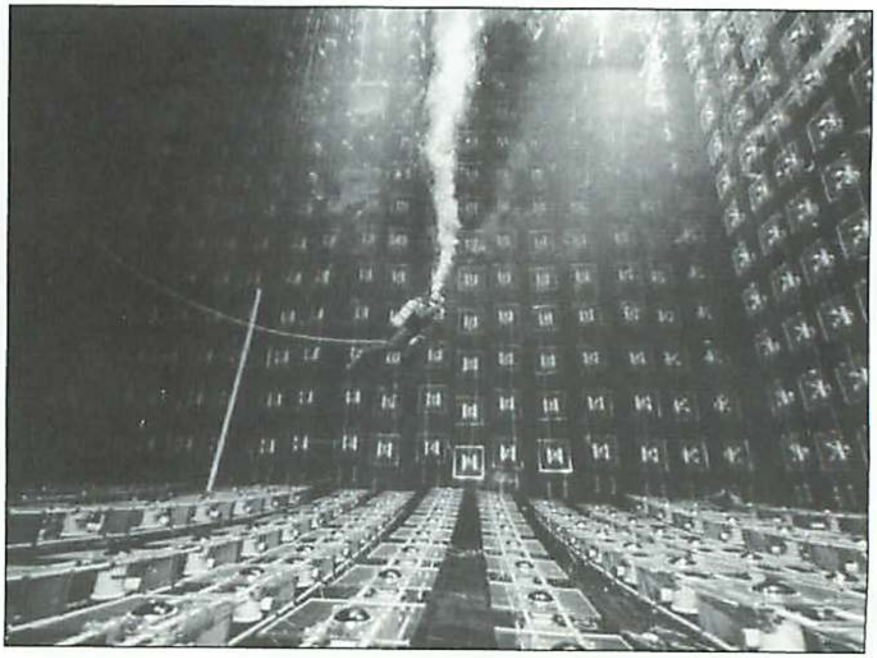
14 Elementary Particles

Quantum mechanics solved the riddles of atomic and nuclear structure. The Schrödinger equation explained the fundamental processes underlying chemistry, material science, geology, and biology. It described nuclei well enough for scientists to work toward safe and secure nuclear power and for doctors to make use of radioisotopes and nuclear magnetism. The physical principles underlying today's technological society have been known for 50 years, but the search for the ultimate building blocks of matter blazes onward. Many "elementary particles" have been found. What are they, what laws do they obey, and how are they related to neutrons and protons? How and why do stars shine? Why



Is matter eternal or will it eventually disappear by a process analogous to radioactivity? An experiment performed in a salt mine deep under Lake Erie proved that the half-life of matter is greater than 10^{31} y. A tank containing 8000 tons of pure water was surrounded by sensitive electronic "eyes" that could detect the decay of a single nucleon. No events were seen, but an even larger experiment is now being deployed in Japan. *Source:* IMB Collaboration/Courtesy, L. Sulak.

are there stars and galaxies, and what happens when stars explode and galaxies collide? Where did the chemical elements come from? How did the universe begin and how will it end? What are the limits of human knowledge? We are headed toward a unified theory of all physical laws and have partial answers to all but the last question. The synthesis of quantum mechanics and special relativity is called quantum field theory. Particles and forces are not independent concepts: Both are included in the concept of quantum fields. Relativistic quantum mechanics describes atoms and electrons to ten-decimal-place precision. Its success has led physicists toward a consistent theory of all the particles and forces of nature, but the road has been full of surprises.

As we plunge deeper into the structure of matter, we shall learn about particles with funny names that are not parts of atoms. Many new particles were discovered by physicists studying the interactions of cosmic rays, which are energetic particles traveling between the stars that occasionally strike Earth. Positrons were discovered in 1932; pions, muons, and "strange particles" a few years later. These particles have been the keys to our understanding of the structure of matter. (Today, positrons are used for medical imaging and pions for radiation therapy.) Section 14.1 describes the prediction and discovery of antimatter and the development of relativistic quantum mechanics. *Quantum electrodynamics,* the theory of electrons and light, has served as a paradigm for today's theory of all elementary particle phenomena. Section 14.2 applies what we have learned to the properties of subnuclear particles. Section 14.3 is an optional digression about the new science of neutrino astronomy.

14.1 The Marriage of Quantum Mechanics and Relativity

Quantum theory, as originally put forward, explained the gross features of the hydrogen spectrum but not its details. Furthermore, the Pauli exclusion principle and the existence of electron spin were not consequences of the theory. They had to be put in by hand if atomic structure were to be understood. Both difficulties reflect the failure of the Schrödinger equation to be consistent with the special theory of relativity.

Because the speed of an atomic electron is about $0.01c$, relativistic effects on atoms are small and can often be neglected. Nonetheless, to obtain a complete and precise description of atomic phenomena, physicists needed a replacement for the Schrödinger equation. Schrödinger himself, in his seminal papers of 1926, had searched for a relativistic equation for the electron but in the end settled for a nonrelativistic approximation. A relativistic generalization of the Schrödinger equation, the *Klein–Gordon equation,* was later developed to describe the behavior of relativistic particles without spin. Particles of this kind were discovered in the 1940s and their behavior is described by the Klein–Gordon equation. A different kind of equation, however, had to be found to deal with spin 1/2 electrons.

Pauli devised a clever way to treat the spinning electron. In Chapter 11, we learned that a measurement of the component of electron spin along any axis must yield the value $\hbar/2$ (an electron spinning "up") or $-\hbar/2$ (an electron spinning "down"). Pauli introduced two wave functions to describe the electron: $\psi_{\rm up}$ for an electron spinning up and $\psi_{\rm down}$ for an electron spinning down. These were combined to form a unified two-component wave function:

$$\Psi = \begin{pmatrix} \psi_{\rm up} \\ \psi_{\rm down} \end{pmatrix}$$

If $\psi_{\rm down} = 0$, the electron spin points up. If $\psi_{\rm up} = 0$, its spin is down. If neither component vanishes, Ψ describes an electron spinning in another direction, where $|\psi_{\rm up}|^2$ is the probability that its spin points up, and $|\psi_{\rm down}|^2$ is the probability that its spin points down. In the absence of a magnetic field, the components of the electron's wave function each satisfy the Schrödinger equation. However, magnetic forces can change the direction of the electron's spin and thereby mix up the two components.

The Klein–Gordon equation is consistent with relativity, but it cannot describe spin. The Pauli equation describes the effect of electromagnetic fields on a slowly moving electron, but it is not relativistic. In 1928, the English physicist Paul Adrien Maurice Dirac (1902–1984) found the relativistic equation for a spin 1/2 electron, the *Dirac equation*. Electron spin is built into Dirac's equation from the start. Furthermore, the equation predicted the existence of *antimatter* and led to the realization that particles could be created and destroyed.

The Dirac Equation

The Dirac equation can be described as the square root of the Klein–Gordon equation. However, the square roots of equations (like those of negative numbers) involve new mathematical concepts. Dirac was led to a wave function of the electron with four components that automatically included a description of electron spin. Maxwell's equations say that a spinning electric charge produces a magnetic field, so a spinning electron should behave like a tiny magnet. Dirac's quantum-mechanical equation predicted the strength of the electron's built-in magnetism—its magnetic moment. The equation applies both to the details of atomic spectroscopy and to the scattering of high-energy electrons.

Some of the solutions of the Dirac equation described the observed behavior of electrons. Other solutions, however, seemed to describe electrons in states of negative energy. If such states existed, one would expect an electron in a positive-energy state to jump to a negative-energy state by emitting a photon. It could then jump to a state of even lower energy by emitting another photon, and so on and on. The world would blow up in a cascade of photons! Dirac, who often expressed the sentiment that his equation was smarter than he was, pondered:

> The problem of the negative-energy states puzzled me for quite a while. The main method of attack to begin with was to try to find some way to avoid the transitions to negative-energy states, but then I approached the question from a different point of view. I was reconciled to the fact that the negative-energy states could not be excluded from the mathematical theory, or so I thought, so let us try to find a physical explanation for them.

To do this, Dirac invoked the Pauli exclusion principle. He proposed that the vacuum is not empty, but instead is chock-full of negative-energy electrons. He likened the universe to a gigantic atom of an inert gas with all of its quantum shells filled by negative-energy electrons. According to the exclusion principle, none of the negative-energy electrons can do anything because all the negative-energy states are occupied to begin with.

Suppose that one of the particles in Dirac's sea of negative-energy electrons is struck by an energetic particle and driven to a positive-energy state. A vacant space or "hole" would be left in Dirac's "sea." Because a hole is the absence of a negatively charged particle, the hole should behave as if it were a particle of positive charge. Dirac wondered whether protons could be holes in an otherwise full sea. In that case, a single equation could treat both protons and electrons, which were then all of the known elementary particles. Dirac soon saw his error. His equation does describe two different kinds of particles, but they are not electrons and protons. The Dirac equation implies the existence of a particle that is not ordinarily found on Earth—the positron.

Dirac was wrong about the sea of negative-energy electrons as well. His equation was correct, but its interpretation is simpler and more subtle than he first thought. As the theory of relativistic quantum mechanics developed, physicists realized that the hypothesis of a vacuum filled with negative-energy electrons was a superfluous scaffold, like the ether had been a generation before. American physicist Robert J. Oppenheimer (1904–1964), who later became the leader of America's atomic weapons program, found that the extra solutions of Dirac's equation do not describe negative-energy states of negatively charged electrons. Rather, they describe positive-energy states of positively charged electrons. These new particles would later be found and given the name *positrons*. Furthermore, Oppenheimer showed, positrons could not be protons, which are almost 2000 times heavier than electrons. He proved that the electron and positron masses must be the same. By 1930, Dirac, Oppenheimer, and the small band of particle theorists agreed that the four components of the Dirac wave function corresponded to electrons and positrons spinning up or down: $e^-\uparrow$, $e^-\downarrow$, $e^+\uparrow$ and $e^+\downarrow$. At the time, nobody had seen a positron, and hardly any experimental physicists took the wild-sounding theoretical ideas of Dirac and Oppenheimer seriously.

A BIT MORE ABOUT
Cosmic Rays

The differences between relativistic and nonrelativistic quantum mechanics are most striking for collisions of energetic particles with velocities near c. Until the advent of particle accelerators, the heavens were the only source of relativistic particles: They were called *cosmic rays* and were discovered by the Austrian physicist Victor F. Hess. In 1912, he wrote: "The results to my [balloon] observations are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above." In the 1920s, Millikan used a cloud chamber to study these peculiar radiations. He confirmed that cosmic rays came from outer space and sometimes penetrated to Earth's surface and below. He believed they were γ rays (energetic photons) released by the nuclear fusion of hydrogen atoms in interstellar space and described them as the birth cries of newly formed atoms. Millikan was wrong. Nuclear fusion takes place deep within stars, not in space. Fusion makes stars shine but does not produce cosmic rays. Later experiments showed that primary cosmic rays (those incident on the atmosphere) are charged particles consisting of energetic protons with a smattering of larger nuclei. Their source lies somewhere outside the solar system but inside the Milky Way. Cosmic ray particles may have been accelerated by interstellar magnetic fields or perhaps are the relics of ancient stellar catastrophes. However important cosmic rays have been in the history of physics, their origin is not yet fully understood.

When cosmic rays collide with nitrogen or oxygen nuclei in the atmosphere, they produce many different kinds of particles. For decades, cosmic ray collisions were the only tiny window into the world of high-energy phenomena. Positrons were discovered among the debris of cosmic ray interactions, as were many other so-called elementary particles.

The Discovery of Positrons

Positrons were first observed in 1932 by the American physicist Carl David Anderson (1905–1991). Anderson studied cosmic rays at the insistence of Millikan, his research advisor. To view the rays, Anderson built a cloud chamber (which he later described to the media as "nothing much but a sealed tube full of water vapor under low pressure") surrounded by a large magnet. Cosmic rays traversing the chamber left tracks of water droplets. The horizontal magnetic field bent the particle trajectories into helices that turned one way if the particle was positively charged, the other way if negatively charged. In his first experiment, Anderson observed as many particles turning one way as the other. It seemed that there were as many negatively charged particles among the sea-level cosmic rays as there were positively charged particles. Were they electrons and protons, or were they something else?

EXAMPLE 14.1 The Motion of a Charged Particle in a Magnetic Field

A charged particle moves horizontally in a region of constant vertical magnetic field **B** (Figure 14.1). Its mass is m, its charge is q, and its velocity is **v**. Recall from Chapter 9 that the particle experiences a horizontal magnetic force $F = qvB$ in the direction perpendicular to **v**. Its effect is to change the direction of **v** but not its magnitude. Consequently, the particle describes a circular orbit at constant speed v.

a. Express the radius of the orbit R in terms of q, B, and the momentum of the particle ($\mathbf{p} = m\mathbf{v}$, if the particle is nonrelativistic).

b. In Anderson's experiment, the strength of the magnetic field was 7.5 tesla. Most of the cosmic ray particles Anderson observed had momenta from 30 MeV/c to 300 MeV/c. If the particles were moving horizontally, what were the radii of their circular orbits?

Solution

a. The centripetal acceleration of a particle moving in a circle of radius R at speed v is v^2/R. Setting the magnetic force qvB equal to the mass m of the particle times its acceleration, we obtain $mv^2/R = qvB$, or $R = mv/qB$. Thus, we obtain the desired relation: $R = p/qB$. This formula is correct for relativistic particles if the relativistic formula for momentum is used: $\mathbf{p} = m\mathbf{v}/\sqrt{(1 - v^2/c^2)}$.

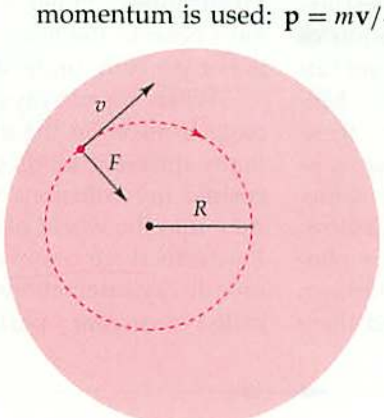


FIGURE 14.1
A positively charged particle moves at speed v through the shaded region, where there is a magnetic field B pointing into the page. The particle experiences a force F perpendicular to its velocity. Therefore, it moves in a circle. The magnetic force is qvB, where q is the charge of the particle. The orbital radius R is proportional to the momentum of the particle and inversely proportional to the magnetic field strength.

b. We are given the particle momenta in MeV/c. Because 1 MeV = 1.6×10^{-13} J, it follows that 1 MeV/c = $(1.6 \times 10^{-13})/(3 \times 10^{8})$ kg m/s. If the particle is singly charged, we put $q = e = 1.6 \times 10^{-19}$ C into the result of part a to obtain

$$R = \frac{p \text{ (in kg m/s)}}{eB} = \frac{1}{300}\frac{p \text{ (in MeV/}c\text{)}}{B}$$

Thus, the radius of the circular orbit of a 30 MeV/c particle is about 1.3 cm, and that of a 300 MeV/c particle is about 13 cm. ■

When particle momenta are large, the tracks left by protons or electrons in the chamber are indistinguishable. However, heavy particles with small momenta leave more ions in their wakes than light ones, thereby making broader tracks. Anderson focused on the tracks left by slow particles that bent the most in the magnetic field. He could tell which of these were made by heavy protons and which were made by less massive electrons. In 1982, Anderson reminisced:*

> Practically all of the low-velocity cases involved particles whose masses seemed to be too small to permit their interpretation as protons. The alternative explanations were that these particles were either electrons moving upward or some unknown lightweight particles moving downward. In the spirit of scientific conservatism, we tended at first to the former interpretation."

The track of a positive particle going down looks the same as that of a negative particle going up. To prove that he had seen a new kind of particle, Anderson had to find a way to determine the direction of a particle leaving a track. His act of genius was to divide the cloud chamber into two parts with a metal partition. As we saw in Example 14.1, the smaller the momentum of a particle, the more it curves in a magnetic field. When a charged particle passed through the partition, it lost energy, slowed down, curved more, and thereby revealed its direction of motion, as shown in the photo.

The first observed positron was traveling up rather than down, as most cosmic rays travel. It entered the bottom of Anderson's cloud chamber with an energy of 63 MeV, passed through a 6-mm lead plate, and emerged with an energy of 23 MeV. Notice how much more curved the trajectory becomes afterward. *Source:* Photo by C.D. Anderson/Courtesy AIP Emilio Segre Visual Archives.

***The Birth of Particle Physics*, ed. L. M. Brown and L. Hoddison (Cambridge, England: Cambridge University Press, 1983), 139–140.

> A lead plate was inserted across the center of the chamber in order to ascertain the direction in which these low-velocity particles were travelling and to distinguish between upward-moving negatives and downward-moving positives. It was not long after that a fine example was obtained in which a low-energy lightweight particle of positive charge was observed to traverse the plate, entering the chamber from below and moving upward through the lead plate. Ionization and curvature measurements clearly showed this particle to have a mass much smaller than that of a proton and, indeed, a mass entirely consistent with an electron mass.

Anderson saw many other positively charged, low-mass particles and proved they were positrons. Dirac's predicted particle had been found, but Anderson had not been guided by Dirac's theory:

> It has often been stated that the discovery of the positron was a consequence of its theoretical prediction by Dirac, but this is not true. The discovery of the positron was wholly accidental. Despite the fact that Dirac's relativistic theory of the electron was an excellent theory of the positron, and despite the fact that the existence of this theory was well known to nearly all physicists, including myself, it played no part whatsoever in the discovery of the positron.

At other times, Anderson remarked: "I was too busy operating this piece of equipment to read [Dirac's] papers," and in any case, "their esoteric character was not in tune with most of the scientific thinking of the day."

Where did the positrons come from? Not from outer space. Primary cosmic radiation (that is, cosmic rays that have not yet struck the atmosphere) consists of protons and larger nuclei. Positrons are the secondary or tertiary by-products of primary collisions with atomic nuclei in the upper atmosphere. A cosmic ray proton strikes a nucleus and produces many particles, each of which makes more collisions and even more particles. Some of these cascading particles are fragments of struck nuclei, but most of them are brand-new particles.

In everyday experience, and even within the atom and its nucleus, particles move slowly compared to c, and their kinetic energies are much smaller than their rest energies. Cosmic rays, however, often have kinetic energies far greater than their rest energies, energies so large that new particles are created by their collisions. If an energetic photon strikes a proton or an electron at rest, it cannot create a single electron or positron because such a reaction would violate charge conservation. But the collision can produce a pair of particles consisting of an electron e^- and a positron e^+:

$$\gamma + p \longrightarrow p + e^- + e^+ \tag{1a}$$

$$\gamma + e^- \longrightarrow e^- + e^- + e^+ \tag{1b}$$

The creation of particles in high-energy collisions is the gist of high-energy physics.

EXAMPLE 14.2 Pair Production The mass of the electron is $m = 0.511\ \text{MeV}/c^2$. The mass of the initially stationary proton is $M = 938\ \text{MeV}/c^2$.

a. What is the minimum photon energy E for reaction (1a) to take place?

b. What is the minimum photon energy for reaction (1b) to take place?

Solution **a.** The invariant energy (see Chapter 11) of the initial state is $\sqrt{(E + Mc^2)^2 - E^2}$. The invariant energy of the final state is at least the sum of the rest energies of the proton (Mc^2), the electron (mc^2), and the positron (another mc^2). Because the invariant energy of an isolated system cannot change, reaction (1a) can take place if

$$\begin{aligned}\sqrt{(E + Mc^2)^2 - E^2} &> Mc^2 + 2mc^2 \\ \text{or} \quad (E + Mc^2)^2 - E^2 &> (M^2 + 4mM + 4m^2)c^4 \\ \text{or} \quad 2Mc^2E &> 4mc^4(M + m) \\ \text{or} \quad E &> 2mc^2(1 + m/M)\end{aligned}$$

We use $mc^2 = 0.511$ MeV and $m/M = 0.0005$ to obtain an explicit answer: $E \simeq 1.02$ MeV.

b. The preceding analysis applies to this case as well. All we need do is replace M by m in the formula for E. We obtain $E = 4mc^2 \simeq 2.04$ MeV. The minimum photon energy is about twice as large for reaction (1b) as for reaction (1a). ■

What happens to positrons once they are made? A physics lab (and any other place) contains loads of electrons but hardly any positrons. A newborn positron is surrounded by hordes of electrons. If the positron is moving slowly, it can combine with an electron to form a structure much like an atom, called a *positronium*, in which the positron plays the role of the proton. This curious system is short-lived because the electron and positron soon annihilate each other. With a half-life of a microsecond or less, the positronium "atom" disappears and is replaced by two or three photons. The annihilation reactions may be written:

$$e^+ + e^- \longrightarrow \gamma + \gamma \qquad \text{or} \qquad e^+ + e^- \longrightarrow \gamma + \gamma + \gamma \tag{2}$$

Despite its short lifetime, the positronium "atom" has been carefully studied and has provided some of the most sensitive tests of quantum electrodynamics.

Antiparticles

The positron is called the *antiparticle* of the electron. The relation is reciprocal: The electron is the antiparticle of the positron. Soon after Anderson discovered the positron, Dirac realized his theory "might be applied to protons. This would require the possibility of existence of negatively charged protons forming a mirror-image of the usual positively charged ones." In fact, relativistic quantum theory demands the existence of an antiparticle corresponding to every kind of particle. The masses of any particle and its antiparticle (like those of an electron and positron) are exactly the same and their electric charges are equal and opposite.

The negatively charged antiparticle of the proton p is called the antiproton $\overline{p}$. Its discovery is discussed in Chapter 15. The antiproton mass has been measured to be the same as the proton mass to an accuracy of a few parts per billion. Neutral particles also have antiparticles. The photon is its own antiparticle, but the neutron's antiparticle is a different particle called the antineutron $\overline{n}$. Nucleons and antinucleons, like electrons and positrons, annihilate each other on contact.

Particles and antiparticles have equal masses and opposite electrical and magnetic properties. They share other properties as well. The antiparticle of a stable particle is stable. If a particle is unstable, so is its antiparticle, and both have the same mean lives. Moreover, particles and antiparticles behave the same way in a gravitational field (that is, antimatter falls down, not up). All these predictions have been, and are being, tested by precise experiments.

Collisions between energetic electrons and positrons often proceed via the annihilation and subsequent creation of new particles. For example, the process

$$e^+ + e^- \longrightarrow \mu^+ + \mu^-$$

where μ is a particle about 200 times heavier than the electron, is routinely seen at accelerator laboratories. This process, and others like it, are correctly and completely described by the theory of *quantum electrodynamics*.

The substance of Earth is made up, by definition, of particles: electrons, protons, and neutrons. Positrons are occasionally produced by natural radioactivity or by cosmic rays. Antiprotons and antineutrons are routinely produced in collisions of energetic particles at accelerator laboratories. However, if the antiparticles synthesized by all the accelerators on Earth were gathered together, they would fit on a pinhead. In principle, antiparticles can be assembled into bulk antimatter. (In fact, the antihelium atom has been synthesized. It consists of two positrons bound to a nucleus made of two antineutrons and two antiprotons.) Scientists once thought that distant galaxies might be made of antimatter, but now it is known that they are not. In the early history of the universe, matter and antimatter played equivalent roles, but most of the matter and antimatter of the universe has been annihilated. For reasons that are just beginning to be understood, the remnant of this process—the stuff of stars, planets, and galaxies—is all in the form of matter. (What is called "matter" is a matter of words. It would be silly, but scientists could have defined electrons and protons as antimatter, and positrons and antiprotons as matter.)

Quantum Electrodynamics

The first offspring of relativistic quantum mechanics were the precise description of atomic structure and the prediction of the positron. And they were just the beginning. Physicists learned that electron-positron pairs were created in energetic collisions, and positrons were annihilated by electrons. The Dirac equation could describe the motions of electrons and positrons, but how could it take into account the creation and destruction of particles? The answer lay in the reinterpretation of the wave function as an operator that could create or destroy particles. What had been wave functions evolved into *quantum fields*, and a new mathematical formalism was developed to handle them. The first quantum field theory dealt with electrons, positrons, and photons, and their electromagnetic interactions. It was called *quantum electrodynamics*, or *QED*, and was developed principally by Richard Feynman, Julian Schwinger, and the Japanese physicist Sin-itiro Tomonaga in the 1940s. The triumphs of QED have made it a paradigm for the construction of today's more ambitious theories.

The creation and destruction of elementary particles is described graphically by Feynman diagrams.* These diagrams describe the processes that take place en route from an initial state to a final state, but they also stand for specific mathematical operations by which the details of these processes may be worked out: their probability of occurrence, how energy and momentum are shared among the particles, and so on. Feynman diagrams depict electrons as arrows pointing from left to right and positrons as arrows pointing from right to left. Photons are denoted by undirected wavy lines. Time runs from left to right: Particles and antiparticles in the initial state enter from the left. Particles and antiparticles in the final state exit to the right.

The simple diagrams shown in Figure 14.2 describe *being* not *becoming*. A is a point in space-time—then and there—from which a particle comes. B is another point in space-time—here and now—to which the particle goes. In Figure 14.2a, a solid arrow directed from A to B denotes the flight of an electron. Of course, there is no well-defined trajectory in quantum theory and the diagram must not be taken literally. Figure 14.2b is the same diagram with the direction of the arrow reversed. This diagram could be thought of as an electron traveling backward in time from B to A. What it really shows is a positron traveling from A to B. The wavy line in Figure 14.2c shows the flight of a photon from A to B. It is shown as an undirected wavy line rather than an arrow because the photon is its own antiparticle.

Electrons, positrons, and photons move freely through space. They satisfy Newton's first law: Their momenta remain constant. Until they interact! But there are no forces as such in diagrammatic language: no fields and no action-at-a-distance. Interactions are represented by means of more complex diagrams than those of Figure 14.2. The next most

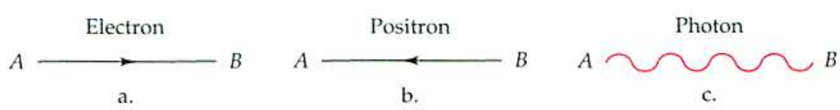


FIGURE 14.2
The ingredients of Feynman diagrams. Quantum electrodynamics describes the interactions of three kinds of particles: electrons, positrons, and photons. Solid arrows indicate electrons or positrons, depending on whether they point to the right or to the left. Wavy lines indicate photons.

*Feynman's small book, *QED: The Strange Theory of Light and Matter* (Princeton, NJ: Princeton University Press, 1985), makes a valiant attempt to explain quantum field theory in simple terms. It is recommended reading.

complicated diagrams, shown in Figure 14.3, portray the six fundamental acts by which particles interact with one another:

1. An electron may emit a photon.
2. An electron may absorb a photon.
3. A positron may emit a photon.
4. A positron may absorb a photon.
5. An electron and positron may annihilate into a photon.
6. A photon may create an electron-positron pair.

Energy and momentum conservation imply that none of these acts can take place as real physical processes. An electron cannot simply emit a photon: The invariant mass of the electron and photon necessarily exceeds that of the initial electron, and the invariant mass of an isolated system cannot change. Similarly, an electron or positron cannot simply absorb a photon. Nor can an electron-positron annihilate into or be created by a single photon. The fundamental acts of QED are forbidden!

Quantum mechanics comes to the rescue. Energy and momentum conservation may be set aside for a moment, as long as they are respected when the process comes to an end. (It's rather like buying a car on a very short-term loan—the actual time over which there may be a violation of the conservation laws is a tiny fraction of a second.) Several unphysical acts may be put together to produce a physically realizable process. Becoming is the result of a concatenation of two or more fundamental and forbidden acts.

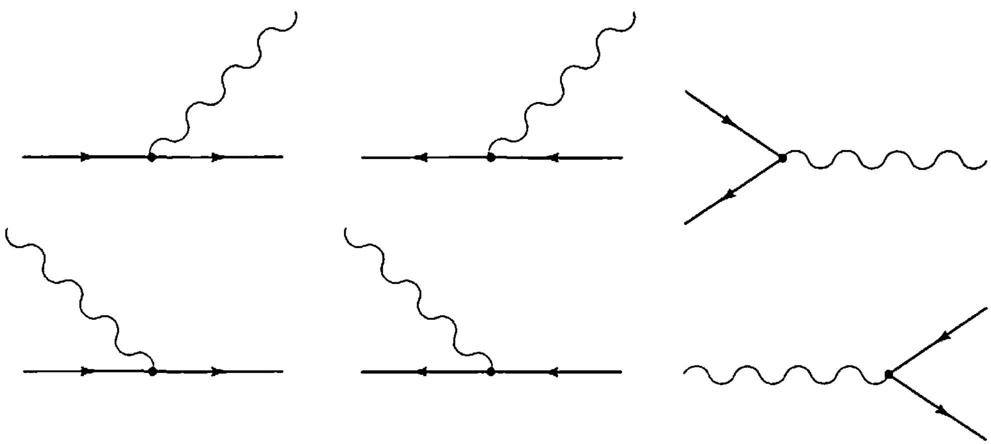


FIGURE 14.3 The fundamental acts of becoming in quantum electrodynamics. These simple acts are assembled into more complex diagrams to describe physically possible processes.

In Figure 14.4, two fundamental acts are wedded together to produce a diagram in which two electrons enter and two emerge. The physical process is the scattering of an electron by another electron, and the dia-

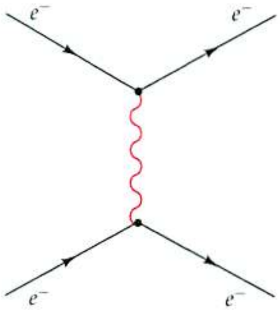


FIGURE 14.4
Two fundamental acts are linked together to form a two-act diagram describing the scattering of one electron by another: $e^- + e^- \rightarrow e^- + e^-$. The wavy line segment denotes a photon that is emitted and absorbed in the course of the process. It is a "virtual photon" in the sense that it acts to mediate the force between the two electrons.

gram is the simplest (and most important) contribution to the scattering process. In classical physics, we would say that one electron's trajectory is affected by the electric field of the other. In quantum mechanics, we would try to solve the Schrödinger equation for one electron in the electric field of the other. In QED, we say that one or more *virtual photons* may be exchanged, thereby transferring energy and momentum between the electrons.

It is not meaningful to ask if a photon is really exchanged. What really matters are the particles coming in and those leaving. All the rest is a computational artifice, a diagrammatic representation of a calculational procedure having nothing to do with "what really happened." Not even the time sequence of virtual processes is important. It doesn't matter whether the virtual particle is emitted by one particle and absorbed by the other, or vice versa. The probability of a particular scattering event is obtained by adding the contributions of the relevant diagrams and squaring the result.

Figure 14.5 shows three apparently distinct diagrams describing the scattering of a photon by an electron. In words, they can be described as follows:

a. An electron absorbs the incident photon and later emits the final photon.

b. An electron emits the final photon and later absorbs the incident photon.

c. The incident photon creates an electron-positron pair. The initial electron annihilates the positron producing the final photon.

Diagrams (14.5a) and (14.5b) represent distinct contributions to the Compton scattering process:

$$\gamma + e^- \longrightarrow \gamma + e^-$$

Changing the (irrelevant) time order of the two interaction points in Figure 14.5c by pulling the electron line straight makes it coincide with Figure 14.5b. They are simply different ways of drawing the same contribution to the photon-electron scattering process.

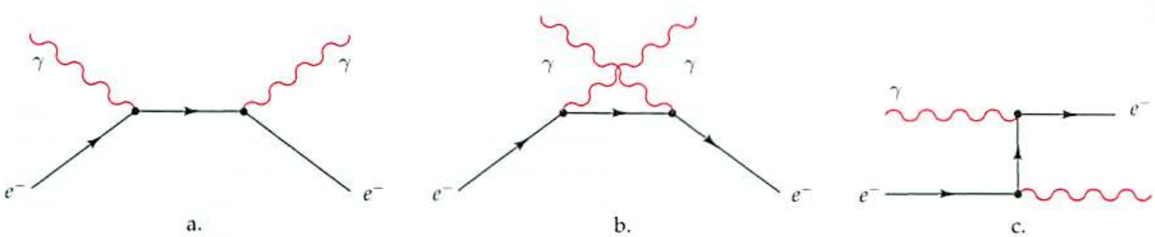


FIGURE 14.5 Three diagrammatic contributions to the scattering of a photon by an electron: $\gamma + e^- \rightarrow \gamma + e^-$. If the electron line is straightened, diagram *c* becomes equivalent to diagram *b*. There are only two distinct contributions to this process in two acts.

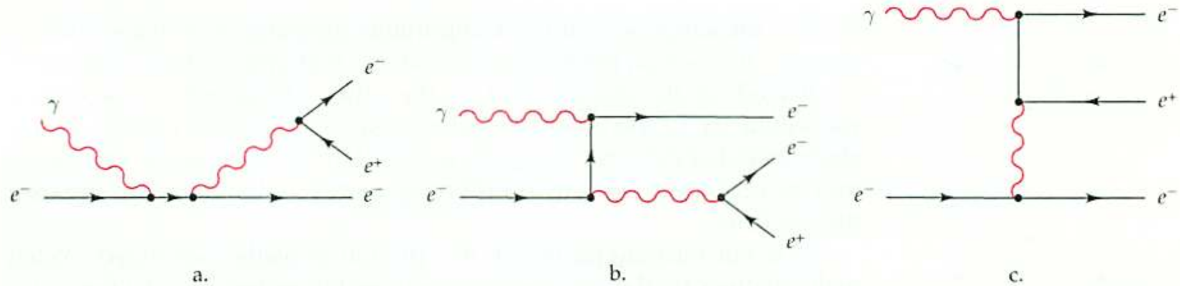


FIGURE 14.6 Three Feynman diagrams contributing to the process by which an electron-positron pair is created in a collision between a photon and an electron.

The three diagrams in Figure 14.6 are each composed of three fundamental acts. They contribute to the pair-production reaction

$$\gamma + e^- \longrightarrow e^- + e^- + e^+$$

The photon strikes an electron and produces an electron-positron pair. QED offers a precise description of this process and any others involving the production, annihilation, or scattering of electrons, photons, and positrons. All possible processes involving electrons, positrons, and photons may be represented by Feynman diagrams.

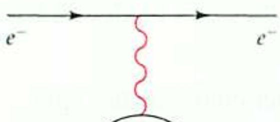


FIGURE 14.7 A complicated Feynman diagram contributing to electron-electron scattering, to which the diagram shown in Figure 14.4 is only a first approximation. To obtain precise results, many diagrams must be taken into account.

The Feynman diagrams discussed so far are the simplest contributions to various physical processes. To obtain greater precision, scientists had to take into account more complex diagrams, such as the contribution to electron-electron scattering shown in Figure 14.7. In the original formulation of relativistic quantum mechanics, however, this procedure led to a paradox. When the indicated calculations were performed, the results came out to be infinity when they should have led to small and sensible corrections to the lowest-order calculations. Infinite anwers don't make sense—something about the theory was very sick. The Austrian-born American physicist Victor Weisskopf put it this way:

> The appearance of infinite magnitudes in QED was noticed in 1930. Because they occurred only when a certain phenomenon was calculated to a higher order of accuracy than the lowest one in which it appeared, it was possible to ignore the infinities and stick to the lowest-order results which were good enough for the experimental accuracy of that period.

As technology developed and accurate experiments were performed, theoretical physicists needed more precise calculations to compare with experiments. They had to find out what was wrong with the theory. The first occasions in which QED runs into trouble correspond to simple diagrams such as that in Figure 14.8, an electron interacting with itself. The net effect of this diagram is to change the mass of the electron. It describes the *self-energy* of the electron due to its own electromagnetic field. However—and this was the principal stumbling block to the creation

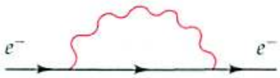


FIGURE 14.8
A Feynman diagram contributing to the electron's self-energy, the effect on its mass caused by its own electromagnetic field.

of QED—this diagram generates an infinite contribution to the electron mass. Of course, the electron mass is not infinite: It is about 10^{-30} kg.

This seemingly intractable problem was overcome in the 1940s by a procedure known as *renormalization*, by which the infinities of the theory are, so to speak, swept under the rug. The observed mass and charge of the electron are put into the theory at the start, and the results of calculations are expressed in terms of these quantities. When that is done, the infinities are transformed into answers to questions that should never have been asked, such as: What would the electron mass have been if electromagnetism did not exist? Because we cannot turn off electromagnetism, this is a philosophical question, not a physics question. When meaningful and measurable quantities are considered, QED always gives correct and finite answers.

Since QED was formulated, enormous theoretical and experimental advances have been made. For example, the magnetic moment of the electron is given as $\mu_0 = e\hbar/2m_e$ by the Dirac equation. Physicists using supercomputers have added up the corrections to this quantity due to hundreds of Feynman diagrams. Its predicted value $\mu_{\rm th}$ is known to ten decimal places. Its measured value $\mu_{\rm ex}$ has been determined with similar precision. The theoretical and experimental results agree:

$$\mu_{\rm th} = 1.001\ 159\ 652\, \mu_0 = \mu_{\rm ex}$$

This is one of many instances of the predictive power of QED. What more can one expect of a theory?

DO YOU KNOW Whether the Photon Is Massless?

QED says the photon is massless, but nature is the ultimate authority. Physicists must determine the consequences of a nonzero photon mass and compare them to what is seen. According to Maxwell's equations, electromagnetic effects decrease gently with the distance between interacting objects. For example, electric force varies with $1/r^2$. If the photon had mass m_γ, Maxwell's equations would fail and electromagnetic effects would fall precipitously at separations beyond $d = \hbar/m_\gamma c$. The strongest limit on the photon mass was described by the Russian physicist G.B. Chibisov in 1976:

> Virtually all physicists believe that the photon rest mass is exactly zero. On the other hand, there is no doubt that experiment has the last word in this important question. All experiments made to determine the photon rest mass give only upper limits for the mass. In particular, the photon mass may be zero. The best limit, obtained from the analysis of the mechanical stability of magnetized gas in the galaxies, shows that the photon's rest mass is at least 32 powers of ten less than the electron's. Do we really have to continue to infinity the succession of these upper limits in order to convince ourselves that the photon rest mass is zero. The answer is no.

Chibisov concluded that $m_\gamma < 3 \times 10^{-27}$ eV$/c^2$ or, equivalently, that the range of the electromagnetic interaction exceeds 10,000 light-years! For all intents and purposes, we may regard photons as massless particles.

QED is a relativistic quantum theory of electromagnetism. It tells everything anyone could want to know about the interactions of electrons, positrons, and photons, but it cannot describe nuclear particles or nuclear forces. The challenge to theoretical physicists was clear: to construct a theory of the strong and weak nuclear forces that was comparable to QED in power, consistency, and elegance. In Section 14.2, we approach this challenge by applying the language of Feynman diagrams to a variety of nuclear and subnuclear processes.

Exercises

1. Millikan knew that some cosmic ray particles at sea level travel upward. Explain how they can do so. (*Hint:* They cannot have passed through Earth from the antipodes.) How did the horizontal lead plate in Anderson's chamber help him to tell particles moving up from those moving down?

2. The rest energy of the muon ($\mu^{\pm}$) is about 106 MeV. Use the analysis of Example 14.2 to determine the minimum photon energy that can produce a pair of oppositely charged muons in the reaction:
$$\gamma + p \longrightarrow p + \mu^{+} + \mu^{-}.$$

3. The Superconducting Supercollider being built in Texas will accelerate protons to momenta of 20 TeV/c, or 2×10^{7} MeV/c. It is in the form of a ring 90 km in circumference. If it were exactly circular, and if magnets were placed along the entire periphery, how powerful would the magnets have to be to keep the protons in their orbits? (*Hint:* The answer is close to the strength of Anderson's magnet.)

4. Figure 14.6 exhibits three distinct Feynman diagrams contributing to $\gamma + e^{-} \rightarrow e^{-} + e^{-} + e^{+}$. Draw a fourth diagram for this process that cannot be deformed into any of the others.

5. Describe an experiment you can do that proves that the mass of the photon is less than a trillionth of the mass of the electron. (*Hint:* If the photon has mass m, the range of the electric force is $\hbar/mc$.)

6. Draw Feynman diagrams describing the following processes:
   a. $e^{+} + e^{-} \longrightarrow \gamma + \gamma$
   b. $e^{+} + e^{-} \longrightarrow \gamma + \gamma + \gamma$
   c. $\gamma + e^{-} \longrightarrow \gamma + \gamma + e^{-}$

14.2 Particles and Their Interactions

As quantum electrodynamics was being developed, other physicists turned to nuclear processes: to the mysteries of the strong and weak nuclear forces. The first suggestion as to the nature of the strong nuclear force came from the Japanese physicist Hideki Yukawa. We have seen that electromagnetic forces are mediated by the exchange of massless photons. In 1934, Yukawa proposed that nuclear forces result from the exchange of particles of a sort that had not yet been imagined, let alone seen in the laboratory.

Yukawa's hypothetical particle was massive so that it would produce a short-range nuclear force.* The relation between the range of a force and the mass of the exchanged particle lies in Heisenberg's uncertainty relation. The typical momentum of the exchanged particle is mc, so the position uncertainty associated with the virtual particle—and the range of the force—is $\hbar/mc$, the Compton wavelength of the particle. Yukawa chose his particle's mass to match the known range of the nuclear force, which is about the size of the proton (1.2×10^{-15} m). His conjectured particle—the proposed agent of the nuclear force, now called the *pion*—had to have a mass of about 150 MeV/c^2. The pion was found, but as we shall find later in this section, there was a surprise ending to the tale of its discovery.

The first hints about the nature of the weak nuclear force came from the study of nuclear β decay. If a nucleus contains too many neutrons for stability, one of its neutrons can become a proton with the simultaneous production of an electron and an antineutrino. We now turn to other processes governed by the weak force.

Positrons and Beta Decay

A high-energy collision can result in the creation of a pair of particles consisting of an electron and a positron. Pair production results from the electromagnetic force and is described by quantum electrodynamics. However, positrons can also be created by the weak nuclear force. It is an historical accident that positrons were first found in cosmic rays because they are produced by natural processes taking place on Earth.

In 1933, the Joliot-Curies (Madame Curie's daughter and son-in-law) were studying the impacts of α particles on atomic nuclei. When they irradiated a sheet of aluminum foil with α particles from a radioactive source, they observed positrons streaming from the foil. At first, the experimenters thought the positrons resulted from the disintegration of protons because, in their own (incorrect) words, "the proton is complex and results from the association of a neutron and a positron." This view is as untenable as its converse, once held by Rutherford, that a neutron is a combination of a proton and an electron. Protons and neutrons are both spin 1/2 particles and are equally elementary. However, the positrons did not emerge instantaneously—the foil continued to emit them long after it was removed from the radioactive source. The positron emission satisfied an exponential decay law with a half-life of a few minutes.

The Joliot-Curies concluded (correctly) that α bombardment of aluminum produced a new type of radioactive nucleus:

$$\alpha + {}^{27}\text{Al}_{13} \longrightarrow {}^{30}\text{P}_{15} + n$$

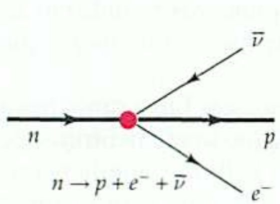
*Yukawa hoped that his new particle would generate both the strong and weak nuclear forces. It doesn't.

The mode of decay of ^{30}P was different from anything seen before. The decaying nucleus emitted a positron rather than an electron by a process akin to β decay. Consequently, the daughter nucleus lies one step below the parent in the periodic table:

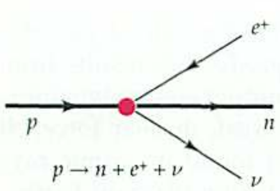
$$^{30}P_{15} \longrightarrow {}^{30}Si_{14} + e^+ + \nu$$

The neutrino hypothesis, and its experimental confirmation, were discussed in Section 13.3. Ordinary β decay (which is more properly called β^- decay) results in the production of an electron and an antineutrino, but the decay of ^{30}P (an instance of β^+ decay) produces a positron and a neutrino. The Joliot-Curies did not mention the neutrino because it was still a highly speculative notion. They shared the 1935 Nobel Prize in chemistry for their discovery of a new form of radioactivity. The Curie women and their spouses earned a total of five Nobel gold medals.

The process of β^+ decay involves the conversion of a proton in a nucleus to a neutron and the simultaneous creation of a positron and a neutrino. Here is what happens inside the nucleus in the two varieties of β decay:



a.



b.

FIGURE 14.9
a. The process of β^- decay. A neutron in a nucleus becomes a proton. At the same time, an electron and an antineutrino are created. *b.* The process of β^+ decay. A proton in a nucleus becomes a neutron. At the same time, a positron and a neutrino are created.

$$\text{In } \beta^- \text{ decay:} \quad n \longrightarrow p + e^- + \overline{\nu} \qquad Z \rightarrow Z+1 \tag{3a}$$

$$\text{In } \beta^+ \text{ decay:} \quad p \longrightarrow n + e^+ + \nu \qquad Z+1 \rightarrow Z \tag{3b}$$

The light neutral particle produced with an electron in β decay is defined to be an antineutrino $\overline{\nu}$, and that made with a positron is defined to be a neutrino ν. Both β processes change the identity of a nucleon and create a particle-antiparticle pair. The $e^- - \overline{\nu}$ pair produced by β^- decay or the $e^+ - \nu$ pair produced by β^+ decay is not present in the nucleus to begin with—it is created by the weak nuclear force.

The processes of β^- and β^+ decay, as described by equations 3, can be portrayed as Feynman diagrams involving two kinds of arrows (Figure 14.9). Neutrons and protons are similar particles: Both are heavy spin 1/2 particles and are subject to the strong nuclear force. The word *nucleon* refers to either of them. In the diagrams, a nucleon is depicted by a colored arrow directed to the right.

Neutrinos and electrons are also similar particles: Both are light spin 1/2 particles and neither is subject to the nuclear force. The word *lepton* refers to electrons, neutrinos, and particles of their ilk. A black arrow directed to the right depicts a lepton, and a black arrow directed to the left depicts an antilepton. The effect of the weak force is shown as a blob into which a lepton line and nucleon line enter, and from which each emerges. In the process, one unit of electric charge is exchanged between the nucleon and the lepton.

Electron Capture

In Section 14.1, we saw how the lines of a diagram describing one process may be turned around to produce a diagram describing another process. The diagrams shown in Figure 14.10 are variants of Figure 14.9b in which a lepton line has been brought from the right (corresponding to a final

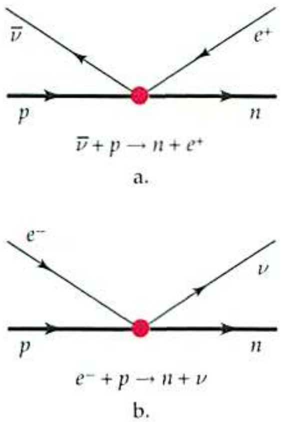


FIGURE 14.10
The Feynman diagrams shown here are obtained by displacing one or another of the lepton lines in Figure 14.9b. *a.* This diagram describes the process $\overline{\nu} + p \rightarrow n + e^+$. *b.* This diagram describes the process $e^- + p \rightarrow n + \nu$.

particle) to the left (corresponding to an initial particle). Figure 14.10a describes a process by which an antineutrino strikes a proton to become a neutron and a positron.

$$\overline{\nu} + p \longrightarrow n + e^+ \qquad (4)$$

This reaction led to the first observations of antineutrinos.

Figure 14.10b describes a reaction by which a proton encounters an electron to form a neutron and a neutrino. This process takes place in some atoms, giving rise to a third form of β radioactivity called *electron capture.* A proton-rich nucleus consumes an orbital electron to become a nucleus with one less proton and one more neutron:

$$\text{In electron capture:} \quad e^- + p \longrightarrow n + \nu \qquad Z + 1 \rightarrow Z \qquad (5)$$

Electron capture is a radioactive process like β^+ decay in which A remains constant but Z decreases by one unit. Many isotopes, such as the naturally occurring but rare isotope ^{40}K, decay by capturing an electron. Electron capture induces the same nuclear transformation as β^+ decay, but requires less energy because an electron is consumed in the former process while a positron must be created in the latter.

DO YOU KNOW
How the Neutrino Was Discovered?

Reaction 4 describes the process by which the American physicists Frederick Reines and Clyde Cowan first detected antineutrinos in 1956. Working at a fission reactor in Georgia, they designed an experiment to detect antineutrinos produced by the nuclear reactions taking place within a nuclear reactor. They placed a large instrumented tank of *liquid scintillator* close to the core of the power-generating reactor at Savannah River, Georgia. The fluid in the tank had three important properties:

1. It converted γ rays into visible photons that were detected electronically.
2. It was rich in hydrogen to act as a target for reaction 4 and to slow down the neuron released by the reaction.
3. It contained cadmium to absorb the neutron. (When a neutron is absorbed, the cadmium nucleus emits several detectable γ rays with a total energy of about 9 MeV).

When an $\overline{\nu}$ from the reactor interacted with a proton in the tank, the resulting positron encountered an electron. The positron and electron annihilated into back-to-back γ rays, each with the rest energy of an electron, about 0.5 MeV. The unambiguous signal of reaction 4 is the detection of the γ rays from positron annihilation, followed immediately by the detection of lower-energy γ rays coming from neutron capture. Cowan and Reines observed these signals and found the neutrino a quarter of a century after Pauli invented it.

To Beta-Decay or Not to Beta-Decay?

Nuclear stability is determined by the masses of the parent and daughter atoms. The standard of mass is the ^{12}C atom (including its six atomic electrons) with a mass of 12 amu, where 1 amu $\simeq$ 931.5 MeV/c^2. We refer to an atom with Z electrons and atomic mass number A as (A, Z) and to its mass as $M(A, Z)$.

Consider two neighboring isotopes with the same A but one step apart in the periodic table. Under what circumstances can (A, Z) β^--decay into $(A, Z+1)$? The nuclear process involves the transformation $n \rightarrow p + e^- + \overline{\nu}$. The final state has just the right number of protons, neutrons, and electrons to constitute the $(A, Z+1)$ atom. The mass of the neutrino is known to be very tiny. Thus, the β^- process takes place if

$$M(A, Z) > M(A, Z+1) \qquad \text{for } \beta^- \text{ decay} \tag{6}$$

Similar reasoning determines the necessary condition for $(A, Z+1)$ nucleus to capture an electron:

$$M(A, Z+1) > M(A, Z) \qquad \text{for electron capture} \tag{7}$$

Because different isotopes never have exactly the same mass, one of the two inequalities, 6 or 7, must be satisfied. We have established an interesting and important result—two neighboring isotopes cannot both be stable. At least one of the isotopes $(A, Z+1)$ and (A, Z) must be radioactive.

It often happens that $M(A, Z+1)$ is sufficiently larger than $M(A, Z)$ to permit the β^+ reaction to compete with electron capture. In this case, the reaction is $p \rightarrow n + e^+ + \nu$. The β^+ process may take place if

$$M(A, Z+1) > M(A, Z) + 2m \qquad \text{for } \beta^+ \text{ decay} \tag{8}$$

Testing the Law of Parity Conservation

The study of β decay in the 1950s led to the extraordinary discovery of *parity violation,* meaning that the fundamental processes of nature are not the same when viewed in a mirror. This result may not seem surprising. After all, your body is not the same when viewed in a mirror. Your heart is on the left and your liver on the right, but in a mirror, the locations are reversed. Biological molecules display a specific handedness as well. However, the left-right asymmetry of living things was probably an evolutionary accident. Life could have evolved differently—mirror-reflected men and women would have been just as good as we are.*

*One in a million of us is born with the wrong handedness. The condition is known in medicine as *situs invertus.* Although their hearts are on their right side and their livers on the left, these individuals can be perfectly healthy. The molecules in their bodies, however, have the same handedness as ours.

In the early 1950s, most physicists were certain that all physical laws were mirror symmetric. The notion was codified as the law conservation of parity and was once regarded as a sacred cow. The strong nuclear force conserves parity. So does the electromagnetic force. However, nobody bothered to ask whether the weak force conserves parity until 1956, when two young Chinese-American physicists at Columbia University, Tsung Dao Lee and Chen Ning Yang, pointed out that the emperor of parity had no clothes:

> The conservation of parity is usually accepted without question... There is actually no a priori reason why its violation is undesirable. As is well known, its violation implies the existence of a right-left asymmetry. We have seen in the above some possible tests of this asymmetry. These experiments test whether the present elementary particles exhibit asymmetrical behavior with respect to the right and the left.

Within months, Chien-Shiung Wu (known as Madame Wu) and her collaborators at Columbia University performed the test Lee and Yang proposed. They prepared a sample of radioactive ^{60}Co in which the nuclear spins were arranged to point in the same direction. The group discovered that the β rays from the ^{60}Co decays emerged preferentially along the nuclear spin direction (Figure 14.11).

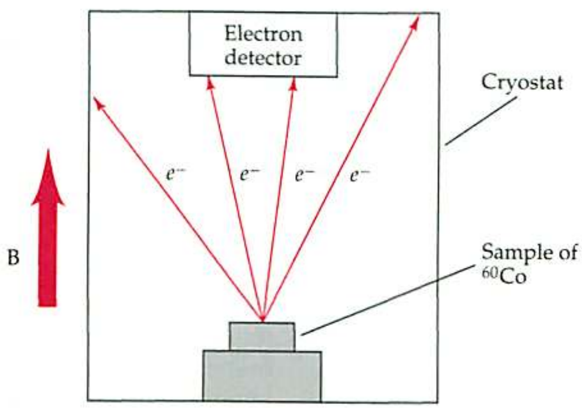


FIGURE 14.11
Madame Wu and her collaborators placed a sample of radioactive ^{60}Co in a cryostat, where it was brought to a very low temperature, and an intense magnetic field caused the nuclear spins to line up with one another. Electrons produced by decaying cobalt atoms were detected and counted. The number of detected electrons when the field pointed down was about twice the number as when the field pointed up. Thus, the electron direction in β decay is correlated to the direction of the nuclear spin.

The specification of a direction of rotation entails a choice of handedness. If the cobalt nuclei spin in the direction of the curled fingers of the *right* hand, their spins—and the emitted electrons—point in the direction of the thumb. This shows that the β decay process is not right-left symmetric because the mirror image of a right hand is a left hand (Figure 14.12). Madame Wu and her colleagues proved that parity is violated by the weak nuclear force.

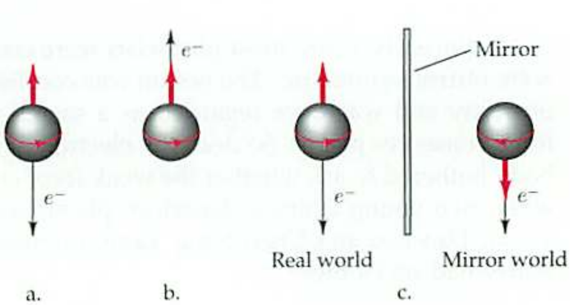


FIGURE 14.12
How the Wu experiment disproves the hypothesis of mirror symmetry. Both *a* and *b* show ^{60}Co nuclei with their spins pointing up along the fat arrows—like the outstretched right thumb when the fingers curl in the direction of nuclear rotation. Experiment revealed that case *a*, where the electron emitted by the decaying nucleus points away from its spin direction, is more probable than case *b*, where the electron points along the nuclear spin. In *c*, we see that the reflected image of case *a* is identical to case *b*. If the experiment were observed in a mirror, case *b* would have been more likely than case *a*. This experiment (and many more) showed that the laws of physics are not mirror symmetric.

Another deeply held belief of physicists fell in the 1960s: the law of microscopic time-reversal symmetry. In the everyday world, time has a well-defined direction. Eggs are eaten, break, rot, or become chickens, never the other way around. The apparent asymmetry of time is not a mystery. Things like neat desks and healthy bodies find more ways to lose their proper order than to keep intact. We need cleaning services and doctors because of the second law of thermodynamics, as explained in Section 5.4. However, the equations governing mechanics and electromagnetism are unchanged under reversal of the arrow of time.

Having lost their cherished mirror symmetry, physicists still clung to the principle of microscopic time-reversal symmetry. They felt certain that the basic laws of microphysics run the same forward or backward in time. Until 1964. At that time, Val Fitch and James Cronin observed a tiny time-reversal violating effect in the behavior of elementary particles. Not only does the weak force violate parity conservation, but it displays a preferred direction in time! This tiny effect is of little practical importance to us now, but it may explain why there is matter in the universe!

DO YOU KNOW
Why We Are Made of Matter, Not Antimatter?

Matter is made of protons, neutrons, and electrons rather than of their antiparticles. Long ago, when the universe was very hot, things were very different. The universe contained a hundred trillion times as many nucleons as it does today. There were an approximately equal number of antinucleons as well. As the universe cooled, nucleons and antinucleons annihilated one another. Fortunately, not all of them were annihilated. We were left with a tiny nucleon excess from which matter has formed. Was the universe created lopsided, or was the small matter-antimatter imbalance forced upon it? Explaining such a development is more satisfying than merely accepting it. Soon after the violation of time-reversal symmetry was detected, Andrei Sakharov (who was both the father of the Soviet hydrogen bomb and a champion of peace) showed how this tiny effect, long ago, may have made possible the existence of matter in today's universe.

Nucleon Number and Lepton Number

The Feynman diagrams describing the weak interactions shown in Figures 14.9 and 14.10 display an important property: Nucleon lines and lepton lines enter and leave the weak interaction blob, but they never appear or disappear. This property can be formulated more generally in terms of quantum numbers and conservation laws. Electric charge $\mathcal{Q}$ is an example of a conserved quantum number. Quantum electrodynamics demands, and experiments confirm, that in all reactions among particles, the sum of the charges of the initial particles is equal to the sum of the charges of the final particles.

Let's introduce two more quantum numbers: *nucleon number* $\mathcal{N}$ and *lepton number* $\mathcal{L}$. Each nucleon carries nucleon number $\mathcal{N} = 1$ and each antinucleon carries $\mathcal{N} = -1$. Similarly, each lepton (electron or neutrino) carries $\mathcal{L} = +1$ and each antilepton (positron or antineutrino) carries $\mathcal{L} = -1$. Because β^- decay produces an electron and an antineutrino, and β^+ decay produces a positron and a neutrino, these processes conserve lepton number $\mathcal{L}$. Table 14.1 shows the quantum number assignments of particles. Their antiparticles have equal and opposite quantum number assignments.

TABLE 14.1 Quantum Number Assignments

Particle	*Lepton Number* $\mathcal{L}$	*Nucleon Number* $\mathcal{N}$	*Electric Charge* $\mathcal{Q}$
Proton	0	1	+1
Neutron	0	1	0
Electron	1	0	−1
Neutrino	1	0	0

The downfall of parity conservation and time-reversal symmetry reminded physicists that things are not always as they seem. Until they are put to the most rigorous experimental tests, nucleon number conservation and lepton number conservation cannot simply be accepted as inviolable laws of nature. The complete list of conserved quantities applicable to reactions involving nucleons, electrons, neutrinos, and their antiparticles includes energy, momentum, and angular momentum along with $\mathcal{Q}$, and possibly $\mathcal{L}$ and $\mathcal{N}$. Any process consistent with all these conservation laws can and does occur in nature, although some processes are more likely to happen than others. Conversely, any process conflicting with a valid conservation law cannot take place.

EXAMPLE 14.3 Conserving Quantum Numbers

Test the following hypothetical decay modes for conservation of $\mathcal{Q}$, $\mathcal{L}$, and $\mathcal{N}$:

$$^{14}C_6 \longrightarrow \begin{cases} ^{15}N_7 + e^- + \overline{\nu} \\ ^{14}N_7 + e^+ + \nu \\ ^{14}N_7 + e^- + \nu \end{cases}$$

Solution

The first process conserves $\mathcal{Q}$ because the parent nucleus has charge 6 (in units of e), which is the sum of the final particle charges. It conserves $\mathcal{L}$, which is 0 on the left and $0 + 1 - 1$ on the right. However, it does not conserve $\mathcal{N}$ because there are 14 nucleons on the left but 15 on the right. This process is forbidden. The second reaction conserves $\mathcal{L}$ and $\mathcal{N}$, but not $\mathcal{Q}$. The third conserves $\mathcal{N}$ and $\mathcal{Q}$, but not $\mathcal{L}$. All three processes are forbidden. The process that correctly describes the β decay of radioactive carbon is:

$$^{14}C_6 \longrightarrow {}^{14}N_7 + e^- + \overline{\nu}$$ ■

Testing the Law of Conservation of Lepton Number

Scientific laws are put forward as hypotheses to be tested by experiments. One of the most sensitive tests of lepton number conservation involves the process of *double β decay*. Suppose that a nuclear species (A, Z) can neither α-decay to $(A-4, Z-2)$, nor β-decay to $(A, Z+1)$, nor electron-capture to $(A, Z-1)$. It can still be radioactive. If the nuclear masses satisfy the relation

$$M(A, Z) > M(A, Z+2)$$

the nucleus (A, Z) can decay by emitting two electrons and increasing its atomic number by two. The pattern of energy levels required for double β decay is shown in Figure 14.13.

Here are two nuclear processes by which Z may increase by two steps:

$$n + n \longrightarrow p + p + e^- + e^- + \overline{\nu} + \overline{\nu}$$

$$n + n \longrightarrow p + p + e^- + e^-$$

Both of these reactions conserve $\mathcal{N}$ and $\mathcal{Q}$. The first version of double β decay also conserves $\mathcal{L}$ because two leptons and two antileptons are produced. The second reaction, which is called no-neutrino double β decay, does not conserve $\mathcal{L}$ but causes it to increase by two units.

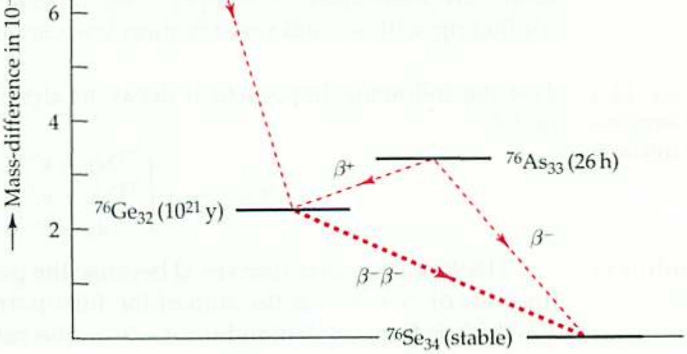


FIGURE 14.13
The atomic masses of ^{76}Ge and its neighbors. About 8 percent of natural germanium consists of the isotope ^{76}Ge. It cannot β-decay to either of its immediate neighbors. In fact, both ^{76}Ga and ^{76}As β-decay into germanium. However, the Ge isotope may jump two units of Z by the process of double β decay to become ^{76}Se. The half-life of this process is more than 10^{20} years. Isotopic masses are shown relative to the mass of the selenium isotope.

The law of conservation of lepton number permits the first reaction but forbids the second. Thus, the search for no-neutrino double-beta-decay can test the law. Dozens of nuclei are energetically permitted to double β decay, and some are known to do so. For example, $^{82}Se_{34}$ transforms itself, by the double β process, into $^{82}Kr_{36}$. Experimental data confirm the hypothesis of lepton number conservation. The allowed two-neutrino double β decay of selenium has been observed and measured in the laboratory. The mean life of ^{82}Se is an extraordinary 10^{20} years! (Thus, no more than one atom per mole decays in an hour!) Many groups of physicists are searching for the forbidden no-neutrino mode of double β decay, but no one has seen it so far. All evidence indicates that the conservation of lepton number is an exact symmetry of nature, but we don't yet know for sure.

Testing the Law of Conservation of Nucleon Number

Nobody has ever observed a process in which nucleon number changes. Perhaps they haven't looked hard enough. Perhaps nucleons decay but with an exceedingly long lifetime. Let's consider the following hypothetical decay scheme for protons:

$$p \longrightarrow e^{+} + \gamma \tag{9}$$

Many other decay modes are possible, but this one (involving familiar particles) serves as an illustration. One thing is clear—the lifetime of the proton is surely very long because there are lots of protons still around in our 10^{10}-year-old universe.

In 1973, Howard Georgi and Sheldon L. Glashow put forward the first theory to unify all the elementary particle forces. Theories of this kind abolish nucleon number conservation. They predict that all matter is radioactive and that the mean life of a nucleon is about 10^{30} y. Could it be that diamonds are not forever? Two teams of scientists set up experiments to see for themselves, one deep within an Ohio salt mine and the other under a mountain facing the Japan Sea. "If protons must die," said Maurice Goldhaber, an old hand in the proton decay story, "let them die in my arms."

Large tanks of very pure water were built deep underground where they were shielded from cosmic rays. If a nucleon decayed in the water, a small amount of the energy of its decay products would be converted into a characteristic pattern of light that would be detected by many sensitive photodetectors surrounding the tanks (Figure 14.14, on page 596). If the nucleon lifetime were 10^{30} years, about one would decay each day per thousand tons of water. The tank had to be enormous. The American tank was a 20-m cube—the size of an apartment house. It contained 8000 tons of water. The Japanese tank was about a third the size but better instrumented. After years of searching, however, neither group detected any proton decays. The experiments proved that the mean life of the nucleon exceeds 10^{31} years.

Experiments with greater sensitivity are being carried out to test the conservation of lepton number and nucleon number. These conservation

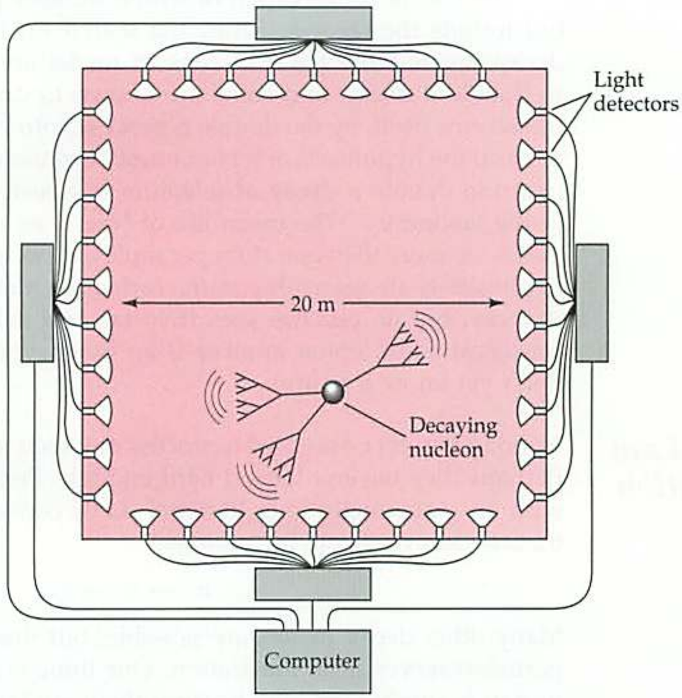


FIGURE 14.14
The most sensitive search for proton decay was carried out by scientists from the University of California at Irvine, Brookhaven National Laboratory, Boston University and the University of Michigan. If a nucleon anywhere in a large underground tank of water had decayed, its decay products would have produced a tiny flash of light. The light would have been detected, and a computer could have constructed a picture of the decay process. The experiment was carried out for a decade, but no sign of proton decay was seen—one of my favorite theories was ruled out.

laws are certainly approximately valid. Whether or not they are exact laws of nature remains to be determined. Theoretical arguments suggest that the proton must decay and that neither nucleon nor lepton numbers are always conserved.

Pions and Muons

In the 1930s and 1940s, cosmic ray physicists discovered many new particles. Cosmic rays were known to be of two sorts: an easily absorbed "soft" component and a more penetrating "hard" component that can be detected hundreds of meters below the ground. The former consists of electrons, positrons, and photons. The latter was mystifying. In 1937, Anderson and Neddermeyer at Cal Tech published a paper claiming the discovery of new particles of intermediate mass:

> Interpretations of the penetrating [tracks] encounter very great difficulties [unless they are produced by] particles of unit charge, but with a mass larger than that of an electron and much smaller than that of a proton.

Confirmations immediately appeared from groups at Tokyo and Harvard University. The discoverers of the new particles named them *mesotrons* from the Greek *mesos* meaning middle because they have middle-sized masses. Many physicists believed that the particles predicted by Yukawa had been found and sometimes referred to them as *yukons.* After all, the new particles had just the mass that Yukawa had forseen. But nature had a big surprise in store for us. So did history: The denouement of the meson (truncated version of *mesotron*) story was deferred for the duration of the Second World War.

"BUT DON'T YOU SEE, GERSHON — IF THE PARTICLE IS TOO SMALL AND TOO SHORT-LIVED TO DETECT, WE CAN'T JUST TAKE IT ON FAITH THAT YOU'VE DISCOVERED IT."

DO YOU KNOW

Why Proton Decay Cannot Power the Sun?

If a proton in the Sun decays by reaction 9 or in other ways, all of its rest energy is soon converted into heat. (Positrons produced by proton decay annihilate with electrons to become γ rays, whose energies would be transferred to the atoms in the Sun.) Imagine that proton decay is the source of the Sun's power. What is the lifetime τ of the proton if this be so? There are $N \simeq 10^{57}$ protons in the Sun. The number of protons decaying per second is N/τ. Each decay releases an energy m_pc^2, so the power resulting from proton decay is $P = Nm_pc^2/\tau$. The rest energy of a proton is $m_pc^2 \simeq 1.5 \times 10^{-10}$ J. We set P equal to the Sun's total power output of 3.8×10^{26} W to find that τ must be about 10^{14} years. Can astrophysicists be mistaken and proton decay, not nuclear fusion, be the power behind the stars?

If protons in the Sun decay, then so must those of Earth. Geologists know how much heat is welling up from Earth's interior. Some geothermal energy is used to generate electricity. Most of Earth's heat comes from radioactivity of the known quantities of uranium and thorium in its crust. Some additional heat trickles up from the still molten interior at a known rate. Because most geothermal power is accounted for, there cannot be another significant source of heat inside Earth. If proton decay is heating Earth, it cannot contribute more than an extra 10^{13} W. A simple calculation, as we did for the Sun, shows that the half-life of the proton must therefore exceed 10^{21} years. Simple geological considerations tell us that proton decay cannot power the Sun and the proton lifetime is at least a hundred-billion times longer than the age of the universe!

The particles making up the penetrating component of cosmic rays were found to be longer lived and more penetrating than expected. In 1946, an Italian collaboration proved that the particles discovered by Anderson and Neddermeyer were not the particles predicted by Yukawa. The observed particles could not mediate the nuclear force because they did not even respond to it.

Let me explain the trap nature prepared. Collisions of primary cosmic rays in the upper atmosphere produce Yukawa's particles in abundance. They are no longer called mesotrons or yukons, but rather *pions*, and they come in three varieties with different charges: positive pions π^+, negative pions π^-, and neutral pions π^0. Charged pions are each other's antiparticles. The neutral pion is its own antiparticle and decays very rapidly into two photons.* All three pions have masses of about 140 MeV/c^2. They comprise an isotopic triplet of similar particles just as neutrons and protons comprise an isotopic doublet.

Charged pions are unstable and short-lived. They decay via the weak force by a process akin to nuclear β decay. Their mean life is about 10^{-8} s and their decay products are almost always muons and neutrinos:

$$\pi^- \longrightarrow \mu^- + \overline{\nu} \qquad \pi^+ \longrightarrow \mu^+ + \nu$$

The penetrating component of cosmic radiation—the particles discovered by Anderson and Neddermeyer—are not pions but muons resulting from the decays of pions in the stratosphere! Pions are the strongly interacting particles predicted by Yukawa. The μ^- has no strong interactions. It is a lepton, like the electron and the neutrino.

Cecil Powell and his group of cosmic ray physicists discovered charged pions in 1947. "In recent experiments," they wrote, "we showed that charged mesons sometimes lead to the production of secondary mesons. We have now extended these observations by examining plates exposed in the Bolivian Andes at a height of 5500 m, and have found, in all, forty examples of the process leading to the production of secondary mesons."

Powell's group trekked to the high Andes because that's where the pions were. Photography is a powerful tool for both astronomy and physics. A charged particle passing through photographic emulsion produces a visible track when the plate is developed. Cloud chambers and photography were the principal tools of cosmic ray physicists. When accelerators were developed, these devices were supplanted by "bubble chambers" and sophisticated electronic techniques for detecting, identifying, and tracking energetic particles. Powell's paper continues:

> Our observations, therefore, prove that the production of a secondary meson is a common mode of decay of [primary] mesons. We represent the primary meson by the symbol π and the secondary by μ. It can thus be shown that the ratio m_π/m_μ is less than 1.45.

*Neutral pions were the first particles to be discovered at accelerators. They were observed in 1950 by the American physicist Jack Steinberger and his collaborators at a cyclotron in Berkeley, California.

The discovery of muons was a surprise. Today, we know what muons are, but we don't know what they are for in the grand scheme of things.* Muons are like fat electrons. That is, they are pointlike, seemingly elementary, electrically charged leptons. Like electrons and neutrinos, they are spin 1/2 particles that are not subject to the strong nuclear force. Their mass is about $200\,m_e$, or 105 MeV/c^2, and they decay with a mean life of 2 microseconds according to the scheme

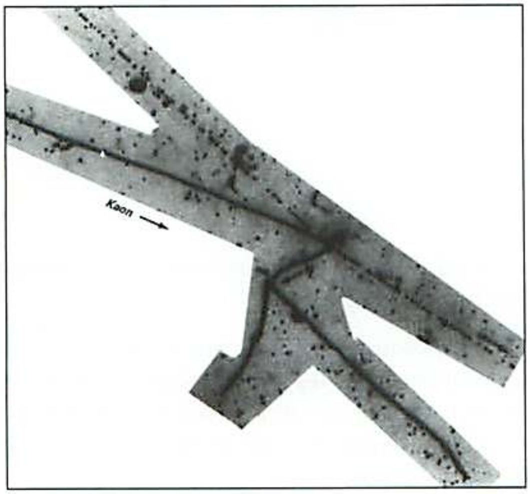
$$\mu^{\pm} \longrightarrow e^{\pm} + \nu + \overline{\nu}$$

For decades, physicists believed that nucleons and pions were as elementary as particles can be. The exchange of pions contributes to the force between nucleons, and for a time they were believed to be the ultimate nuclear glue. The list of particles and antiparticles encountered so far is not overwhelming:

- Nucleons (n and p) and antinucleons ($\overline{n}$ and $\overline{p}$)
- Leptons (e^-, μ^-, and ν) and antileptons (e^+, μ^+, and $\overline{\nu}$)
- Pions (π^+, π^0, and π^-)
- Photons (γ)

Strange Particles

It didn't take long, however, before particles were found that didn't fit into this simple picture. The trouble began two months after Powell's triumphant discovery of the pion. Once again, cosmic rays presented us with a puzzle and a challenge. G. D. Rochester and C. C. Butler, in Manchester, England, published a paper in 1947 entitled *Evidence for*



The first strange particles were detected at sea level in a cloud chamber. Another technique involves bringing photographic plates to a mountaintop. Cosmic rays passing through the plate produce tracks when the plate is developed: They photograph their own trips! C. F. Powell and his group of cosmic ray physicists at the University of Bristol published this photograph of a charged kaon (a strange particle) entering from the left and decaying into three charged pions. (One of the pions subsequently scattered from a nucleus.) *Source:* Department of Physics, University of Bristol/Courtesy, Meyers Photo-Art.

*The American physicist Luis Alvarez found a practical use for muons. In the late 1960s, he led an American-Egyptian project to search for hidden galleries within the Pyramid of Chephren. The team of scientists used cosmic ray muons to produce "X-ray" images of the pyramid. They proved there are no undiscovered treasures.

the Existence of New Unstable Elementary Particles. They had discovered charged and neutral *kaons*: spinless particles with masses between pions and nucleons and with mystifying properties. Soon afterward, other particles were discovered that decayed into nucleons and pions. None of these had been anticipated, and all of them displayed weird properties. They became known as *strange particles* and would fascinate and bewilder particle physicists for decades.

Strange particles were the tip of an enormous iceberg. The development of the cyclotron made available an intense and reliable source of energetic particles. By 1940, it was used to synthesize neptunium and plutonium, the first of the transuranic elements. As larger and larger accelerators were built, more and more particles were discovered: hundreds of them! Things would seem hopelessly complicated before nature's simplicity would emerge. In 1979, Philip Handler, the late president of the National Academy of Sciences, wrote about the scientific progress he had witnessed in his long career:

> Man learned for the first time the nature of life, the structure of the cosmos, and the forces that shape the planet, although the interior of the nucleus became if anything, even more puzzling.

Dr. Handler was not well informed about particle physics. Just a few years before, many of the wildest speculations of theoretical physicists had been assembled into what now seems to be a correct, complete, and coherent theory of the behavior of elementary particles. This *standard model* of elementary particle physics—the triumphant conclusion (for the moment) of the search for the basic building blocks of matter—is presented in Chapter 15.

Exercises

7. Extend Table 14.1 to include the quantum numbers of antileptons and antinucleons.

8. The following reactions are forbidden because they do not conserve one or more of lepton number, nucleon number, or electric charge. Which conservation laws are violated by each process? The symbols $\overline{p}$ and $\overline{n}$ denote the antiproton and antineutron.

   a. $\nu + p \longrightarrow e^- + n$

   b. $p \longrightarrow e^+ + \gamma$

   c. $\gamma + p \longrightarrow e^+ + n$

   d. $n + p \longrightarrow \overline{p} + \overline{n} + e^+ + e^+$

   e. $e^- + p \longrightarrow \overline{\nu} + n$

9. How do you suppose that no-neutrino double β decay can be distinguished experimentally from the two-neutrino process?

10. Give an example of a mode of proton decay other than reaction 9 that is compatible with electric charge conservation.

11. What is the mass in MeV/c^2 of a particle whose Compton wavelength is 1.2×10^{-15} m?

12. The decay $\mu \rightarrow e+\gamma$ has never been observed. Can you invent a new quantum number whose conservation explains why this process is forbidden?

13. Suppose that a pion at rest decays into a muon and a massless neutrino. What is the energy of the neutrino?

14. Consider the reaction $p + p \rightarrow p + p + \pi^0$. If the target proton is at rest, what is the minimum kinetic energy of the incident proton for which this reaction is energetically allowed?

14.3 Neutrino Astronomy (Optional)

The wondrous spectacle of the night sky gave birth to astronomy and its flawed sibling astrology. At first, astronomers studied the patterns and motions of heavenly bodies. Simple telescopic measurements led to Newton's grand synthesis. Centuries later, spectroscopy and photography enabled astronomers to determine the composition of stars and the velocities of galaxies. But modern astronomy is not restricted to the tiny slice of the electromagnetic spectrum eyes can see. Ultraviolet and infrared radiations have their secrets to tell. So do X rays and γ rays, radio waves, and microwaves. Modern astronomers study photons in a wavelength range spanning 24 powers of 10!

There are other ways to learn about the heavens. Meteors streak through the skies, and those falling to Earth as meteorites bring vital information about complex molecules made in space and complex nuclei made by ancient supernova. Cosmic rays introduced us to elementary particles and their interactions. The most recent addition to the astronomical arsenal is neutrinos. The science of neutrino astronomy began with the search for neutrinos produced by nuclear reactions in the solar core.

A New Science Is Born

Two American scientists, Raymond Davis, an experimenter, and John Bahcall, a theorist, were the founders of solar neutrino astronomy. "Theory and experiment depend on each other for their significance in solar neutrino research," they wrote. It is not enough to detect the neutrinos coming from the Sun—the result must be compared to theoretical expectations. They continued:

> The early literature on nuclear fusion as the basis to solar energy production did not mention the possibility of testing the ideas by observing neutrinos. In the great papers by Bethe, neutrinos were not included specifically in the nuclear reactions... The principle of lepton number conservation was not clearly articulated and one was not required to balance leptons as well as nucleons.

By the early 1950s, Davis set about to search for solar neutrinos. He proposed to detect them through the reaction

$$\nu \text{ (from the Sun)} + {}^{37}\text{Cl} \longrightarrow e^- + {}^{37}\text{A} \tag{10}$$

by which a solar neutrino strikes a chlorine atom converting it into a radioactive argon atom. The argon atoms would be collected and their individual decays would be detected and counted. His prototype experiment, completed in 1955, used a few tons of chlorine-rich cleaning fluid as a target. The reviewer of Davis's paper was amused:

> Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos. One would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than eight feet from the top of the mountain.

Davis learned his lesson. His new experiment would be 10,000 times more sensitive. Before we describe his startling results, we return to the theory of stellar energy generation.

The Solar Furnace

In Chapter 13 , we explained how the Sun derives much of its power from the fusion reaction

$$^3\text{He} + ^3\text{He} \longrightarrow {}^4\text{He} + p + p + 12.9\ \text{MeV} \tag{11}$$

The fuel to maintain this reaction is fueled by the two-step process:

$$p + p \longrightarrow {}^2\text{H} + e^+ + \nu \tag{12a}$$

$$^2\text{H} + p \longrightarrow {}^3\text{He} + \gamma \tag{12b}$$

To make a ^{4}He nucleus from four protons, two of them must be converted into neutrons by means of the weak interaction process (12a), releasing two positrons and two neutrinos. The synthesis of one ^{4}He nucleus produces a total of 28 MeV. The positrons annihilate with electrons in the Sun and contribute to its radiant energy production. The neutrinos, which carry about 2 percent of the Sun's radiant energy, are so weakly interacting that they easily pass through the Sun. About 6×10^{14} neutrinos from the *pp* reaction (12a) reach Earth per square meter per second. Day and night, enormous numbers of neutrinos stream harmlessly through our planet, our bodies, and Davis's huge tank of cleaning fluid. However, their energies (typically 0.3 MeV) are too small to induce reaction 10.

Many other thermonuclear reactions take place in the Sun. Among them is the side chain:

$$^{3}\text{He} + {}^{4}\text{He} \longrightarrow {}^{7}\text{Be} + \gamma \tag{13a}$$

$$^{7}\text{Be} + p \longrightarrow {}^{8}\text{B} + \gamma \tag{13b}$$

$$^{8}\text{B} \longrightarrow {}^{8}\text{Be} + e^{+} + \nu \tag{13c}$$

$$^{8}\text{Be} \longrightarrow \alpha + \alpha \tag{13d}$$

These reactions produce a tiny fraction of the Sun's power. They are important because the neutrinos resulting from reaction 13c are more energetic than those produced by the dominant *pp* reaction and are therefore easier to detect. The mean energy of the ^{8}B neutrinos is about 6 MeV, but only 1 in 10,000 solar neutrinos is of this kind.

The end product of the Sun's thermonuclear reactions is ^{4}He. Because no $A = 8$ nucleus is stable, the Sun cannot pursue nuclear fusion beyond this point. All the larger elements that exist on Earth and in the Sun are remnants of the fiery deaths of earlier generations of stars.

Astrophysicists are confident of their knowledge of the processes that take place within the Sun and other stars, and they can explain stellar history and evolution. The Sun, when it runs out of hydrogen, will begin to collapse and heat up. When the core reaches a critical temperature, its helium will start to burn by the *triple* α process:

$$\alpha + \alpha + \alpha \longrightarrow {}^{12}\text{C} + \gamma$$

This process will proceed more like a bomb than a reactor and will some day cause the Sun to explode and engulf the planets. Stars larger than the Sun may withstand the triple-α process, but they face an even more calamitous death later on. They may become supernova.

Are the stars as well understood as we think? The light from a star comes from its surface, but the neutrinos produced by a star originate at its core. By detecting solar neutrinos on Earth and measuring their energies, scientists can confirm their theory of stellar energy generation. The chlorine experiment, to everyone's surprise, taught us that something is amiss in our understanding of either particles or stars.

The Chlorine Experiment

Since 1970, Davis has deployed a tank containing 600 tons of C_2Cl_4 deep underground at the Homestake Gold Mine in South Dakota. Reaction 10 can only take place if the neutrino's energy exceeds 1 MeV. Every few days, an energetic solar neutrino coming from ^{8}B decay succeeds in transmuting one chlorine atom into argon. Every month or so, for the last 20 years, Davis and his collaborators have been extracting and counting (and are still extracting and counting!) the argon atoms produced by solar neutrinos.

The good news is that Davis has observed neutrinos coming from the Sun. The experiment has detected decaying ^{37}A atoms at an average rate of about 12 per month. Thus, the Sun is most certainly a fusion reactor. The bad news is that Davis has seen too few neutrinos. Detailed astrophysical calculations by Bahcall and others imply that Davis should see about 30 events per month. Why has this not happened? The solar neutrino problem has three possible resolutions:

1. Davis erred and the experimental data are wrong. This is unlikely. The results of the chlorine experiment have been confirmed by other experiments.
2. Bahcall erred and the astrophysical calculation of the expected number of solar neutrinos is wrong. This is also unlikely. Other calculations confirm Bahcall's result.
3. The currently favored explanation for the observed discrepancy between experiment and theory is that something happened to the neutrinos on their way out of the Sun. There are three different kinds of neutrinos in nature, of which only one is involved in the process of β decay. Many physicists believe that solar neutrinos change their identities on their journey through the Sun and to Earth.

The truth is that scientists are not really sure about what is going on, although they hope to find out in the near future.

Other Experiments

I described the negative results of the search for nucleon decay in Section 14.2. The Japanese nucleon-decay detector (called *Kamiokande* because it is sited near the town of Kamioka) has been recycled—today, it searches for neutrinos from space. The most energetic neutrinos from ^{8}B decay produce the following reaction within this giant underground water tank:

$$\nu + e^- \longrightarrow \nu + e^-$$

Much of the neutrino's kinetic energy is transferred to the struck electron, which, in turn, produces a characteristic light signal in the tank. Kamiokande has detected solar neutrinos and confirmed the Davis result—only about half the predicted number of neutrinos were seen.

Two other large experiments sensitive to the copious, but lower energy, *pp* neutrinos are now under way. Both use gallium and the neutrino-induced reaction

$$\nu + {}^{71}\text{Ga} \longrightarrow e^- + {}^{71}\text{Ge}$$

In these experiments, radioactive germanium atoms produced by solar neutrinos are collected and counted, as in the chlorine experiment. Most of the Sun's neutrinos are energetic enough to react with gallium nuclei. One of these experiments, the GALLEX experiment, is primarily a European collaboration. It involves 30 tons of gallium (about the annual world production) placed in an underground laboratory under Gran Sasso Mountain near Rome. A second experiment, still known by the acronym SAGE, for Soviet-American Gallium Experiment, is being done in Russia. Published reports from both gallium experiments confirm that fewer solar neutrinos are seen than are expected.

Unless there is something wrong with the solar model, we are forced to believe that electron neutrinos are turned into other neutrino species on their way out of the Sun. This means that neutrinos must have nonzero masses and must be endowed with properties that are not yet fully understood. Within a few years, scientists at two new, large solar neutrino laboratories—one in Canada and one in Japan—will detect and measure thousands of solar neutrinos. Solar neutrino physics, which began as an attempt to confirm the theory of solar structure and evolution, has turned about completely. It is telling us things about neutrinos (or perhaps, something about the Sun) we could never have discovered without neutrino astronomy. Serendipity is rampant in science—no one can tell what surprises await the intrepid experimenter.

Supernova Neutrinos

All stars produce neutrinos, but only the Sun is near enough to let us see its neutrinos—unless it's a star that suddenly becomes supernova. A supernova explosion releases 2×10^{47} J of energy in a few seconds—hundreds of times more than the Sun produces in its entire lifetime! Only a tiny fraction of this energy appears as starlight. Even so, the star becomes billions of times brighter than it was. Almost all the energy of a supernova is emitted in a few seconds in the form of neutrinos! Supernovae are rare occurrences; the average galaxy produces supernovae at a rate of a few per century. The last one known to have exploded in the Milky Way (our galaxy) was seen in 1604.

Thus, scientists were delighted on February 23, 1987, when a supernova appeared. The exploding star is in the Larger Magellanic Cloud, an appendix to the Milky Way, 160,000 light-years away. The new supernova was clearly visible to observers in the southern hemisphere—and to particle physicists in Japan and Ohio! The two great experiments searching for proton decay did not see what they set out to see; they saw supernova neutrinos instead. Within a 12-second interval, Kamiokande detected 12 neutrino events, the American group another 8. The results agreed with the predictions of astrophysicists, whose theory of stellar collapse was confirmed by the newborn science of neutrino astronomy. The next time a star in our galaxy explodes as a supernova—perhaps in a century, or maybe next year—neutrino astronomers will observe thousands of its neutrinos. The tiniest elementary particles will tell us what we cannot otherwise know about the death throes of a giant star.

Exercises

15. Explain why a fission reactor is a source of antineutrinos while the Sun is a source of neutrinos.

16. What is the mass of hydrogen in kilograms consumed by the Sun in each second? How much of the solar mass is converted into energy per second?

17. The reaction $p + p \rightarrow {}^2H_1 + e^+ + \nu$ is exothermic. In principle, the two protons in a hydrogen molecule could fuse, releasing 1.5 MeV of energy. Why is it that this process is never observed on Earth?

18. The flux of solar neutrinos on Earth is about 6×10^{14} per square meter per second. Their mean energy is 0.3 MeV.
    a. Estimate the number of neutrinos radiated by the Sun in one second.
    b. Estimate the power radiated by the Sun in the form of neutrinos.
    c. What fraction of the solar luminosity is the result of part b?

19. The radius of a nucleus containing A nucleons is about $1.2 \times 10^{-15} A^{1/3}$ m. What would the radius of the Sun become if it were compressed to nuclear density? (*Hint:* the Sun is made up of about 10^{57} nucleons.)

20. An exploding supernova releases 2×10^{47} J of energy. Calculate the mass in kilograms that has been converted into energy. Compare your result to the mass of the Sun.

Where We Are and Where Are We Going

Quantum electrodynamics is a precise and predictive theory describing the interactions of photons, electrons, and positrons. However, other forms of matter exist in the universe as well. In particular, there are neutrons and protons that somehow stick together to form nuclei. Are these elementary, or are they made from simpler things? What is the origin of the force that holds nucleons together? Radioactivity was understood as a nuclear transformation. The β process allows a proton to become a neutron, and vice versa. At the same time, a pair of leptons is produced. What is the fundamental mechanism underlying this process?

In Chapter 15, we shall answer all these questions. The 1970s was a time of explosive development of our knowledge of the microworld. The behavior of elementary particles results from the interplay of three fundamental forces of nature: electromagnetism and the strong and weak nuclear forces. Using quantum electrodynamics as a model, scientists developed a theory, called the standard model of elementary particle physics, that describes these forces. Experiment after experiment has confirmed the predictions of the standard model, which offers a consistent picture of all elementary particle phenomena. Although the model appears to be correct, it is also manifestly incomplete and some day will be replaced by a more powerful deluxe model. As questions about nature are posed and then solved, new and deeper questions arise. The more we learn about the universe, the more we want to learn.