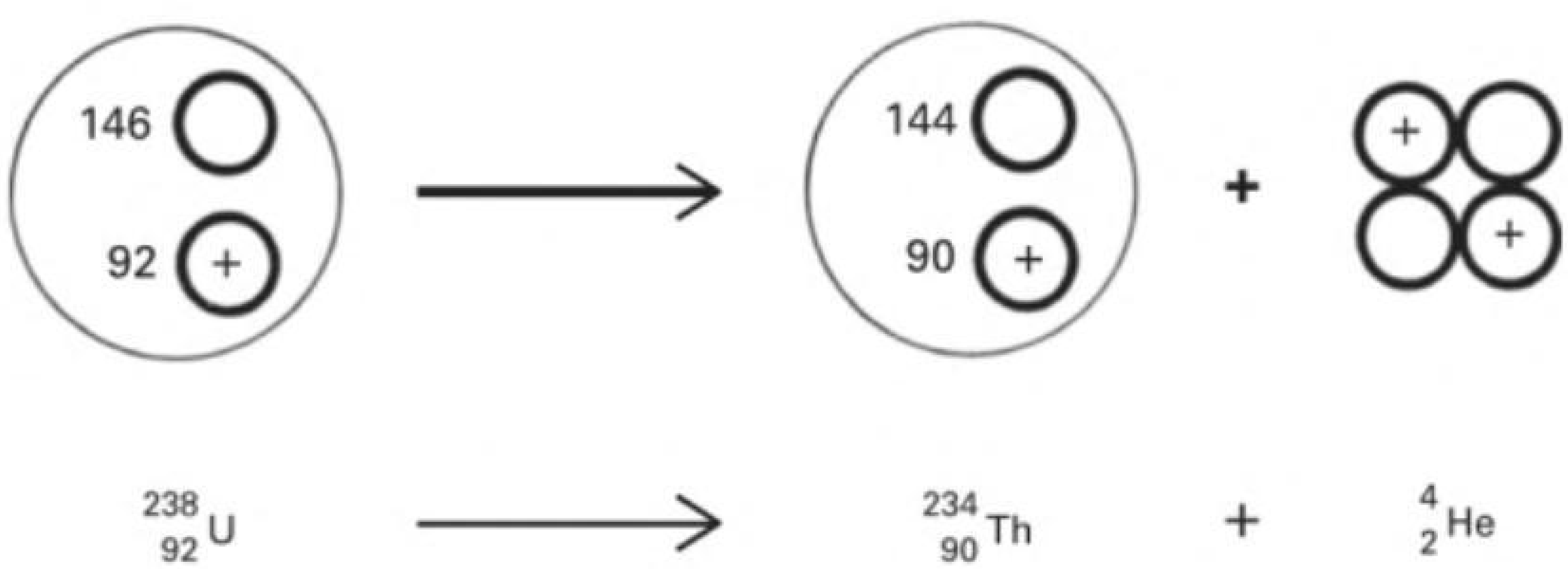


Figure 3.2
Alpha decay of uranium-238 yields an alpha particle (helium-4 nucleus) and thorium-234.

Unstable nuclei with too many neutrons would like either to rid themselves of neutrons or to gain protons. Remarkably, they do both at once. In the process of **beta decay**, a neutron turns into a proton and an electron. The electron, also called a **beta particle**, flies out of the nucleus, leaving the nucleus with one more proton and one fewer neutron than it previously had. Since there's one more proton, the atomic number increases by 1. But the total number of nucleons remains the same, so the mass number is unchanged. Figure 3.3 shows a typical beta decay,

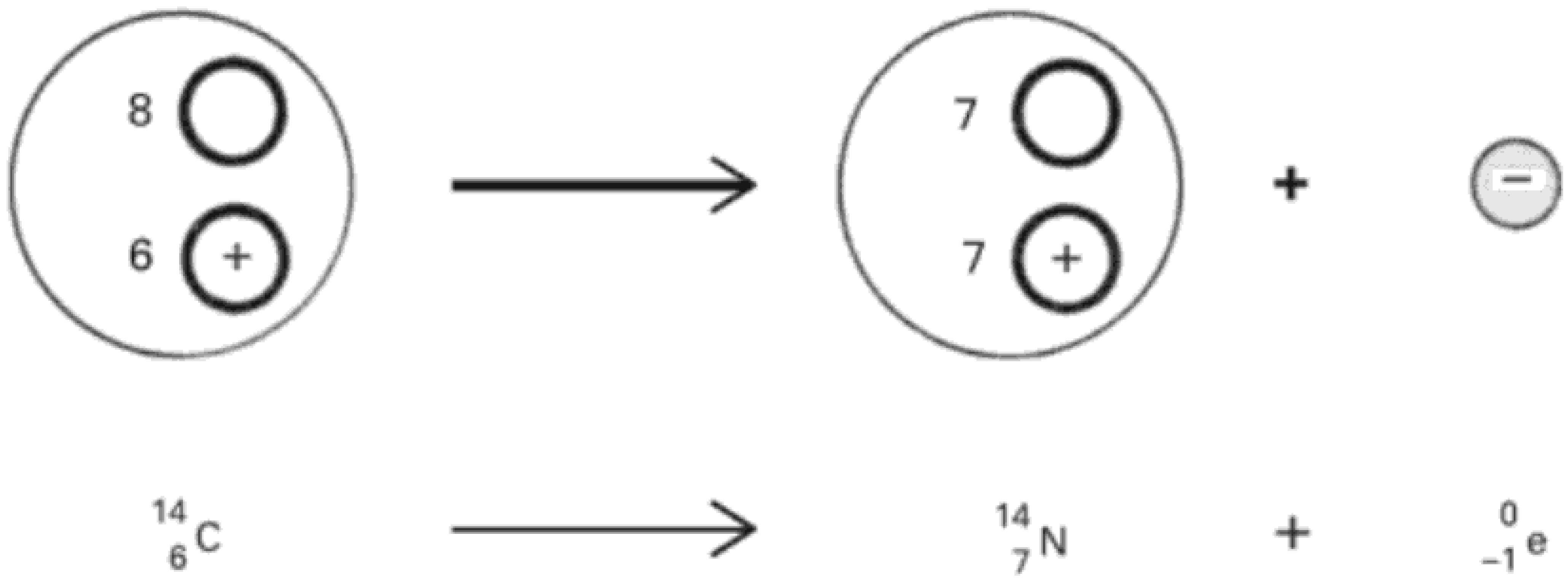


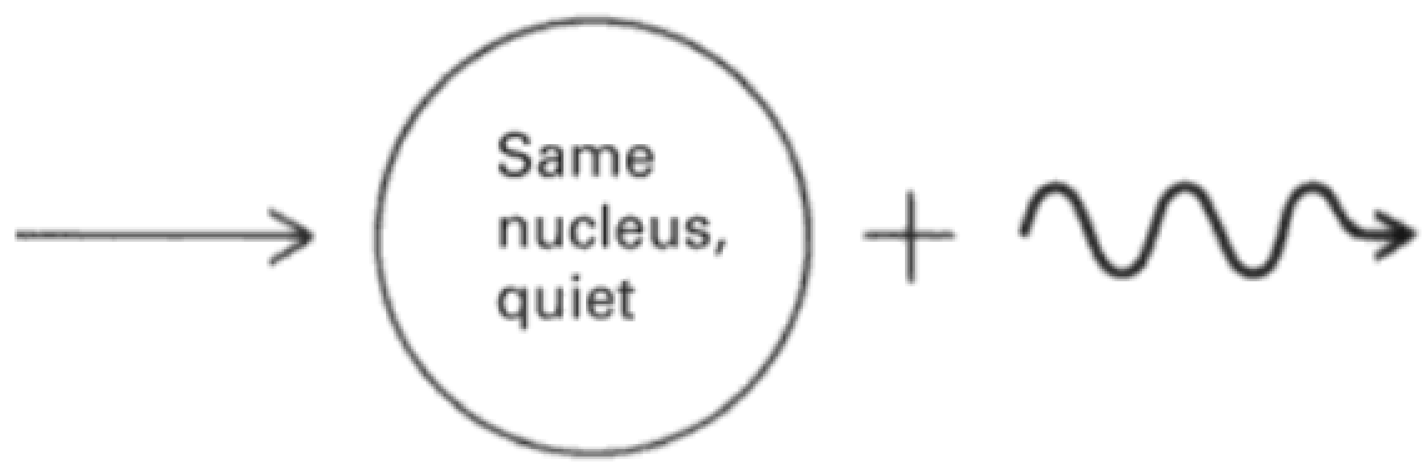
Figure 3.3
Beta decay of carbon-14. A neutron in C-14 turns into a proton and an electron; the electron is ejected, leaving nitrogen-14. Note that the mass number remains unchanged (6 + 8 for C-14 and 7 + 7 for N-14).

that of carbon-14. The end product, nitrogen-14, is the common stable isotope of nitrogen. In writing the decay symbolically, we've indicated the electron as $^{0}_{-1}e$; since it carries one unit of *negative* charge, the electron's atomic number is –1, and its mass number is 0 because its mass is far less than that of a nucleon. Using these numbers, the sum of the atomic numbers on the right is equal to that on the left, and similarly for the mass numbers. This equality must hold in any nuclear reaction.

You might wonder how the electron got mixed up with beta decay, given that nuclei contain only protons and neutrons. Was the electron somehow hiding in there? Or is a neutron really a combination of a proton and an electron? No, but a neutron can, through one manifestation of the forces we've subsumed under the term *electric*, spontaneously turn into a proton and an electron.[1] In fact, a free neutron—one that isn't part of a nucleus—will do so in less than an hour. And a neutron inside a nucleus with an excess of neutrons can also change into a proton and an electron—hence, beta decay. Only when they're constituents of stable nuclei can neutrons last indefinitely.

A variant of beta decay occurs when a nucleus emits a **positron**, the electron's positively charged antiparticle. This drops the atomic number by 1. Short-lived positron emitters are used in the medical imaging technique known as *positron emission tomography* (PET). Another process that lowers the atomic number is **electron capture**, in which a nucleus captures one of the innermost atomic electrons. The electron combines with a proton to make a neutron, in what's essentially the inverse of beta decay.

Sometimes a nucleus is struck by another particle that bounces off or goes right through without causing a nuclear reaction. Then the nucleus



An excited nucleus (arrows suggest vibration) sheds excess energy by emitting a gamma ray (wavy line). No nucleons or electric charge leave the nucleus, so it retains its identity.

retains its identity, but it may be "shaken up" in the process, acquiring excess energy. The same thing can happen when a new nucleus forms as a result of a nuclear reaction such as electron capture, discussed above. The energetic nucleus is like a gong that's been struck by a hammer; originally it was quiet, but now it's vibrating. A nucleus with excess energy is said to be **excited**. Unlike the gong, which starts getting rid of its excess energy immediately in the form of sound, the nucleus can temporarily store the energy. It then emits the energy suddenly, in the form of a little energy bundle called a **gamma ray**. A gamma ray is a high-energy version of ordinary visible light and is yet another manifestation of the electric force. Once the nucleus has shed its excess energy by this process of **gamma decay**, it returns to its original quiet state. Figure 3.4 depicts a gamma decay.

Nuclear Radiation

Each radioactive decay results in a modified nucleus and a much smaller entity—either an alpha particle (He-4 nucleus), a beta particle (electron), or a gamma ray. Those entities are highly energetic: alpha particles from uranium-238 move at some 10,000 miles per second, beta particles from carbon-14 at some 150,000 miles per second, and gamma rays at the speed of light—186,000 miles per second. Each gamma ray "energy bundle" packs a million times the energy of a "bundle" of visible light. Again, the nuclear difference: the forces binding nuclei are so strong that large energies are involved any time a nucleus gets disrupted.

The energetic particles emitted in radioactive decay constitute **nuclear radiation**. Because of its high energy, nuclear radiation can damage atoms and molecules in its path. That's the reason for concern about radiation exposure to humans and other organisms. Even nonliving materials suffer radiation damage. We'll discuss radiation effects in the next chapter. Here, we explore further the physical aspects of radiation and radioactivity.

Although all nuclear radiation is highly energetic, the three forms of radiation differ in their ability to penetrate matter. Alpha particles, the slowest-moving, have relatively little penetrating power; typically, alpha particles can be stopped by a sheet of paper, a layer of clothing, or an inch of air. Thus it's easy to shield against alpha radiation—unless alpha-emitting material ends up on or inside the body. Radiation-induced lung cancers, for example, can result from alpha emitters lodging in the lungs.

Beta particles—electrons—are much lighter than alpha particles and move much faster. They can penetrate a fraction of an inch in solids and liquids (including the human body) and several feet in air.

Both alpha and beta particles are ultimately slowed because they're electrically charged particles that interact strongly with electrons in materials through which they pass. Gamma rays, in contrast, are electrically neutral and are therefore highly penetrating. The penetrating power of gamma rays depends on their energy: The highest-energy gamma rays encountered in nuclear technology may require several feet of dense shielding material.

Measuring Radiation

A technician refueling a nuclear reactor is accidentally exposed to highly radioactive spent fuel. A biologist working with radioactive material spills a carbon-14 solution in the lab. A Japanese citizen steps outdoors as a rainstorm brings down radioactive fallout from the 2011 Fukushima event. An airline pilot is regularly bombarded by cosmic rays. How serious are their radiation exposures? To answer that question, we need ways to describe amounts of radiation and radioactivity.

A simple way to characterize the level of radioactivity in a chunk of material is to give its **activity**—the number of radioactive decays that occur in a given time. The standard unit of activity is the **becquerel** (symbol Bq), defined as one decay per second. An older unit is the **curie** (Ci), named in honor of the Curies. One curie is 37 billion decays per second, approximately the activity of one gram of radium-226, an isotope that Marie Curie discovered. The 1979 Three Mile Island nuclear accident released some 15 curies, or 500 billion Bq, of iodine-131, while the 2011 release at Fukushima was a million times greater. In contrast, a typical banana has an activity of about 20 becquerels, or 500 picocuries (500 trillionths of a curie), because of its relativity high concentration of

Figure 3.5
(a) Simplified diagram of a Geiger counter; (b) a Geiger counter in use. (Hank Morgan/Science Source)

Can't afford a Geiger counter? The light-sensing chip in your smartphone's camera can also detect gamma radiation. Apps are available that let you use your smartphone to measure gamma exposure. You have to cover the camera's lens to block visible light, and your phone won't be sensitive to alpha or beta radiation because they can't penetrate the lens.

Radiation often strips electrons from atoms. When electrons and atoms recombine, they emit a flash of light. Detectors using this phenomenon contain light sensors that record the flash and, by measuring its intensity, determine the radiation energy.

Radiation leaves permanent records in some materials. Radiation detectors made from such materials record long-term exposure. Workers subject to on-the-job radiation often wear these detectors. The presence of low-level radioactive contaminants such as radon gas in homes is detected by similar means.

Exposure and Contamination

Stand near radioactive material and you'll be exposed to radiation. The longer you stay, the greater your radiation dose. Move away and the exposure stops. If, on the other hand, radioactive material gets on you—or worse, inside you—then you're contaminated and continuously exposed to radiation. All unnecessary radiation exposure should be avoided. But **contamination** is especially dangerous, since the exposure will continue until the contaminant is removed. If radioactive material lands on your skin or clothing, washing may be enough for decontamination. But if you eat food containing biologically active radioisotopes—such as strontium-90, which is incorporated into bone, or iodine-131, which is absorbed by your thyroid—then decontamination can be particularly difficult.

Half-Life

For a single unstable nucleus, radioactive decay is a truly random event. But large numbers of nuclei show a pattern to their decays. Start with 1,000 radioactive nuclei and you'll find that after a certain time about 500 will have decayed. That time is the **half-life**. You can't predict which 500 will decay, and the number may vary slightly from one experiment to another, but on average the nuclei decay with remarkable regularity. If you wait another half-life, half the remaining nuclei will decay, leaving only 250 from the original sample. In another half-life, 125 of those will decay, leaving only 125. The process continues until all nuclei have decayed (figure 3.6).

Figure 3.6 shows that a radioactive sample has substantially decayed after a few half-lives have passed; after seven half-lives, only 1/128—less than 1 percent—of the original sample remains. Eight half-lives, and it's down to 1/256; nine, and it's only 1/512; 10 half-lives, and only 1/1,024 of the original nuclei remain undecayed. A good rule of thumb is that after 10 half-lives, only about one-thousandth of the original radioactive nuclei remain. Wait another 10 half-lives—for a total of 20—and only one-thousandth of those are left, or one-millionth of the original nuclei. After 30 half-lives you're down another factor of 1,000, with only a billionth of the original sample remaining. So it doesn't take very many half-lives for essentially all of a radioactive sample to decay.

Half-lives vary dramatically from one radioactive isotope to another. Excited states of some nuclei decay with half-lives around a thousandth of a trillionth of a second, whereas uranium-238's half-life is 4.5 billion years. Most nuclei lie between these extremes; half-lives of minutes to years are common. Table 3.2 lists the half-lives of some typical radioactive isotopes, many of which will concern us as we explore nuclear technologies and their consequences.

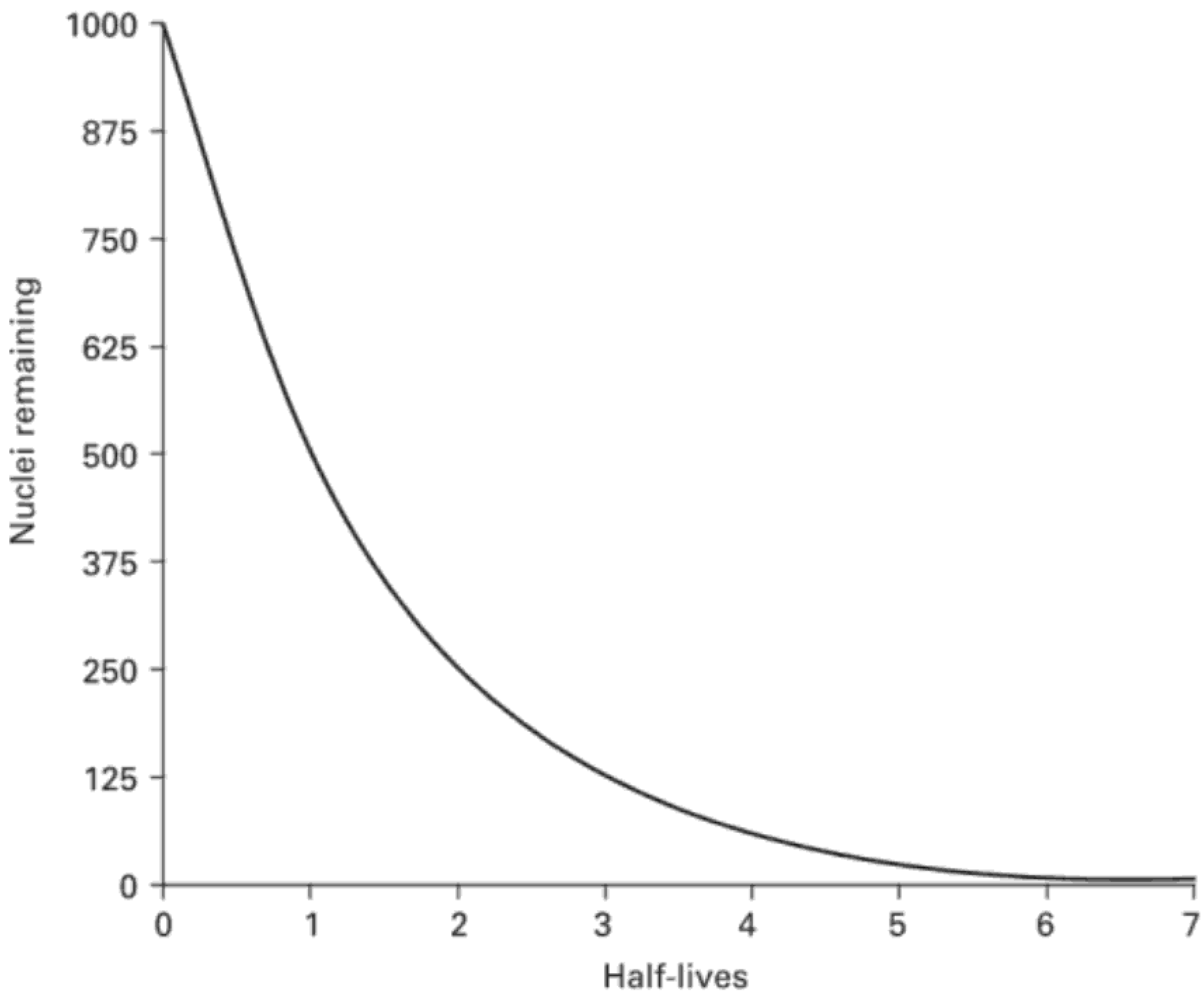


Figure 3.6
Decay of a radioactive material. In one half-life, half the nuclei still present will decay.

Table 3.2 shows that tritium decays with a half-life of about 12 years. You would have to wait 10 times this long, or about 120 years, for a given sample of tritium to decay to 1/1,000 of its original level. On the other hand, a few years is enough for a small but significant change in the amount of tritium present. Tritium used to boost the explosive yield of nuclear weapons must therefore be replenished regularly.

It would take 45 billion years (10 half-lives) for a sample of U-238 to drop to 1/1,000 of its original level. That's about three times the age of the universe! Plutonium-239 decays much more rapidly, with a 24,000-year half-life. But you would still have to wait 240,000 years for a plutonium sample to drop to 1/1,000 of its original level. Strontium-90, a significant component of nuclear waste, has a 29-year half-life, so you'd wait several human lifetimes for a factor-of-1,000 drop in activity. The 1986 Chernobyl accident contaminated much of Europe with iodine-131, which gets into cow's milk and then concentrates in the thyroid glands of humans who drink the milk. For some countries, contaminated milk had more than 10 times the allowed level of I-131. But I-131's eight-day half-life meant that a few weeks' wait were enough to bring I-131

Table 3.2
Half-lives of selected isotopes

Isotope	Half-life	Significance
carbon-14 $^{14}_{6}C$	5,730 years	Radioisotope formed in Earth's atmosphere by cosmic rays; used in radiocarbon dating.
iodine-131 $^{131}_{53}I$	8.04 days	Product of nuclear fission, released in weapons explosions and reactor accidents. Concentrates in milk and is absorbed in the thyroid.
oxygen-15 $^{15}_{8}O$	2.04 minutes	Short-lived oxygen isotope used in PET scans.
plutonium-239 $^{239}_{94}Pu$	24,110 years	Produced in nuclear reactors and used in most nuclear weapons. Sustains a vigorous chain reaction.
radium-226 $^{226}_{88}Ra$	1,600 years	Highly radioactive isotope discovered by Marie and Pierre Curie. Forms in the decay chain of U-238.
radon-222 $^{222}_{86}Rn$	3.82 days	Radioactive gas formed in the decay of Ra-226. Seeps into buildings, where it can give significant radiation exposure.
strontium-90 $^{90}_{38}Sr$	29 years	Fission product that mimics calcium, concentrating in bones. A particularly dangerous component of fallout from nuclear weapons.
tritium $^{3}_{1}H$	12.3 years	Used in biological studies and to enhance nuclear weapons yields.
uranium-235 $^{235}_{92}U$	704 million years	Scarce fissile isotope used as fuel in nuclear reactors and some nuclear weapons.
uranium-238 $^{238}_{92}U$	4.5 billion years	Predominant uranium isotope, making up 99.3 percent of natural uranium. Cannot sustain a chain reaction.
oganesson-294 $^{294}_{118}Og$	0.69 milliseconds	Isotope of the highest atomic number element (118) so far produced.

levels to within safety standards. Finally, oxygen-15, used in PET scans, has a two-minute half-life. Twenty minutes after injection with O-15, a patient's body contains only 1/1,000 of the initial radioactivity. After an hour—30 half-lives—only a billionth remains. For that reason, O-15 and other short-lived isotopes are particularly safe for medical studies.

Suppose we have a chunk of uranium-238 and chunk of strontium-90, with the same number of nuclei in each. How do their activities compare? It will take 4.5 billion years for half the U-238 nuclei to decay, but only 29 years for the Sr-90. So the strontium must decay at a much greater rate—greater by the ratio of 4.5 billion years to 29 years. Given equal quantities of different radioactive materials, those with the shorter half-lives will therefore be more highly radioactive. That's one reason why the relatively short-lived waste products from nuclear reactors are much more dangerously radioactive than the long-lived nuclear fuels that go into the reactors.

The Origin of Radioactive Materials

The lighter nuclei that make up our world—those up to about iron (atomic number 26)—were created through nuclear reactions in stars that existed long before Sun and Earth formed. (We'll explore this special status of iron in chapter 5.) The violently explosive deaths of those stars as *supernovas* spewed into space materials that would later become our solar system and ourselves. Most lighter elements formed while the stars shone steadily, through a process we'll explore in chapter 5. Until very recently physicists believed that heavier nuclei formed primarily during supernova explosions. But the 2017 detection of gravitational waves from a collision of two neutron stars—Sun-mass objects made almost entirely of neutrons—showed that some of the heavier elements arise in neutron-star collisions. Among the heavy elements produced in supernovae and neutron-star collisions are radioactive isotopes of uranium and other elements.

Earth and Sun formed about 5 billion years ago, and the nuclei that constitute them formed even earlier. So radioactive nuclei that were incorporated into our planet have had plenty of time to decay. Even uranium-238, with its 4.5-billion-year half-life, is only half as abundant as when Earth was new. For isotopes with half-lives substantially less than Earth's age, so many half-lives have passed that essentially all the nuclei originally present have long since decayed. For example, Earth's age is equal to nearly 200,000 half-lives of plutonium-239. Even if Earth had been pure Pu-239 (an impossibility for many reasons), dividing in half 200,000 times would have left none of the original Pu-239.

Figure 3.8
(a) Sources of background radiation for the average human. Natural sources, especially radon-222, dominate. The average yearly dose is about 3 millisieverts. (b) In the United States just over half the background radiation is from artificial sources, especially medical procedures. The U.S. average yearly dose is some 6 mSv, twice the global average. (Data source: UN Scientific Committee on the Effects of Atomic Radiation)

radiation we give ourselves is significant—about 9 percent of our total dose. In all, about 80 percent of the global average radiation exposure comes from natural sources, for an annual natural radiation dose of about 2.4 millisieverts (mSv) or 0.24 rem.

Of the remaining 20 percent of global average radiation exposure, nearly all comes from medical procedures. Less than 1 percent is attributable to nonmedical sources, including consumer products as well as nuclear power and weapons activities. Worldwide, the average exposure from all sources amounts to about 3 mSv (0.3 rem) per year.

Figure 3.8b shows a different picture for the United States, where medical procedures account for nearly half the average radiation dose. Consumer products, including smoke detectors, tobacco (which incorporates radioactive phosphorus from fertilizers), pottery and antique glassware, and granite countertops, account for some 2 percent of U.S. radiation exposure. Together, artificial sources provide slightly over half the average U.S. resident's total radiation exposure, which, at 6 mSv/year, is twice the global average.

The radiation doses in figure 3.8 are, of course, averages. Actual doses vary significantly and depend on choices you make. If you choose to live in Denver or to work on airplanes, your higher altitude results in greater cosmic-ray exposure. Should you work in a U.S. nuclear power plant, you may legally receive up to 50 mSv (5 rems) per year—nearly 10 times the average U.S. background dose. Sand in the coastal state of Kerala, India, is especially high in thorium; should you choose to live in Kerala, your yearly background radiation dose will be considerably higher than average. On the other hand, you can choose to lower your medical exposure by avoiding procedures involving radiation.

But should you avoid X-rays or nuclear medicine? Should you move out of the mountains to reduce your exposure to cosmic rays? Should you give up your job as a pilot, or sell your beach house in Kerala? Should you install a basement ventilation system to lower the radon level in your home? And what about the smoke detector that warns you of fire but contains a microcurie of americium-241? Should you get rid of it to avoid radiation exposure? These and similar questions force us to make nuclear choices. In the next chapter, we'll explore effects and uses of radiation that bear on these choices.

Summary

Unstable nuclei inevitably decay, emitting alpha, beta, or gamma radiation. This nuclear radiation is invisible but highly energetic, and readily detectable with instruments. The rate of decay of a radioactive sample is its activity, measured in becquerels or curies. Each radioisotope has a characteristic half-life, the time it takes half the nuclei in a sample of that isotope to decay; half-lives range from fractions of a second to billions of years. The effect of radiation on materials or living things is measured in sieverts or rems. We're all exposed to background radiation from natural and artificial sources; worldwide, the total background exposure is about 3 millisieverts (0.3 rem) per year; in the United States, it's twice that. Radiation exposure varies greatly with occupation, geographical location, house construction, medical procedures, and other factors.

Glossary

activity The rate at which a sample of radioactive material decays, measured in becquerels or curies.

alpha decay Radioactive decay by emission of a helium-4 nucleus, also called an alpha particle. The remaining nucleus has atomic number reduced by 2 and mass number by 4.

alpha particle A helium-4 nucleus (^4_2He), consisting of two protons and two neutrons, that's emitted in radioactive decay.

background radiation Radiation from natural or artificial sources in the everyday environment.

becquerel (Bq) A unit of radioactivity, equal to 1 decay per second.

beta decay A radioactive decay in which a neutron turns into a proton and an electron. The electron is ejected from the nucleus, leaving a nucleus with atomic number increased by 1 and mass number unchanged.

beta particle A name for the electron emitted in beta decay.

contamination Radioactive material in an undesired location.

cosmic rays High-energy particles from space that constitute a significant component of background radiation.

curie A unit of radioactivity, equal to 37 billion decays per second (37 billion Bq).

decay chain A series of isotopes formed as a result of successive radioactive decays.

electron capture The process in which an atomic nucleus captures one of the atoms innermost electrons, lowering the atomic number by 1.

excited nucleus A nucleus containing excess energy, which it may give up by emitting a gamma ray.

gamma decay The process whereby an excited nucleus sheds excess energy by emitting a gamma ray.

gamma ray A bundle of energy emitted by an excited nucleus.

Geiger counter A radiation detector in which radiation strips electrons from atoms in a gas-filled tube, resulting in a burst of electric current.

gray (Gy) The standard unit for the energy an object absorbs when exposed to radiation, equal to 100 rem.

half-life The time it takes for half the nuclei in a given radioactive material to decay.

nuclear radiation High-energy particles—alpha, beta, or gamma—emitted by radioactive nuclei.

positron Antiparticle to the electron. Positrons have the same mass as electrons but carry one unit of positive electric charge.

rad A unit that measures the energy an object absorbs when exposed to radiation, equal to 0.01 Gy.

radiation See **nuclear radiation.**

radioactive Describes a substance, in particular an isotope, which undergoes radioactive decay.

radioactive decay The process in which an unstable nucleus comes apart, usually by emitting a particle.

radioisotope Short for radioactive isotope, an isotope that undergoes radioactive decay.

radon-222 A radioactive gas formed in the decay sequence of uranium-238 and constituting a significant portion of background radiation.

rem A unit of radiation dose that describes the radiation's effect on the human body, equal to 0.01 Sv.

sievert (Sv) The standard unit of radiation dose that describes the effect of radiation on the human body, equal to 100 rem.

Note

1. In fact, a third particle is involved: an electrically neutral particle of negligible mass, called a *neutrino*. The neutrino has essentially no interaction with ordinary matter, and in this book we'll neglect it.

Further Reading

European Union and EDP Sciences. radioactivity.eu.com. An authoritative website covering all aspects of radiation and radioactivity. The predecessor of EDP Sciences was founded in 1920 by Marie Curie and other prominent physicists.

Lawrence Berkeley Laboratory (LBL), radioactivity website at https://www2.lbl.gov/abc/wallchart/chapters/03/0.html. Website intended to educate the general public about radioactivity, designed in conjunction with LBL's chart of stable and unstable nuclides.

Lillie, David W. *Our Radiant World*. Ames: Iowa State University Press, 1986. A well-written primer on radiation from both natural and artificial sources, written at about the level of this book and covering in much more depth the material of chapters 3 and 4. Mostly objective, but the author's industrial background shows. Excellent bibliography. Dated but authoritative.

Redniss, Lauren. *Radioactive: Marie and Pierre Curie: A Tale of Love and Fallout*. New York: Dey Street Books, 2015. This delightfully illustrated book combines history, biography, and physics. A moderate antinuclear bias is evident.

Tuniz, Claudio. *Radioactivity: A Very Short Introduction*. Oxford, UK: Oxford University Press, 2012. A brief but thorough introduction to radioactivity as it occurs both in nature and in technological applications.

4

Radiation

People fear radiation for good reasons: It harms biological systems, including ourselves. It's invisible and undetectable without special equipment. And nuclear technologies have created new sources of potentially hazardous radiation.

But radiation's dangers aren't the whole story. Risk from radiation exposure depends on the radiation dose one receives. Furthermore, some uses of radiation are distinctly beneficial. Many people are alive today who wouldn't be had radiation not helped diagnose or treat otherwise fatal diseases. Radiation helps us in less obvious ways, too. Food safety and shelf life are improved by irradiation. Radiation-induced sterilization reduces insect populations. Sensitive detection and analysis of pollutants relies on radiation techniques. And we're enriched by the knowledge of our own past that archaeologists gain through radioisotope dating. This chapter explores the harmful effects of radiation and also samples its beneficial uses.

Biological Effects of Radiation

Radiation consists of high-energy particles, including alpha, beta, and gamma rays as well as X-rays. Their high energy enables these particles to knock electrons out of atoms—the process of **ionization**, and hence the term **ionizing radiation**. Molecules containing ionized atoms are chemically very active. In living tissue such molecules may undergo chemical reactions whose products are detrimental to life. Ionization of water, for example, leads the formation of substances that act as cell poisons. Radiation striking more complex biological molecules, such as proteins or nucleic acids, may break the molecules and prevent their proper functioning. Loss of cell vitality, decreased enzyme activity, cancer, and genetic changes are among the possible outcomes.

Somatic Effects

Somatic effects of radiation are effects on an individual that aren't passed on to future generations. High radiation doses of several sieverts destroy cells that normally divide rapidly, diminishing the body's ability to replenish its red and white blood cells and the cells that line the intestinal tract. Nausea and vomiting are the first symptoms of acute **radiation sickness**, typically appearing a few hours after exposure. There follows a lull of several days to a week or more during which the victim may feel fine. But then, as red blood cells die without being replaced, anemia sets in. Intestinal bleeding, complicated by the loss of blood-clotting factors, exacerbates the illness. As white blood cells go unreplaced, the body's immunity declines. Death may follow in a matter of weeks or months. At a radiation exposure of 4 Sv, about half the victims die of radiation sickness. Blood transfusions and bone-marrow transplants can improve survival by allowing the body to make new red blood cells.

Victims exposed to doses of a few Sv exhibit similar symptoms but generally recover in several months. The same is true for those lucky enough to survive higher doses. These victims seem to recover completely and, except for an increased cancer risk, go on to lead normal lives.

While doses above about 1 Sv cause radiation sickness, doses of a few tenths of a sievert may produce no obvious effects. How are we to determine whether such radiation exposures are harmful? And how can we possibly establish harmful effects at the much lower doses—typically only a few thousandths of a sievert—received by the general public in nuclear incidents or through medical procedures? Answering these questions requires statistical analysis of large populations exposed to low-level radiation.

Cancer and Radiation

The most significant result of low-level radiation exposure is increased incidence of cancer. Numerous studies have confirmed this effect. For example, X-ray technicians working in the first half of the twentieth century showed substantial increases in a variety of cancers. Watchmakers in the 1920s applied radium-containing paint to make watch hands visible in the dark. Workers painting watch hands often licked their brushes, ingesting radium in the process. Nearly all of them eventually died of bone cancer or radiation-induced anemia. Uranium miners, exposed to radon gas trapped in the mines, used to develop lung cancer at a much higher than average rate. Many early nuclear scientists—including Marie Curie and her daughter Irene—died from leukemia that was undoubtedly caused by radiation exposure. (Pierre Curie was spared this fate; he was killed in the street when a horse bolted from its carriage.)

Today, we know enough to avoid painting our watches with radium. Strict controls on uranium mines have dropped radon exposure to the point where some American homes have higher radon levels than uranium mines. Scientists and medical personnel are more conscious of radiation's dangers and take precautions to minimize exposure. Are we then safe from radiation? Or do much lower levels still pose a risk?

A look at survivors of Hiroshima and Nagasaki shows why the issue of low-level radiation is still clouded. Figure 4.1 plots the incidence of solid cancers among Hiroshima residents exposed to radiation from the bomb, as a percent of the number of deaths expected in the absence of bomb radiation. Where that percentage is substantial, we can assume that the additional cases are due to radiation. And sure enough, large doses of radiation result in greatly increased cancer incidence—nearly double the expected rate for exposures over 2 grays.[4] But for exposures under 0.1 Gy, the cancer excess is less than 2 percent. In fact, given the statistical uncertainty, it's even possible that very low doses resulted in fewer cases than expected!

Figure 4.1
Excess solid cancers as a percentage of expected cancer incidence in Japanese bomb survivors, as a function of dose in grays (Gy). (Data source: D. L. Preston et al., "Solid Cancer Incidence in Atomic Bomb Survivors: 1958–1998," *Radiation Research* 168, no. 1 [July 2007], Table 9.)

The results shown in figure 4.1 typify an ongoing controversy over the health effects of radiation: Should effects at low doses, which are hard to measure, be extrapolated proportionately from the easier-to-measure effects at high doses? And at very low doses, should the extrapolation continue straight to zero effect at zero dose? Or are there reasons why the response at low doses might deviate from a direct proportionality? Those same repair enzymes that help ward off radiation-induced mutations at low radiation doses might also repair DNA damage that could lead to cancer. Many radiation specialists therefore suggest that risks at low doses should be lower than implied by a direct proportionality. Some would argue for a threshold dose, below which there are no harmful effects. And a few would claim **hormesis**, a response in which very low radiation doses are actually beneficial. (If that sounds absurd, note that hormesis is well established for chemicals that are toxic at high doses but beneficial at low doses.) Alternatively, it might be that low radiation doses are actually more harmful than a proportional extrapolation would suggest. Figure 4.2 shows **dose-response curves** corresponding to these possibilities.

Absent unambiguously solid evidence for radiation effects at low doses, many scientific bodies and regulatory agencies take a conservative approach, adopting the **linear no-threshold (LNT) model**. This model assumes that the risk of radiation-induced cancer is directly proportional (*linear*, in math-speak) to the dose, right down to zero dose. Some LNT models for cancer risk use a so-called *dose and dose-rate effectiveness factor*, which reduces the risk at low doses by a factor of typically 1.5 or 2 relative to the measured risk at high doses. But these models are still linear, which implies that *any* radiation exposure, no matter how small, carries some risk.

Scholarly bodies recommending use of the LNT model include the United Nations Scientific Committee on the Effects of Atomic Radiation, the International Commission on Radiological Protection, and the U.S. National Academy of Sciences in its report *Biological Effects of Ionizing Radiation* (BEIR VII, phase 2). The LNT model is the basis of radiation-protection regulations in many countries, including those promulgated by the U.S. Nuclear Regulatory Commission (NRC). A notable exception is France, whose Academy of Sciences has questioned the validity of LNT at doses below 100 mSv.

The debate over LNT and other models in figure 4.2 might seem an arcane matter, best left to scientists and statisticians. But it's not; rather, the choice of which low-dose model to adopt is a nuclear choice with

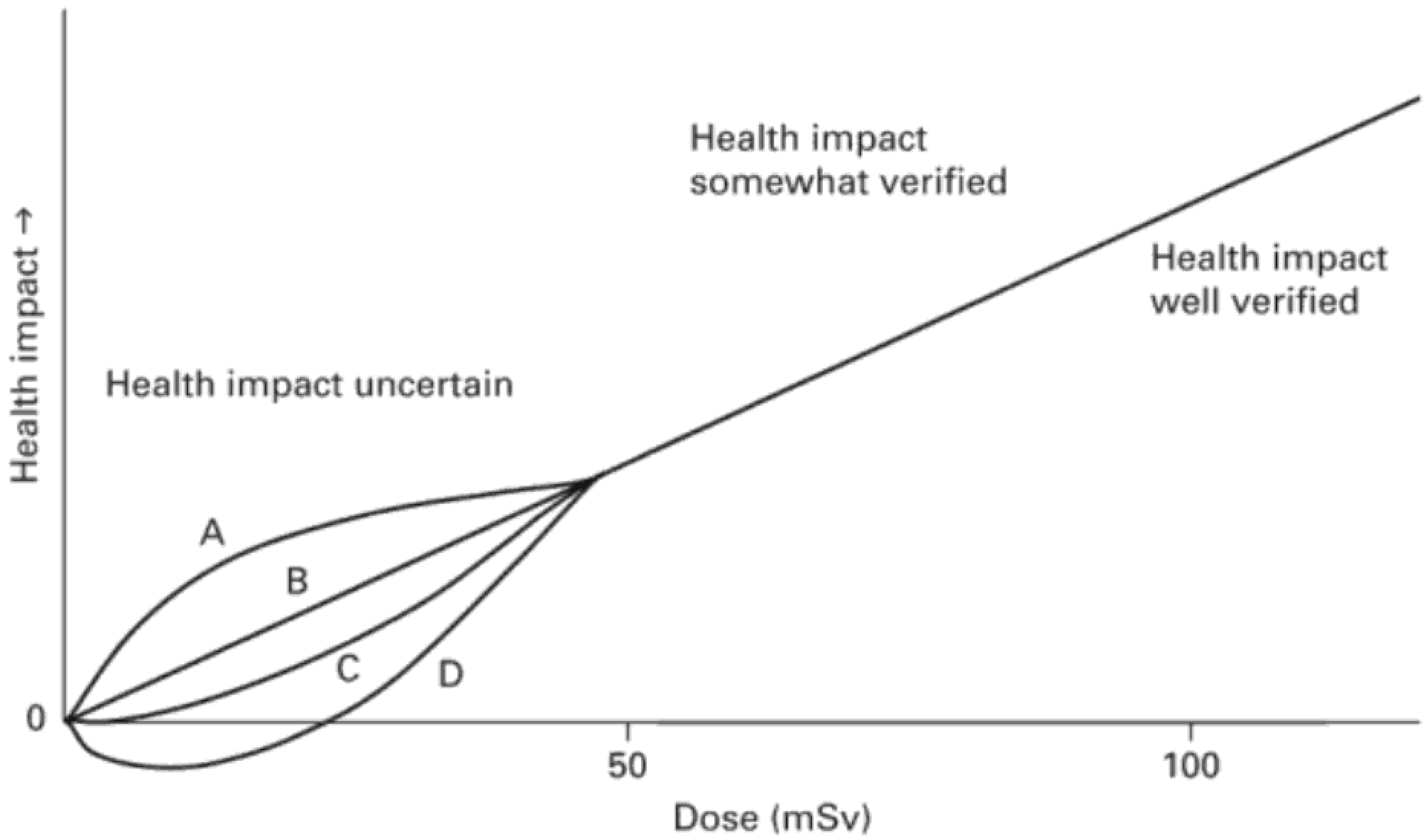


Figure 4.2
Dose-response curves corresponding to different hypotheses about the health impact of low radiation doses. Curve A indicates higher risk at low doses. Curve B is the linear no-threshold model. Curve C shows lower risk at low doses, and curve D is a hormesis model with a threshold below which radiation is actually beneficial. All are in essential agreement at higher doses (above 50 mSv), where health impacts become increasingly well verified.

enormous consequences. The size of the evacuation zone at Fukushima was based in part on the assumed risks of low-dose radiation. Adopt a threshold model instead of the LNT and many people would be spared the stress of evacuation—which brought its own health consequences. Were those consequences worse than the danger from radiation? Quite possibly—but the answer depends on assumptions about radiation risks at low doses. After the Chernobyl accident thousands of pregnancies were intentionally terminated across Europe out of fear of genetic damage. Was that a sensible precaution or an overreaction? The answer requires knowing the impact of low radiation doses. A physician's decision to administer a CAT scan or nuclear medicine procedure is predicated on the calculation that the risks of the disease being diagnosed or treated outweigh the risks of low-dose radiation associated with the procedure. Protecting the public from radiation emitted by nuclear power plants requires costly shielding and other expensive measures—and thus contributes to the economic predicament that nuclear power currently faces, especially in the West. Yet nuclear power arguably offers a low-carbon source of energy that could help stave off global warming. In all these examples, the risks of radiation weigh against non-nuclear risks, and someone has to make a choice. Intelligent choice requires understanding the effects of radiation at low doses.

The BEIR VII report develops a rough rule of thumb for estimating cancer effects of low-level radiation. It suggests that a radiation dose of 0.1 Sv (100 millisieverts or some 30 times the global average annual background dose) results in a 1-in-100 lifetime chance of developing cancer. That means that if 100 people are exposed to 100 mSv each, we can expect that, on average, one of them will eventually develop cancer as a result of their radiation exposure. Expose 1,000 people and expect 10 cancers. Consider these numbers in light of the fact that, on average, 42 out of 100 people will develop cancer in their lifetimes. Consider also that 100 mSv is a large dose—at the upper limit of what's considered "low dose" and far above the doses experienced by the general public in the worst nuclear accidents.

So what's the cancer impact of more realistic and much lower radiation exposures? If the LNT hypothesis is correct, then we can simply scale down from the BEIR-VII's 1-in-100 cancer risk for a dose of 100 mSv. For example, the 1979 Three Mile Island (TMI) nuclear accident in Pennsylvania resulted in a dose of about 0.1 millisievert to the approximately 36,000 people within five miles of TMI. That's only one one-thousandth of the 100-mSv dose that gives a 1-in-100 cancer risk. So, assuming LNT, we would expect a risk of 1 in $(100 \times 1{,}000)$ or 1 in 100,000. The exposed population was only about one-third of 100,000, so our calculation suggests it's unlikely that any cancers resulted from that accident. On the other hand, the most exposed region outside the exclusion zone from the 2011 Fukushima accident saw doses averaging from 1 to 10 mSv. For an average of 5 mSv, or one-twentieth of the 1-in-100 cancer dose, our extrapolation would then suggest a lifetime cancer risk of 1 in (100×20) or 1 in 2,000—one cancer for every 2,000 people exposed. The population of the affected region is about 2 million, so we might expect some $2{,}000{,}000/2{,}000 = 1{,}000$ lifetime cancers resulting from the accident. That sounds like a lot, but the lifetime cancer incidence in Japan is 41 in 100, implying that there should be more than 800,000 cancers, not associated with the Fukushima accident, in the affected population. Cancer rates fluctuate naturally, making detection of an additional 1,000 cancers over many decades essentially impossible. Our estimate of 1,000 Fukushima cancers is consistent with more careful studies, including one from Stanford University that put the number of cancers in the range from 24 to 1,800.[5]