27 The Ultimate Structure of Matter

KEY IDEA

All matter is made of quarks and leptons, which are the fundamental building blocks of the universe.

PHYSICS AROUND US . . . Looking at Sand and Stars

Ancient poets did not have the language to express really large numbers. So they would refer to the number of stars in the sky or leaves in a forest or grains of sand on the shore. And if you look at the night sky or go into the woods in summer or let a handful of sand sift through your fingers, these seem to be truly enormous numbers.

But they're not. Next time you lie on a beach, look at a single tiny grain of sand and think about its microscopic structure. Imagine that you could magnify that grain a thousandfold, a millionfold, or even more. What would you see?

At 1000 magnification, the rounded grain would appear rough and irregular, but no hint of its atomic structure could be seen. At 1 million magnification, individual atoms, each about one ten-billionth of a meter across, would begin to be visible. At 1 trillion magnification, the atomic nuclei would appear as tiny points, surrounded by almost nothing. There are more protons, electrons, and neutrons in a grain of sand than there are grains of sand on any beach you can imagine.

But is that it? Or is there some incredibly tiny structure to the particles that make up atoms? What are the ultimate building blocks of matter?

OF WHAT IS THE UNIVERSE MADE?

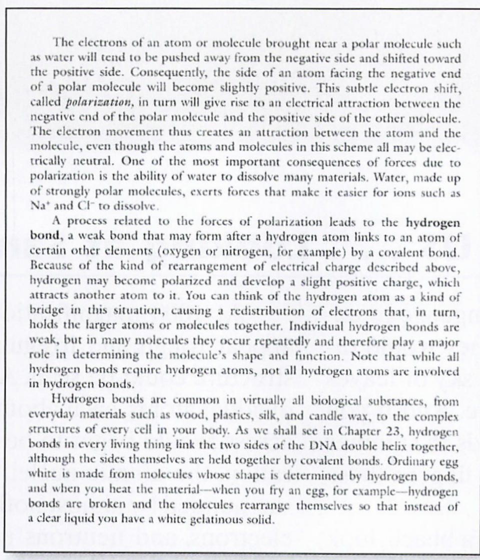
The Library

The next time you head over to the library, wander through the stacks and think about what constitutes the fundamental building blocks of the library. Your first reaction might be to say that books are the fundamental building blocks—row after row, shelf after shelf, of bound volumes. But a library is not just a collection of books: the volumes are arranged with an order to them. You could describe the set of rules that dictates how books are arranged in libraries—the Dewey decimal system or the Library of Congress classification scheme, for example. Thus a complete description of a library at this most superficial level includes two things: books as the fundamental building blocks and rules about how the books are organized.

Inside a book, the various volumes are not as different from one another as they might seem at first. They are all made of an even more fundamental unit—the word. You could argue that words are the fundamental building blocks of the library. Also, as was the case for the cataloged books, we require a set of rules, called grammar, that tells us how to put words together to make books. Words and grammar, then, take you down to a more basic level in your probe of a library's reality.

You probably wouldn't be content very long with the notion of words as the fundamental building blocks, because all of the thousands of words are different combinations of a small number of more fundamental things—letters. Only 26 letters (at least in the English alphabet) provide the building blocks for all the thousands of words on all the pages in all the books of the library. Furthermore, we need a set of rules (spelling) that tells us how to put letters together into

(a)

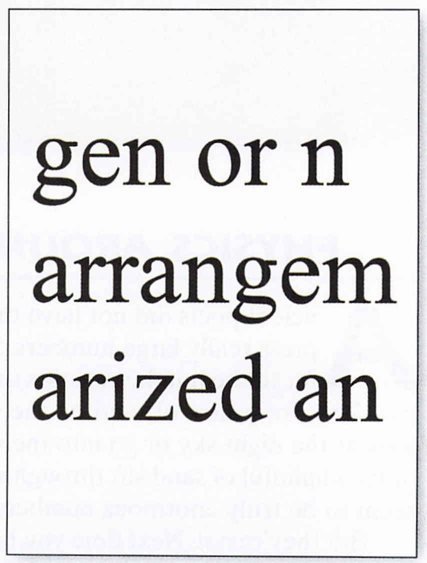


The electrons of an atom or molecule brought near a polar molecule such as water will tend to be pushed away from the negative side and shifted toward the positive side. Consequently, the side of an atom facing the negative end of a polar molecule will become slightly positive. This subtle electron shift, called ***polarization***, in turn will give rise to an electrical attraction between the negative end of the polar molecule and the positive side of the other molecule. The electron movement thus creates an attraction between the atom and the molecule, even though the atoms and molecules in this scheme all may be electrically neutral. One of the most important consequences of forces due to polarization is the ability of water to dissolve many materials. Water, made up of strongly polar molecules, exerts forces that make it easier for ions such as Na^+ and Cl^- to dissolve.

A process related to the forces of polarization leads to the **hydrogen bond**, a weak bond that may form after a hydrogen atom links to an atom of certain other elements (oxygen or nitrogen, for example) by a covalent bond. Because of the kind of rearrangement of electrical charge described above, hydrogen may become polarized and develop a slight positive charge, which attracts another atom to it. You can think of the hydrogen atom as a kind of bridge in this situation, causing a redistribution of electrons that, in turn, holds the larger atoms or molecules together. Individual hydrogen bonds are weak, but in many molecules they occur repeatedly and therefore play a major role in determining the molecule's shape and function. Note that while all hydrogen bonds require hydrogen atoms, not all hydrogen atoms are involved in hydrogen bonds.

Hydrogen bonds are common in virtually all biological substances, from everyday materials such as wood, plastics, silk, and candle wax, to the complex structures of every cell in your body. As we shall see in Chapter 23, hydrogen bonds in every living thing link the two sides of the DNA double helix together, although the sides themselves are held together by covalent bonds. Ordinary egg white is made from molecules whose shape is determined by hydrogen bonds, and when you heat the material—when you fry an egg, for example—hydrogen bonds are broken and the molecules rearrange themselves so that instead of a clear liquid you have a white gelatinous solid.

(b)



(c)

At first glance, the fundamental units of a library might appear to be books (*a*), but a closer inspection reveals that books are made from words (*b*), which in turn are made from letters (*c*).

words. The discovery of letters and spelling would provide perhaps the ultimate description of a library and its organization.

So the library can be described in this way: We use spelling to tell us how to put letters together into words. Then grammar tells us how to put words together into books. Finally, we use organizing rules to tell us how to put books together into a library.

As we shall see, this building-block approach is how scientists attempt to describe the entire physical universe.

Reductionism

How many different kinds of material can you see when you look up from this book? You may see a wall made of cinder blocks, a window made of glass, and a ceiling made of fiberglass panels. Outside the window you may see grass, trees, blue sky, and clouds. We encounter thousands of different kinds of materials every day. They all look different—what possible common ground could there be between a cinder block and a blade of grass? They all look different, but are they really?

For at least two millennia, people who have thought about the physical universe have asked this question. Is the universe just what we see, or is there some underlying structure, some basic stuff, from which it's all made? In some respects, this is one of the most fundamental of scientific questions.

Philosophers refer to the quest for the ultimate building blocks of the universe as *reductionism*. Reductionism is an attempt to reduce the seeming complexity of nature by first looking for underlying simplicity and then trying to understand how that simplicity gives rise to the observed complexity. This pursuit is a continuation of an old intellectual belief that the appearances of the world do not tell us its true nature but that its true nature can be discovered by the application of thought and, in the case of science, experiment and observation.

The Greek philosopher Thales (625?–546 B.C.) suggested that all materials are made of water. This supposition was based on the observation that in everyday experience water appears as a solid (ice), a liquid, and a gas (water vapor). Thus, alone among the common substances, water seemed to exhibit all the states of matter (see Chapter 9). Thales's followers later expanded this notion to include the familiar four elements of the ancient Greeks—earth, fire, air, and water. This was the first attempt to find the basic building blocks of the universe.

The Building Blocks of Matter

To many people, the library analogy presents a profoundly satisfying way of describing complex systems. Some would even argue that everything you could possibly want to know about the physical organization of the library is contained in letters and their organizing principles. In just the same way, physicists want to describe the complex universe by identifying the most fundamental building blocks and deducing the rules by which they are put together.

At first, you might say the most fundamental building block of the universe is the atom. All the myriad solids, liquids, and gases are made of just 100 or so different kinds of chemical elements. The complexity of materials that appears to the senses results from the many combinations of these relatively few kinds of atoms. The rules of chemistry tell us how atoms bind together to make all of the materials we see.

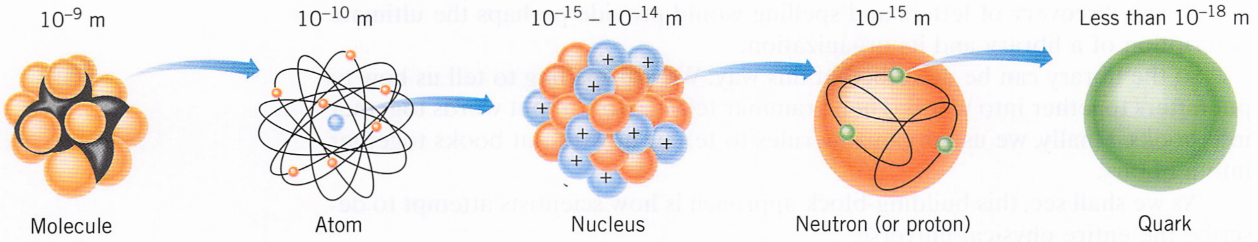


FIGURE 27-1. The modern picture of the fundamental building blocks of the universe. Molecules are made from atoms, which contain nuclei, which are made from elementary particles, which in turn are made from quarks.

However, early in the twentieth century physicists learned that atoms are not really fundamental but are made up of smaller, more fundamental bits—protons, neutrons, and electrons. These particles arrange themselves according to their own set of rules, with massive neutrons and protons in the positively charged nucleus and negatively charged electrons in orbit around the nucleus. A picture of the universe with only these three fundamental building blocks is very simple and appealing. Protons and neutrons together form nuclei, and electrons orbit the nucleus to form atoms. Electrons combine and interact with one another to form all the materials we know about.

However, just as words and grammar gave us a false level of simplicity in the analogy of the library, this simple picture of the universe based on just three particles didn't stand up to more detailed experiments and observations. As we have hinted, the nucleus contains more than just protons and neutrons, although physicists did not understand the full implications of this statement until the post–World War II era. If we are going to follow the reductionist line in dealing with the universe, we have to start thinking about what makes up the nucleus. By common usage, the particles that make up the nucleus, together with particles such as the electron, were called *elementary particles* to reflect the belief that they are the basic building blocks of the universe (Figure 27-1). The study of these particles and their properties is the domain of a field known as **high-energy physics,** or **elementary-particle physics.** (We see later that the study of elementary particles requires the use of very high energies.)

DISCOVERING ELEMENTARY PARTICLES

Nowhere in nature is the equivalence of mass and energy more obvious than in the interactions of elementary particles. Imagine that you have a source of protons traveling at very high velocities, approaching the speed of light. This source might be astronomical in nature, or it might be a machine that accelerates particles. Once the proton has been accelerated, it has a very high kinetic energy. If this high-energy proton collides with a nucleus, the nucleus can be split apart. In this process, some kinetic energy of the original proton can be converted into mass according to the equation $E = mc^2$ (see Chapter 12). When this happens, new kinds of particles that are neither protons nor neutrons can be created.

Cosmic Rays

During the 1930s and 1940s, physicists used a natural source of high-energy particles, called **cosmic rays,** to study the structure of matter. Cosmic rays are particles (mostly protons) that rain down continuously on the atmosphere of Earth after they are emitted by stars in our galaxy and in other galaxies.

Space is full of cosmic rays. When they hit the atmosphere, they collide with molecules of oxygen or nitrogen and produce sprays of very fast-moving secondary particles. These secondary particles, in turn, can make further collisions and produce even more particles, building up a cascade in the atmosphere. It is not uncommon for a single incoming particle to produce billions of secondary particles by the time the cascade reaches the surface of Earth. Indeed, on average, several of these rays pass through your body every minute of your life.

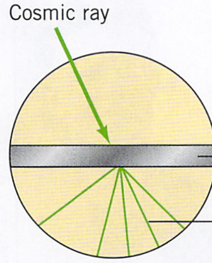


FIGURE 27-2. In a typical cosmic ray experiment, cosmic rays hit a lead nucleus, producing a spray of particles.

Physicists in the 1930s and 1940s set up their apparatuses on high mountaintops and observed what happened when fast-moving primary cosmic rays or slightly slower-moving secondary particles collided with nuclei. A typical apparatus incorporated a gas-filled chamber several centimeters across (Figure 27-2). A thin sheet of target material such as lead was located midway in the chamber. Cosmic rays occasionally collided with one of the nuclei in the piece of lead, producing a spray of secondary particles. By studying particles in that spray, physicists hoped to understand what was going on inside the target nucleus.

By the early 1940s, when the international effort in physics research shut down temporarily because of World War II, physicists working with these cosmic ray experiments had discovered particles in addition to the proton, neutron, and electron. And when the research effort started up again after the war, these discoveries multiplied as more and more particles were found in the debris of nuclear collisions, both by cosmic ray physicists and by those working at the new particle accelerators (which we discuss shortly).

The net result of these discoveries was that the nucleus can no longer be considered to be a simple bag of protons and neutrons. Instead, we have to think of the nucleus as a very dynamic place. All kinds of newly discovered elementary particles in addition to protons and neutrons are found there. These exotic particles are created in the interactions inside the nucleus, and they give up their energy (and, indeed, their very existence) in subsequent interactions to make other kinds of particles. This constant dance of the elementary particles inside the nucleus has been well documented since these early explorations.

Connection

Detecting Elementary Particles

If elementary particles are even smaller than an individual nucleus, how do we know they're there? Experimental physicists have raised detection of elementary particles to a fine art over the years. Nevertheless, the basic technique used in any detection process is the same: the particle in question interacts with matter in some way, and we measure the changes in matter that result from that interaction.

If an elementary particle has an electric charge, it may tear electrons loose as it goes by an atom. Thus, a charged elementary particle moving through material such as a photographic emulsion leaves a string of ions in its wake, much as a speedboat going across a lake leaves a trail of troubled water. The earliest kinds of detectors were simple photographic plates; the plates were angled so the particle's path would lie in the plane of the emulsion.

A more modern detection method is to allow the particles to pass though a grid of thin conducting wires (usually made of gold). As a particle passes a wire, it exerts a force on the electrons in the metal, creating a small pulse of current. By measuring the time when this pulse arrives at the end of the wire, and by putting together such information from many wires, a computer can reconstruct the particle's path with high precision.

Uncharged particles such as neutrons are much more difficult to detect because they do not leave a string of ions in their path. Typically, the passage of an uncharged particle cannot be detected directly; instead, we wait until it collides with something. If that collision produces charged particles, then we can detect them by the techniques just outlined and can work backward and deduce the property of the uncharged particle.

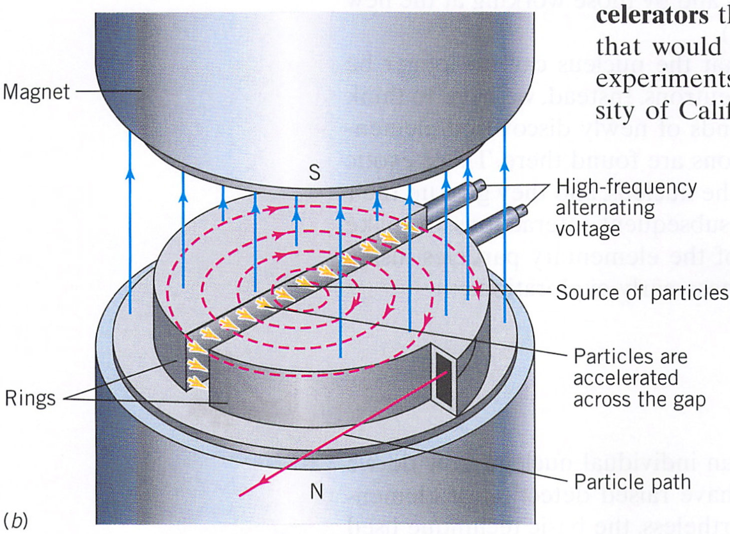
Particle Accelerators: The Essential Tool

For a time, physicists had to sit around and wait for nature to supply high-energy particles (in the form of cosmic rays) so that they could study the fundamental structure of matter. The arrival of cosmic rays could not be controlled and it could be very time-consuming waiting for one to hit. Physicists realized that they had to build machines that could produce streams of artificial cosmic rays—**particle accelerators** that scientists could turn on and off at will and that would take the place of the sporadic cosmic rays in experiments. At the beginning of the 1930s at the University of California at Berkeley, Ernest O. Lawrence began producing a new kind of accelerator called a *cyclotron,* an invention for which he won the 1939 Nobel Prize in physics.

The cyclotron works by applying an electric force to groups of charged particles, usually electrons or protons, that are forced to move in circles by large magnets (Figure 27-3). In this system, the magnets supply a centripetal force that keeps the particles moving in circles. In one region of the circular path, an electric field accelerates the particles in the direction of their motion, increasing their speed. As the particles pass through this region over and over again, they are eventually accelerated almost to the speed of light. Once they have acquired this much kinetic energy, they are allowed to collide with other particles. These collisions provide the interactions that physicists study.

Lawrence's first cyclotron was no more than a dozen centimeters across and produced energies that were pretty puny by today's standards. Modern particle accelerators are huge high-tech structures, capable of producing particle energies as high as all but the most energetic cosmic rays.

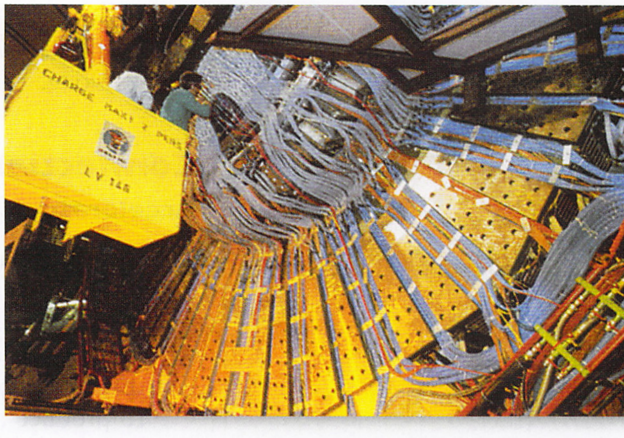
(a)



(b)

FIGURE 27-3. (a) Ernest O. Lawrence posed in the 1930s with his invention, the cyclotron, which was the first particle accelerator. (b) The cyclotron accelerates charged particles in a spiral path by generating an intense magnetic field.

In the type of accelerator called a *synchrotron*, the main working part is a large ring of magnets that keep the accelerated particles moving in a circular track. As we have seen in Chapter 16, magnetic fields exert a force on moving charged particles. That force tends to make charged particles move in a circular track. As a particle in a synchrotron moves around the circle, the large electromagnets are adjusted to keep its track within a small chamber (typically several centimeters on a side) in which a near-perfect vacuum has been produced. This chamber, in turn, is bent into the large circle that marks the particle's orbit. Each time the particles come around to a certain point, an electric field boosts their energy. As the velocity increases, the field strength in the magnets is also increased to compensate, so that the particles continue around the same circular track. Eventually, the particles reach the desired speed and they are brought out into an experimental area where they undergo collisions. Note that in a synchrotron the particles move in a circle of constant radius, while in a cyclotron the particles spiral outward.



The four-story-high Fermilab CDF particle detector. Particle detectors have gone from being small, desktop pieces of apparatus to huge high-technology instruments such as the one shown.

As the energy required to stay at the frontier of particle physics increases, so too does the size of accelerators. The highest-energy accelerator in the world today is at the Fermi National Accelerator Laboratory (Fermilab) outside Chicago, Illinois. There, protons move around a ring almost 2 kilometers (about 1 mile) in diameter and achieve energies of 1 trillion electron volts. Even higher energies are expected to be produced at the Large Hadron Collider in Geneva, Switzerland. Located in an underground tunnel about 8 km (5 miles) across, it will accelerate protons to over 7 trillion electron volts when it becomes operational in 2004.

The *linear accelerator* provides an alternative strategy for making high-velocity particles. This device relies on a long, straight vacuum tube into which electrons are injected. The electronics are arranged so that an electromagnetic wave travels down the tube, and electrons ride this wave more or less the way a surfer

(*a*)

(*b*)

(*a*) Fermilab in Illinois and (*b*) Stanford Linear Accelerator Center (SLAC) in California are two of the world's most powerful accelerators.

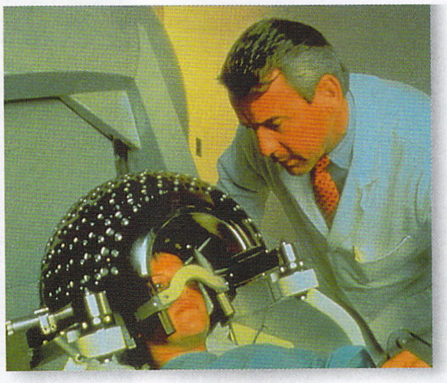
rides a wave on the ocean. The largest linear accelerator in the world, at the Stanford Linear Accelerator Center in California, is about 3 kilometers (almost 2 miles) long.

Connection
Accelerators in Medicine

The ability to build machines that accelerate charged particles has had an important effect in many areas of medicine, most notably in the treatment of cancer. Often the goal of this treatment is to destroy malignant cells in tumors, and subjecting those cells to high-energy X rays or gamma rays is a particularly effective way of doing this for some cancers.

To produce a beam of gamma rays for cancer therapy, a small accelerator produces an intense beam of high-speed electrons. These electrons are then directed into a block of heavy metal such as copper, which stops them abruptly. As we learned in Chapter 19, electrically charged objects that are accelerated (or, in this case, decelerated) emit electromagnetic waves. In the case of electrons accelerated to an appreciable fraction of the speed of light and suddenly stopped, those waves are in the form of gamma rays. The direction of the electron beam is arranged so that the gamma rays pass through the tumor, killing cells as they pass through. In a treatment known as gamma knife surgery, the gamma rays are focused through holes in a shield worn by the patient, so that their energy is concentrated on the tumor cells and damage to healthy cells is minimized.

A form of cancer therapy still under development involves using beams of accelerated protons, which are directed to hit a metal target and produce another kind of elementary particle, called a "pi-meson." When beams of pi-mesons enter tissue, the distance they travel depends on their energy. Thus the accelerator can be set so that the particle beam stops in the tumor itself, delivering large amounts of energy to a relatively small region. ●



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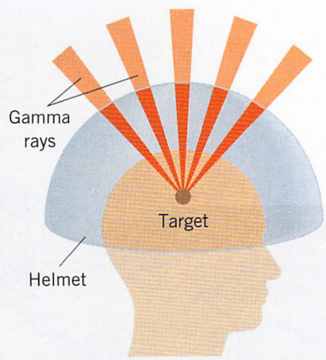


(b)

Gamma knife surgery employs a beam of gamma rays, which is focused through holes in a shield worn by the patient (a). In this manner the gamma-ray energy is concentrated on the tumor cells and damage to healthy cells is minimized (b).

THE ELEMENTARY PARTICLE ZOO

At the beginning of the 1960s, the first generation of modern particle accelerators began to produce copious results, and the list of elementary particles began to grow rapidly. The list now numbers in the hundreds. A few important groups of particles are summarized in the following sections and in Table 27-1.

Leptons

Leptons are elementary particles that do not participate in the strong force that holds the nucleus together, and they are not part of the nuclear maelstrom. Instead, they interact by the weak nuclear force, as we describe later in this chapter. Some leptons have electric charge, so they also react by the electromagnetic force. We have encountered two leptons so far—the *electron,* which is normally found in orbit around the nucleus rather than in the nucleus itself, and the *neutrino* (see Chapter 6), a light neutral particle that hardly interacts with matter at all. Since the 1940s, physicists have discovered four additional kinds of leptons, for a total of six. If you keep in mind that the electron and the neutrino are typical leptons, you will have a pretty good idea of what the others are like. The six leptons seem to be arranged in pairs—in each pair there is a particle like the electron, which has a mass, and a specific kind of neutrino, which has a very small mass.

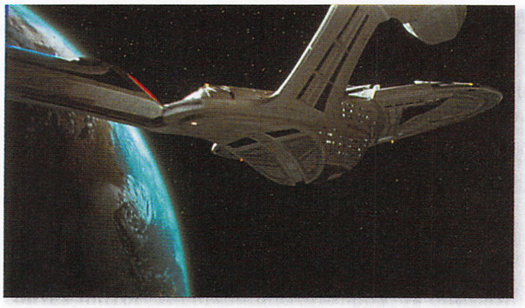
Hadrons

All the different kinds of particles that exist inside the nucleus are referred to collectively as **hadrons** ("strongly interacting ones"). The array of these particles is truly spectacular. Hadrons include particles that are stable, such as the proton, particles that undergo radioactive decay in a matter of minutes, such as the neutron (which undergoes beta decay), and still other particles that undergo radioactive decay in 10^{-24} seconds. This third kind do not live long enough to travel across even a single nucleus! Some hadrons carry an electric charge, while

TABLE 27-1 Summary of Elementary Particles

Type	Definition[a]	Examples
Leptons	Interact by weak and electromagnetic forces	Electron, neutrino
Hadrons	Interact by strong, weak, and electromagnetic forces	Proton, neutron, roughly 200 others
Antiparticles	Particles with the same mass as the corresponding particles but with opposite charge and other properties	Positron

[a]All elementary particles that have mass also interact through the gravitational force, but this is so weak compared to the other forces that it is usually ignored.



Matter–antimatter annihilation reactions are often employed by science fiction writers to power futuristic spaceships, such as the starship *Enterprise* in the *Star Trek* series.

others are neutral. But all these particles are subject to the strong force and all participate in holding the nucleus together; thus, they help make the physical universe possible.

Antimatter

For every particle that we see in the universe, it is possible to produce an antiparticle. Every particle of **antimatter** has the same mass as its matter twin, but the particles have opposite charge and opposite magnetic characteristics. For example, the antiparticle of the electron is a positively charged particle known as the *positron.* It has the same mass as the electron, but a positive electric charge. Antinuclei, composed of antiprotons and antineutrons and orbited by positrons, can form antiatoms. (Such antiatoms have been produced in the laboratory.)

When a particle collides with its antiparticle, both masses are converted completely to energy in a process called *annihilation,* the most efficient and violent process that we know in the universe. The original particles disappear, and this means that energy appears as a spray of rapidly moving particles and electromagnetic radiation. Science fiction writers have long adopted this fact in their descriptions of futuristic weapons and power sources. (The starship *Enterprise* on *Star Trek,* for example, has matter and antimatter pods as its power source.

Although antimatter is fairly rare in the universe, it is routinely produced in particle accelerators. High-energy protons or electrons strike nuclear targets, and the energy of the particles is converted to equal numbers of other particles and antiparticles. Thus the existence of antimatter is verified daily in laboratories.

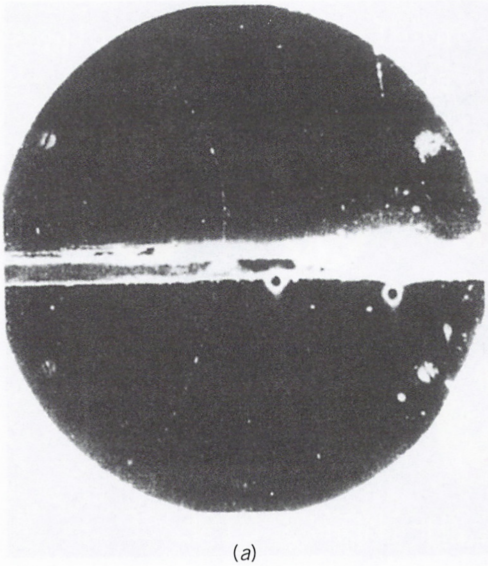
Physics in the Making

The Discovery of Antimatter

In 1932, Carl Anderson, a young physicist at the California Institute of Technology, performed a rather straightforward cosmic ray experiment of the type described in this chapter. Cosmic rays entered a type of detector called a "cloud chamber." In Anderson's cloud chamber, a cosmic ray particle would move through a moisture-laden gas, leaving behind a string of ions. Pulling out a piston at the bottom of the chamber lowered the gas pressure, causing the liquid (usually alcohol) that had been in gaseous form to condense out into droplets. The ions acted as nuclei for the condensation of these droplets, so that the path of the particle was marked by a string of droplets in the chamber.

The key innovation in Anderson's experiment was the positioning of the cloud chamber between the poles of powerful magnets. These magnets caused electrically charged cosmic rays to move in curved tracks, with the amount of curving dependent on the particle's mass, speed, and charge. Furthermore, the tracks of positively and negatively charged particles curved in opposite directions under the influence of the magnetic field.

Soon after he switched on his apparatus, Anderson saw tracks of particles whose mass seemed to be identical to that of the electron, but whose tracks curved in the opposite direction from those of electrons being detected (Figure 27-4). This feature, he concluded, had to be the result of a "positive electron," a phrase he contracted to *positron.* Although no one realized it at the time, Anderson was the first human being to see antimatter.



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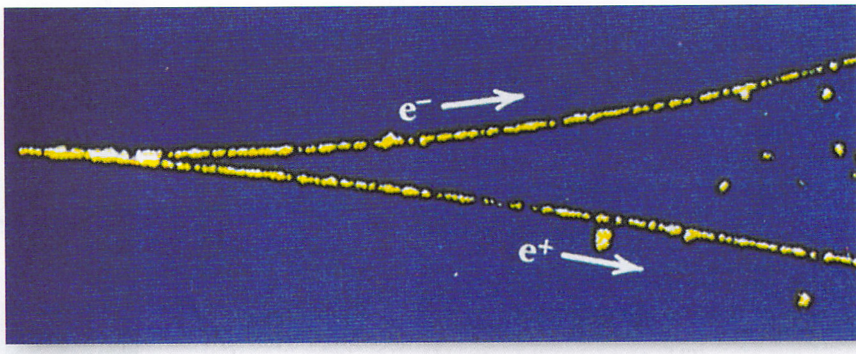


(b)

FIGURE 27-4. Carl Anderson identified the positron (the antiparticle of the electron) from the distinctively curved path left in a bubble chamber. In Anderson's original photograph (*a*) the positron path curves upward and to the left. In a more recent photograph (*b*) an electron (e^-) and a positron (e^+) curve in opposite directions in a magnetic field.

Develop Your Intuition: Curved Particle Tracks

How might Anderson have interpreted his results if he had seen tracks of particles curving in the same direction as the electrons' tracks, but curving a different amount? (*Hint:* Remember Newton's second law of motion.)

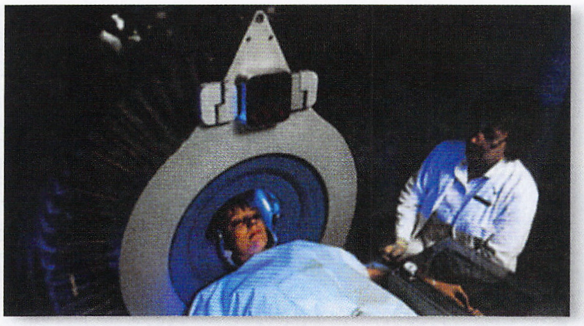
The direction of curvature in a magnetic field depends on the sign of the particle's electric charge, as we have seen in Chapter 16. If the track curves in the same direction as electrons' track, it must have the same sign of charge; that is, negative charge. However, the amount of curvature—that is, the change in velocity, or acceleration—depends on the mass and velocity of the particle. If we assume the particle has the same speed as the electron, and if we assume the particle track curves more than that of an electron, the particle must have a larger acceleration for the same amount of magnetic force; that is, the particle must have less mass than an electron has. If the track curves less than that of an electron, the particle must have more mass than the electron has. Anderson would have discovered a new particle, but not the positron.

Connection

How Does the Brain Work?

The study of elementary particles often seems quite abstract, but situations do arise where elementary particles play a very important role in understanding the real world. The relatively recent technology of *positron emission tomography (PET)*, for example, is helping scientists probe the mysterious workings of the brain.

In this medical technique, molecules such as glucose (a sugar that the body uses to provide energy for its cells) are created using an unstable isotope of an element such as oxygen and then are injected into a patient's bloodstream. Organs in the body, including the brain, take up these molecules. They go to the



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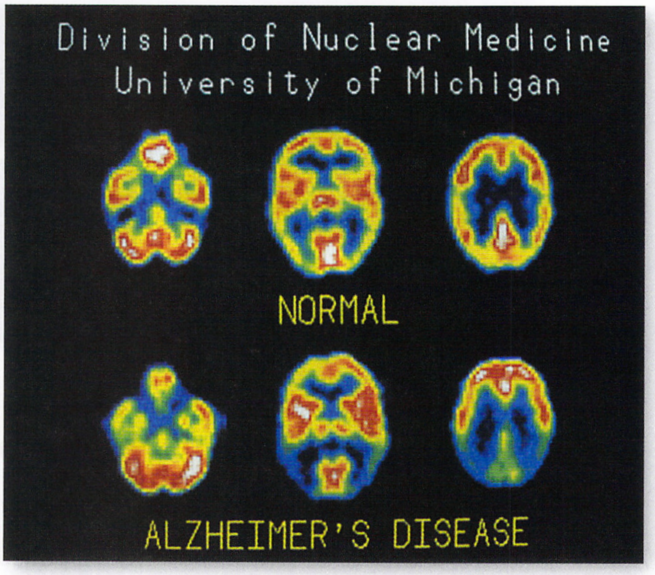


(b)

FIGURE 27-5. Positron emission tomography, commonly called the PET scan, reveals activity in the human brain. (*a*) A patient undergoing a PET scan. (*b*) Scans of a normal brain reveal bright spots where large amounts of glucose are being used by the brain. By contrast, a scan of a person suffering from Alzheimer's disease shows decreased brain activity.

parts of the brain that need glucose; that is, the parts that require extra energy at the time (see Figure 27-5).

The isotopes chosen for this technique are ones that emit a positron, the antiparticle of an electron, when they decay. These positrons quickly "annihilate" with ordinary electrons in the surrounding tissue, emitting two gamma rays that are relatively easy to detect from outside the body. A PET scan works like this: After the radioactive glucose is injected into the bloodstream, the patient is asked to do something—talk, read, do mathematical problems, or just relax. Each of these activities uses a different region of the brain. Scientists watching the emission of positrons can see those regions of the brain light up as they are used. In this way, scientists use antimatter to study the normal working of the human brain without disturbing the patient, as well as to detect and study abnormalities that can perhaps be treated. ●

QUARKS

When chemists understood that the chemical elements could be arranged in the periodic table, it wasn't long before they realized what caused this regularity. Atoms of different chemical elements were not elementary, as Dalton had suggested, but were structures made up of things more elementary still. The same thing is true of the hundreds of elementary hadrons, or nuclear particles. They are not themselves elementary, but are made up of units more elementary still—units that are given the name **quark** (pronounced "quork"). First suggested in the late 1960s by American physicist Murray Gell-Mann, quarks have come to be accepted by physicists as *the* fundamental building blocks of hadrons. Even though they never have been (and probably cannot be) isolated in the laboratory, the concept of quarks has brought order and predictability to the complex zoo of elementary particles. (It is important to remember that only hadrons, not leptons, are made from quarks.)

Quarks are different from other elementary particles in several ways. Unlike any other known particle, they have fractional electric charge, equal to $\pm\frac{1}{3}$ or $\pm\frac{2}{3}$ the charge on an electron or proton. In this model of matter, quarks in pairs or triplets make up all the hadrons, but once they are locked into these particles, no amount of experimental machination can ever pry them loose. Quarks existed as free particles only briefly in the very first stages of the universe (see Chapter 29).

In spite of these strange properties, the quark picture of matter is a very appealing one. Why? Because instead of our having to deal with dozens of different hadrons, all atomic nuclei are reduced to only six kinds of quarks (and six antiquarks). The quarks, like many things in elementary-particle physics, have been given fanciful names: up, down, strange, charm, top, and bottom (see Table 27-2). Physicists have seen evidence for elementary particles that contain all these six quarks, although only as pairs or triplets in any single particle.

From these six simple particles, all of the hadrons that we know about—all those hundreds of particles that whiz around inside the nucleus—can be made. The proton, for example, is the combination of two up quarks and one down quark, while the neutron is the combination of two down quarks and one up quark. In this scheme, the charge on the proton, equal to the sum of the charges on its three quarks, is

$$\frac{2}{3} + \frac{2}{3} + \left(-\frac{1}{3}\right) = +1$$

while the charge on the neutron is

$$\frac{2}{3} + \left(-\frac{1}{3}\right) + \left(-\frac{1}{3}\right) = 0$$

In the more exotic particles, pairs of quarks circle one another in orbit, like some impossibly tiny star system.

TABLE 27-2 Quark Properties

Name of Quark	Symbol	Electric Charge[a]
Down	d	$-\frac{1}{3}$
Up	u	$+\frac{2}{3}$
Strange	s	$-\frac{1}{3}$
Charm	c	$+\frac{2}{3}$
Bottom	b	$-\frac{1}{3}$
Top	t	$+\frac{2}{3}$

[a]Quarks with the same charge differ from one another in mass and other properties.

Develop Your Intuition: The Quark Model

Hadrons can be categorized into two families of particles: baryons, which consist of three quarks, and mesons which consist of a quark and an antiquark. The xi baryon (*xi* is a Greek letter) is made of two strange quarks and one up quark. The K meson is made of an up quark and a strange antiquark. What are the charges of these particles?

For the xi particle, we can look up the charges of the three quarks in Table 27-2 and add them together. We get

$$\frac{2}{3} + \left(-\frac{1}{3}\right) + \left(-\frac{1}{3}\right) = 0$$

The xi baryon is neutral; it has no electric charge. For the K meson, we have to remember that an antiquark has the opposite charge of its corresponding quark. The strange quark has a charge of $-\frac{1}{3}$, so the strange antiquark must have a charge of $+\frac{1}{3}$. Adding the two charges, we get

$$\frac{2}{3} + \frac{1}{3} = 1$$

This particular K meson has a charge of +1, the same as the proton.

Quarks and Leptons

The quark model gives us a picture of the universe that restores the kind of simplicity that was brought by both Dalton's atoms and Rutherford's nucleus. All the elementary particles in the nucleus are made from various combinations of six kinds of quarks and their antiquarks. These elementary particles are then put together to make the nuclei of atoms. The six different leptons—primarily the electrons—are located outside the nucleus. Different atoms interact with one another to produce what we see in the universe. In this scheme, the quarks and leptons are the letters of the universe; they are the basic stuff from which everything else is made. The fact that there are six leptons and six quarks has not escaped the notice of physicists. This phenomenon is built into almost all theories of elementary particles. The question of *why* nature should be arranged this way remains unanswered.

Quark Confinement

It would be nice to be able to study individual quarks in the laboratory, and physicists have conducted extensive searches for them. Yet there has been no generally accepted experimental isolation of a quark, and many particle theorists suspect that quarks can never be pried loose from confinement within a hadron. In these theories, once a quark has been taken up into a particle, it can move from one particle to another during a nuclear reaction but it can never escape confinement in a hadron and be isolated from other quarks.

You can hit elementary particles as hard as you like in an attempt to shake the quarks loose, but every time you start to pull out a quark, you've also supplied enough energy to the system to make more quarks and antiquarks, and those new quarks are immediately taken up into ordinary hadrons. If you hit one particle hard enough, you wind up with lots of other elementary particles.

THE FOUR FUNDAMENTAL FORCES

In our excursion into the library, finding the letters of the alphabet wasn't enough to explain what we saw. We had to know the rules of spelling and grammar by which letters are converted into words and words made into books. In the same way, if we are going to understand the fundamental nature of the universe, we have to understand not only the quarks and leptons, but also the forces that influence them and make them behave the way they do.

One useful analogy is to think of the quarks and leptons as the bricks of the universe. The universe appears to be built of these two different kinds of bricks that are arranged in different ways to make everything we see. But you cannot build a house using bricks alone. There has to be something like mortar to hold the bricks together. The mortar of the universe—the things that hold the elementary particles together and organize the physical universe into the structures we know—are the forces. At the moment, we know of only four fundamental forces in nature. Two of these, *gravity* (Chapter 5) and *electromagnetism* (Chapter 17), were known to nineteenth-century physicists and are part of our everyday experience. They are forces with infinite range—that is, objects such as stars and planets can exert these forces on one another even though they are very far apart.

The other two forces are less familiar to us because they operate in the realm of the nucleus and the elementary particles. They have a range comparable to the size of the nucleus (or smaller) and hence play no role in our everyday experience. The *strong force* holds the nucleus together, while the *weak force* is responsible for processes such as beta decay (see Chapter 26) that tear nuclei and elementary particles apart.

Each of the four fundamental forces is different from the others in strength and range (see Table 27-3). The important point about the four forces is that whenever anything happens in the universe, whenever an object changes its motion, it happens because one or more of these forces is acting.

Force as an Exchange

We know that forces cause matter to accelerate—nothing happens without a force. We know of four: the gravitational force, the electromagnetic force, the strong force, and the weak force. Each has its own distinctive effects on nature. We have not, however, asked how these forces work.

TABLE 27-3 The Four Forces

Force	Relative Strength[a]	Range	Gauge Particles
Gravity	10^{-39}	Infinite	Graviton
Electromagnetic force	$\frac{1}{137}$	Infinite	Photon
Strong force	1	10^{-13} cm	Gluon
Weak force	10^{-5}	10^{-15} cm	W and Z

[a]Relative to the strong force.

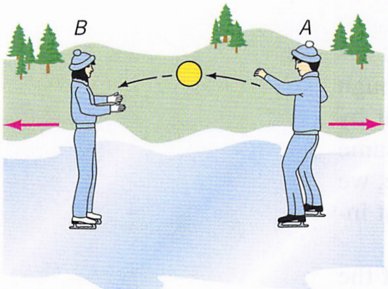


FIGURE 27-6 The exchange of a ball between two skaters provides an analogy for the exchange of a gauge particle. Skater A, who throws the ball, recoils, and skater B recoils when the ball reaches her. Thus both skaters change velocity, and, by Newton's first law, we say that a force acts between them.

The modern understanding of forces may be thought of schematically as illustrated in Figure 27-6. Every force between two particles corresponds to the exchange of a third kind of particle, called a *gauge particle* for historical reasons. That is, a first particle (an electron, for example) interacts with a second particle (say, another electron) by the exchange of a gauge particle. The gauge particles produce the fundamental forces, such as electricity, that hold everything together.

In Chapter 4 we used the analogy of someone standing on skates throwing baseballs to explain Newton's third law of motion. Suppose a person on skates throws a baseball, and another person standing on skates catches the baseball some distance away. The person who threw the baseball would recoil, as we have discussed. The person who subsequently caught the baseball would also recoil. We can describe the situation this way: Two people stand still before anything happens. After some time, the two people are moving away from each other. From Newton's first law, we conclude that a repulsive force has acted between those two people. Yet it's very clear in this analogy that the repulsive force is intimately connected with (a physicist would say "mediated by") the exchange of the baseball.

In just the same way, we believe that every fundamental force is mediated by the exchange of some kind of gauge particle (Figure 27-7). For example, the electromagnetic force is mediated by the exchange of photons. That is, for example, the magnet holding notes onto your refrigerator is exchanging huge numbers of photons with atoms inside the refrigerator metal to generate the magnetic force.

In the same way, the gravitational force is mediated by particles called "gravitons." Right now you are exchanging large numbers of gravitons with Earth, an exchange that prevents you from floating up into space. The four fundamental forces and the gauge particles that are exchanged to generate each of them are listed in Table 27-3.

The two familiar forces of gravity and electromagnetism act over long distances because they are mediated by massless, uncharged particles (of which the

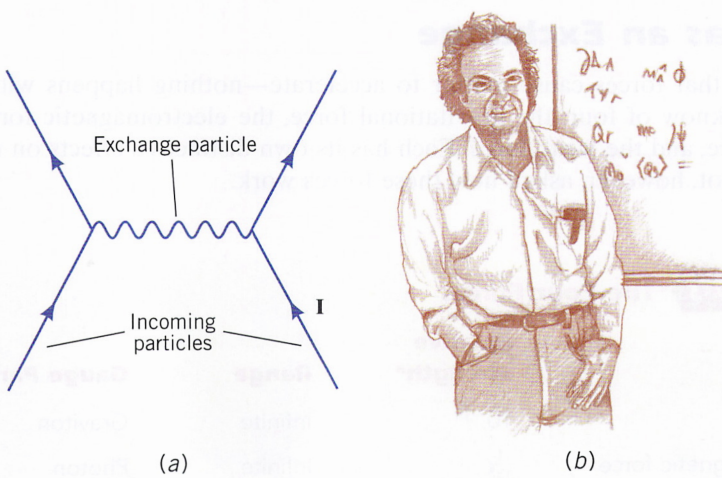


FIGURE 27-7 (*a*) Exchange diagrams, introduced by physicist Richard Feynman, provide a model for particle interactions and the fundamental forces. Two incoming particles (such as two electrons) exchange a gauge particle (a photon) and thus are deflected by the force. (*b*) Richard Feynman (1918–1988) was one of the greatest physicists and physics teachers of the twentieth century.

familiar photon is one). The weak interaction, on the other hand, has a short range because it is mediated by the exchange of very massive particles—the *W* and *Z particles*—that have masses about 80 times that of the proton. Like the photon, the W and Z are particles that can be seen in the laboratory—they were first discovered in 1983 and are now routinely produced at accelerators around the world.

The situation with the strong force is a bit more complicated. The force that holds quarks together is mediated by particles called *gluons* (they glue the hadrons together). These particles are supposed to be massless, like the photon; but, like the quarks, they are confined to the interior of particles.

Unified Field Theories

Although a universe with six kinds of quarks, six kinds of leptons, and four kinds of forces may seem to be a relatively simple one, physicists have discovered an even greater underlying simplicity. The four fundamental forces turn out not to be as different from one another as their properties might at first suggest. The current thinking is that all four of these fundamental forces may simply be different aspects of a single underlying force.

Some physicists suggest that the four forces appear to be different because we are observing them at a time when the universe has been around for a long time and is at a relatively low temperature. The situation is somewhat analogous to freezing water. When water freezes, it can adopt many apparently different forms—powdered white snow, solid ice blocks, delicate hoarfrost on tree branches, and a smooth, slippery layer on the sidewalk. You might interpret these forms of frozen water as very different things, and in some respects they are distinct. But heat them up and they are all simply water.

Similarly, the four forces look different at the relatively low temperatures of our present existence. However, if you could heat matter up to trillions of degrees, then the different forces would not appear different at all. Theories in which fundamental forces are seen as different aspects of one force are called **unified field theories.**

The first unified field theory in history was Isaac Newton's synthesis of Earthly gravity and the circular motions observed in the heavens. To medieval philosophers, Earthly and heavenly motions seemed as different as the strong and electromagnetic forces do to us. Nevertheless, they were unified in Newton's theory of universal gravitation. In the same way, physicists today are working to unify the four fundamental forces.

The general idea of these theories is that if the temperature can be raised high enough—that is, if enough energy can be pumped into an elementary particle—the underlying unity of the forces will become clear. At a few laboratories around the world, it is possible to take protons and antiprotons (or electrons and positrons), accelerate them to extremely high energies, and let them collide. (As we have noted, proton–antiproton collisions involve the process of annihilation between particle and antiparticle as well as an ordinary collision.) When these collisions occur, for a brief moment the temperature in the volume of space about the size of a proton is raised to temperatures that have not been seen in the universe since it was less than 1 second old. In the resulting maelstrom, particles are produced that can be accounted for only if the electromagnetic and weak forces become unified.

In 1983, experiments at the European Center for Nuclear Research (CERN) and the Stanford Linear Accelerator Center (SLAC) demonstrated that this kind

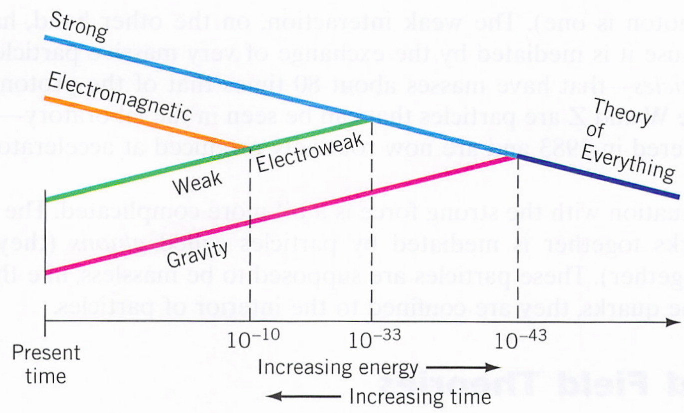


FIGURE 27-8. The four forces become unified at extremely high temperatures, equivalent to those at the beginning of the universe. At 10^{-43} second after the moment of creation, the universe had already cooled sufficiently for gravity to separate from the other three forces. The strong force separated at 10^{-33} second, while the weak and electromagnetic forces separated at 10^{-10} second.

of unification does occur. When protons and antiprotons (at CERN) or electrons and positrons (at SLAC) were accelerated and allowed to collide head-on, W and Z particles were seen in the debris of the collisions. Not only were the reactions seen, but the properties of the resulting particles and their rates of production were exactly those predicted by the first unified field theories.

The expectations of today's physicists regarding the unification of forces can be illustrated in a simple flow diagram (Figure 27-8). Scientists have already seen the unification of the electromagnetic and weak force in their laboratories. The resulting force, which physicists call the *electroweak force,* will be studied in great detail by the next generation of particle accelerators. At much higher energies, energies that will probably never be attained in Earth-based laboratories, we expect the strong force to unify with the electroweak. The theories that make up this prediction constitute the *standard model*—the best model we have today of elementary particles and their interactions. Physicists have accumulated a fair amount of experimental evidence supporting the standard model.

Finally, at still higher energies, we hope to see the force of gravity unify with the strong electroweak force. No theory yet describes this unification successfully, and attempts to develop a successful model are very much a frontier issue. Scientists have, only half in jest, started to refer to theories that combine all four forces as TOEs—*theories of everything.*

THINKING MORE ABOUT

The Theory of Everything

As often happens at a research frontier, many scientists are devoting great effort into finding a theory of everything. Some of them joke about finding the ultimate equation that explains everything, that can be written on the back of an envelope (or, better yet, on a T-shirt). Of several intriguing candidates for this ultimate theory, perhaps the best known is called *string theory.* String theory pictures quarks and leptons as being vibrations on tiny stringlike structures. Experts in this field regard their search for such a theory as the culmination of a 2000-year-old quest for a basic understanding of the universe.

However, other physicists argue that finding a theory of everything, while it would answer questions in particle physics, would not be very useful in other areas. Knowing that a silicon microchip or the Florida Everglades are ultimately made of quarks and leptons doesn't help you much in dealing with practical questions about electronics or the environment. They argue that too much attention is paid to glamorous endeavors such as the search for the ultimate theory and not enough to things that might actually pay off in human terms.

This isn't a conflict between basic and applied research, but between different areas of basic research. How much attention do you think ought to be paid to searching for the solutions to fundamental problems such as the ultimate nature of the universe and how much to basic research into fields such as the study of complex behavior systems? Do you think that there ought to be a limit on how much government support is directed toward theories of everything? Why?

Summary

High-energy physics, or **elementary-particle physics,** deals with bits of matter that we cannot see and with forces and energies totally outside our everyday experience. Nevertheless, the study of the subatomic world holds the key to understanding the structure and organization of the universe.

All matter is made up of atoms, which are made up of even smaller particles—electrons, protons and neutrons—but these are not the most fundamental building blocks of the universe. Physicists originally examined collisions between energetic **cosmic rays** and nuclei to study elementary particles. They now employ **particle accelerators,** including synchrotrons and linear accelerators, to collide charged particles at near-light speeds. These scientists have discovered hundreds of subatomic particles.

One class of particles, the **leptons** (including the electron and neutrino), are not subject to the strong force and thus do not participate in holding the nucleus together. Nuclear particles called **hadrons** (including the proton and neutron), according to present theories, are made from **quarks,** which are particles that have fractional electric charge and cannot exist alone in nature. Together, leptons and quarks are the most fundamental building blocks of matter that we know. Each of these particles has an **antimatter** particle, such as the positron, the positively charged antiparticle of the electron.

The four known forces—gravity, electromagnetism, the strong force, and the weak force—cause particle interactions that lead to all the organized structures we see in the universe. Particle interactions are mediated by the exchange of gauge particles, with a different gauge particle for each of the different forces.

While the four known forces appear to us to be quite different from one another, we believe that early in the universe, when temperatures were extremely high, the four forces were unified into a single force. At the forefront of modern physics research is the search for a **unified field theory** that describes this single force.

Key Terms

antimatter Any substance that annihilates with an equal amount of ordinary matter, resulting in a complete conversion to electromagnetic energy. (p. 590)

cosmic rays High-speed particles (mostly protons) that originate in space and travel throughout the universe. (p. 585)

hadron Any particle that exists within the nucleus of the atom; hadrons interact with the strong force. (p. 589)

high-energy physics or **elementary-particle physics** The study of elementary particles and their properties. (p. 584)

lepton Elementary particle that does not participate in the strong nuclear force; the electron and the neutrino are examples of leptons. (p. 589)

particle accelerator A scientific instrument that increases the speed of charged particles. (p. 586)

quark The fundamental particle that is the building block of all hadrons. (p. 592)

unified field theory A theory that sees the fundamental forces as different aspects of the same force. (p. 597)

Review

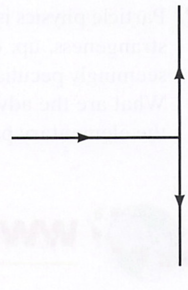
1. What is reductionism?
2. How is the search for elementary particles an example of reductionism? Why is reductionism appealing?
3. What are the fundamental building blocks of a library? Why is there more than one correct answer?
4. Why is "high-energy physics" an appropriate alternative name for "elementary-particle physics"?
5. What are cosmic rays? Where do they come from and how do they interact with matter here on Earth?
6. How were scientists in the 1930s and 1940s able to make use of cosmic rays to study elementary particles? What types of devices did they use to accomplish this?
7. How do scientists detect the presence of subatomic particles? How can charged particles be detected? Uncharged particles?
8. The first particle accelerator was the cyclotron used in the 1930s. What did this device do? Why was it invented and how did it work?
9. What is a synchrotron?
10. How does a linear accelerator differ from a synchrotron?
11. How might you detect the presence of a charged elementary particle?
12. Small particle accelerators can be used to kill cancer cells. How is this done?
13. What are leptons? How do we know they exist?
14. Why are leptons said to be weakly interacting particles?
15. What are hadrons and where are they located?
16. What force are all hadrons subject to?
17. Why are there so many different kinds of hadrons, but only a few kinds of leptons? Are hadrons or leptons more elementary?
18. What observations led Carl Anderson to conclude that he had discovered a particle with the same mass as the electron, but with a positive electric charge?
19. What is antimatter and how do we know it exists?
20. What is a positron? What is its charge and mass?
21. When matter meets antimatter, what happens? What is this called?
22. What is a PET scan? How does it employ elementary particles to enable the activity of a brain to be viewed?
23. Why is it appealing for physicists to think that there are only six kinds of quarks, as opposed to more than 100 hadrons?
24. How do quarks differ from other elementary particles? Is there any way to prove that quarks exist? Explain.
25. What are the similarities in the modern argument over the reality of quarks and the nineteenth-century argument over the reality of atoms? What are the differences?
26. Describe how quarks and leptons are put together to make all the matter we see.
27. What does it mean to say that a quark is "confined"?
28. Name the four fundamental forces. How is it that these forces are often considered the mortar of the universe?
29. What is the strong force? The weak force? Where do these act?
30. Each of the fundamental forces can be considered an exchange of particles. Explain how this could be.
31. What is a gauge particle?
32. What specific particle is exchanged to generate each of the four fundamental forces?
33. How do we know that gravity and electromagnetic force act over enormous distances while the strong and weak forces act only at very short range?
34. What does it mean to say that all four fundamental forces were unified?
35. What is a unified field theory? Give an example.
36. Identify what might be considered the fundamental units and rules of organization of (a) a grocery store and (b) a parking garage. How many levels of organization can you identify? (Remember, not all questions have only one correct answer.)

Questions

1. Which particle–antiparticle interaction releases more energy: an electron–positron annihilation or a proton-antiproton annihilation? How does the law of conservation of energy come into play?
2. Some particle accelerators accelerate particles around in circular paths up to speeds very close to the speed of light. It is advantageous to make the diameters of these circles as large as possible. Why?
3. When an electron and a positron annihilate, they form a pair of photons. Suppose a friend told you that sometimes, instead of two photons, the positron and electron annihilate into a proton and a neutron. Why is this impossible?
4. How many quarks are there in a helium-4 nucleus? How many quarks are there in a carbon-12 nucleus?
5. A neutron is made of three quarks. Is it possible that two up quarks and a down quark could make a neutron? Explain.

6. As a particle passes through a bubble chamber, it leaves tracks. The figure represents the tracks of a particle (moving left to right) that decayed into two particles as it passed through the chamber. One of the particles curved upward in the magnetic field and the other kept going straight. What is the charge of the original particle before it decayed? Explain why these tracks are impossible.

7. A particle moving left to right decays into two other particles. The paths of the particles are shown in the figure. Why could this figure not possibly represent a real situation? (*Hint:* What conservation law is violated?)



Problems

1. Arrange the four fundamental forces according to strength from strongest to weakest. What is the range of each of these forces?
2. What is the electric charge of an antiproton? An antineutron? Why?
3. A hadron called the sigma particle is made from two down quarks and one strange quark. What is the charge of the sigma particle?
4. Are any leptons made up of quarks? Explain.
5. Mesons are made from a quark and an antiquark. A particle called the pi-meson is made from an up quark and an anti-down quark. What is the charge of this particle?
6. A proton and an antiproton, both at rest with respect to one another, mutually annihilate into two gamma rays. How much energy is produced in this annihilation? (*Hint:* How are mass and energy related to one another?)
7. One naturally occurring reaction in a radioactive decay process is nitrogen-12 (atomic number 7) decaying into carbon-12 (atomic number 6) plus an unknown particle. What are the properties (atomic mass, atomic number, and charge) of this unknown particle, and how does it compare with the properties of an electron?
8. Some astronomers have theorized that galaxies (matter) and antigalaxies (antimatter) have existed. Each galaxy contains about 10^{11} masses of the Sun (the mass of the Sun is 1.9×10^{30} kg). Calculate the total energy released if a matter–antimatter galaxy pair annihilated.
9. Temperature can be related to energy by the equation $E = \frac{1}{2}kT$, where $k = 1.38 \times 10^{-23}$ J/K and the temperature T is in kelvins. What is the difference in the temperatures generated between an electron–positron annihilation and a proton–neutron annihilation?

Investigations

1. The superconducting supercollider (SSC) was planned to be perhaps the last of the great particle accelerators. The ultimate goal was to see the details of the unification of the weak and electromagnetic forces and, perhaps, to learn why particles have mass. The project was started and then in 1994 was killed when Congress failed to allocate the money for the project after much debate. Discuss the SSC controversy in terms of differences between basic and applied research.
2. How did your congressional representative and senators vote on SSC funding in Congress? Why did they vote that way? Why do you agree or disagree with their vote?
3. Locate the nearest PET-scan facility and arrange a visit. Where do the physicians obtain the special form of glucose used in the procedure? What kind of educational training would you need to operate such a facility?
4. Watch an episode of *Star Trek* and discuss the use of matter and antimatter in the propulsion system of the *Enterprise.* Can you find any other uses of antimatter in science fiction stories?
5. What does it mean that the fundamental building blocks of the universe are things we can never isolate and study? Does that mean they aren't real? You might want to think about the question of the reality of atoms for a historical precedent to this situation.
6. There is a significant amount of information on particle physics and elementary particles available on the Internet. Go to your favorite search engine and type in the keywords "elementary particles" or "high-energy physics." Explore the sites devoted to these topics. What are the major research accelerators throughout the United States and the world? What types of equipment do they have, and what are some of the specific projects they are currently working on? Can you find any good tutorials that help further explain and illustrate the concepts in this chapter?

7. Particle physics is often described with such words as charm, strangeness, up, down, the eightfold way, and many other seemingly peculiar terms for such a serious scientific subject. What are the advantages of using such language to describe the elementary particle zoo? What are, perhaps, some of the disadvantages? Does language make a difference in, say, funding or understandability? Using examples from the world of high-energy physics, comment on the use of this descriptive language.

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.aip.org/history/lawrence/** The history of the original accelerator and its inventor from the American Institute of Physics.
2. **http://particleadventure.org/particleadventure/** The *CPEP Particle Adventure*—the best, most lavish site for particle physics education, by Lawrence Berkeley National Laboratory.