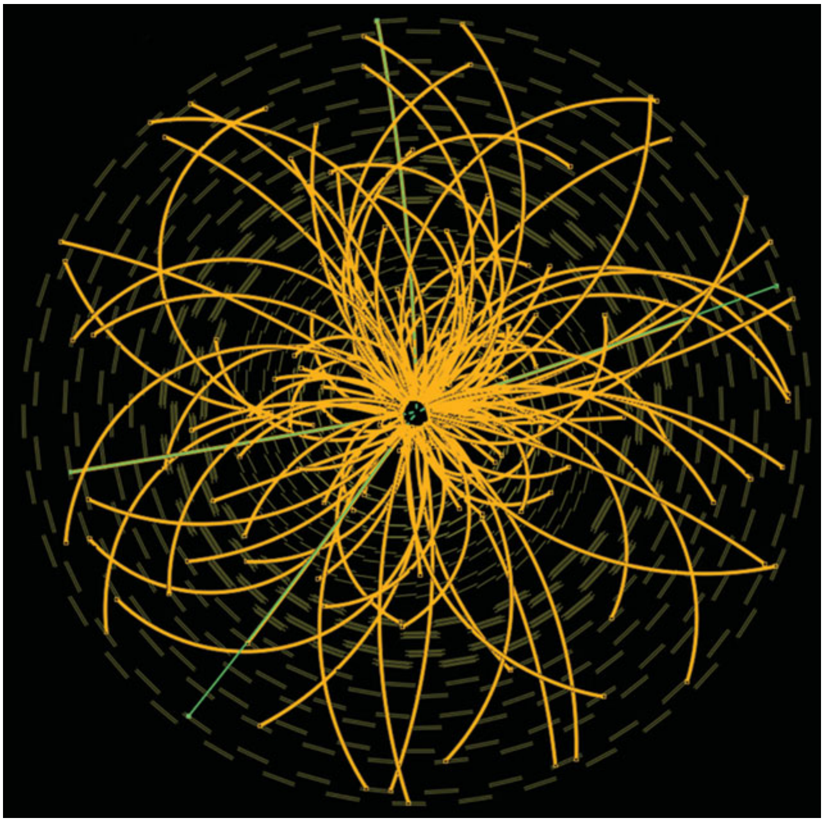

This photo is a computer reconstruction of particles produced due to a 7 TeV proton–proton collision at the Large Hadron Collider (LHC). It is a candidate for having produced the long-sought Higgs boson (plus other particles). The Higgs in this case could have decayed (very quickly $\sim 10^{-22}$ s) into two Z bosons (which are carriers of the weak force):

$$\mathrm{H}^0 \rightarrow \mathrm{Z}^0 + \mathrm{Z}^0.$$

We don't see the tracks of the Z^0 particles because (1) they are neutral and (2) they decay too quickly ($\sim 10^{-24}$ s), in this case:

$$\mathrm{Z}^0 \rightarrow \mathrm{e}^- + \mathrm{e}^+.$$

The tracks of the 2 electrons and 2 positrons are shown as green lines. The Higgs is thought to play a fundamental role in the Standard Model of particle physics, importantly providing mass to fundamental particles.

The CMS detector of this photo uses a combination of the detector types discussed in Section 30–13. A magnetic field causes particles to move in curved paths so the momentum of each can be measured (Section 20–4). Tracks of particles with very large momentum, such as our electrons here, are barely curved.

In this Chapter we will study elementary particle physics from its beginnings until today, including antiparticles, neutrinos, quarks, the Standard Model, and theories that go beyond. We start with the great machines that accelerate particles so they can collide at high energies.

CHAPTER 32

Elementary Particles

CHAPTER-OPENING QUESTIONS—Guess now!

1. Physicists reserve the term "fundamental particle" for particles with a special property. What do you think that special property is?

(a) Particles that are massless.
(b) Particles that possess the minimum allowable electric charge.
(c) Particles that have no internal structure.
(d) Particles that produce no force on other objects.

2. The fundamental particles as we see them today, besides the long-sought-for Higgs boson, are

(a) atoms and electrons.
(b) protons, neutrons, and electrons.
(c) protons, neutrons, electrons, and photons.
(d) quarks, leptons, and gauge bosons (carriers of force).
(e) hadrons, leptons, and gauge bosons.

In the final two Chapters of this book we discuss two of the most exciting areas of contemporary physics: elementary particles in this Chapter, and cosmology and astrophysics in Chapter 33. These are subjects at the forefront of knowledge—elementary particles treats the smallest objects in the universe; cosmology treats the largest (and oldest) aspects of the universe. The reader who wants an understanding of the great beauties of present-day science (and its limits) will want to read these Chapters. So will those who want to be good citizens, even if there is not time to cover them in a physics course.

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In this penultimate Chapter we discuss *elementary particle* physics, which represents the human endeavor to understand the basic building blocks of all matter, and the fundamental forces that govern their interactions.

Almost a century ago, by the 1930s, it was accepted that all atoms can be considered to be made up of neutrons, protons, and electrons. The basic constituents of the universe were no longer considered to be atoms (as they had been for 2000 years) but rather the proton, neutron, and electron. Besides these three "elementary particles," several others were also known: the positron (a positive electron), the neutrino, and the γ particle (or photon), for a total of six elementary particles.

By the 1950s and 1960s many new types of particles similar to the neutron and proton were discovered, as well as many "midsized" particles called *mesons* whose masses were mostly less than nucleon masses but more than the electron mass. (Other mesons, found later, have masses greater than nucleons.) Physicists felt that these particles could not all be fundamental, and must be made up of even smaller constituents (later confirmed by experiment), which were given the name *quarks*.

By the term **fundamental particle**, we mean a particle that is so simple, so basic, that it has no internal structure[†] (is not made up of smaller subunits)—see Chapter-Opening Question 1.

Today, the fundamental constituents of matter are considered to be **quarks** (they make up protons and neutrons as well as mesons) and **leptons** (a class that includes electrons, positrons, and neutrinos). There are also the "carriers of force" known as **gauge bosons**, including the photon, gluons, and W and Z bosons. In addition there is the elusive **Higgs** boson, predicted in the 1960s but whose first suggestions of experimental detection came only in 2011–2013. The theory that describes our present view is called the **Standard Model**. How we came to our present understanding of elementary particles is the subject of this Chapter.

One of the exciting developments of the last few years is an emerging synthesis between the study of elementary particles and astrophysics (Chapter 33). In fact, recent observations in astrophysics have led to the conclusion that the greater part of the mass–energy content of the universe is not ordinary matter but two mysterious and invisible forms known as "dark matter" and "dark energy" which cannot be explained by the Standard Model in its present form.

Indeed, we are now aware that the Standard Model is not sufficient. There are problems and important questions still unanswered, and we will mention some of them in this Chapter and how we hope to answer them.

32–1 High-Energy Particles and Accelerators

In the late 1940s, after World War II, it was found that if the incoming particle in a nuclear reaction (Section 31–1) has sufficient energy, new types of particles can be produced. The earliest experiments used **cosmic rays**—particles that impinge on the Earth from space. In the laboratory, various types of particle accelerators have been constructed to accelerate protons or electrons to high energies so they can collide with other particles—often protons (the hydrogen nucleus). Heavy ions, up to lead (Pb), have also been accelerated. These **high-energy accelerators** have been used to probe more deeply into matter, to produce and study new particles, and to give us information about the basic forces and constituents of nature. The particles produced in high-energy collisions can be detected by a variety of special detectors, discussed in Section 30–13, including scintillation counters, bubble chambers, multiwire chambers, and semiconductors. The rate of production of

---

[†] Recall from Section 13–1 that the word "atom" comes from the Greek meaning "indivisible." Atoms have a substructure (protons, neutrons) so are not fundamental. Yet an atom is still the smallest "piece" of an element that has the characteristics of that material.

any group of particles is quantified using the concept of *cross section*, Section 31–1. Because the projectile particles are at high energy, this field is sometimes called **high-energy physics**.

Wavelength and Resolution

Particles accelerated to high energy can probe the interior of nuclei and nucleons or other particles they strike. An important factor is that faster-moving projectiles can reveal more detail. The wavelength of projectile particles is given by de Broglie's wavelength formula (Eq. 27–8),

$$\lambda = \frac{h}{p}, \tag{32–1}$$

showing that the greater the momentum p of the bombarding particle, the shorter its wavelength. As discussed in Chapter 25 on optical instruments, resolution of details in images is limited by the wavelength: the shorter the wavelength, the finer the detail that can be obtained. This is one reason why particle accelerators of higher and higher energy have been built in recent years: to probe ever deeper into the structure of matter, to smaller and smaller size.

EXAMPLE 32–1 **High resolution with electrons.** What is the wavelength, and hence the expected resolution, for 1.3-GeV electrons?

APPROACH Because 1.3 GeV is much larger than the electron mass, we must be dealing with relativistic speeds. The momentum of the electrons is found from Eq. 26–9, and the wavelength is $\lambda = h/p$.

SOLUTION Each electron has $\text{KE} = 1.3\,\text{GeV} = 1300\,\text{MeV}$, which is about 2500 times the rest energy of the electron $\left(mc^2 = 0.51\,\text{MeV}\right)$. Thus we can ignore the term $\left(mc^2\right)^2$ in Eq. 26–9, $E^2 = p^2c^2 + m^2c^4$, and we solve for p:

$$p = \sqrt{\frac{E^2 - m^2c^4}{c^2}} \approx \sqrt{\frac{E^2}{c^2}} = \frac{E}{c}.$$

Therefore the de Broglie wavelength is

$$\lambda = \frac{h}{p} = \frac{hc}{E},$$

where $E = 1.3\,\text{GeV}$. Hence

$$\lambda = \frac{\left(6.63 \times 10^{-34}\,\text{J}\cdot\text{s}\right)\left(3.0 \times 10^{8}\,\text{m/s}\right)}{\left(1.3 \times 10^{9}\,\text{eV}\right)\left(1.6 \times 10^{-19}\,\text{J/eV}\right)} = 0.96 \times 10^{-15}\,\text{m},$$

or 0.96 fm. This resolution of about 1 fm is on the order of the size of nuclei (see Eq. 30–1).

NOTE The maximum possible resolution of this beam of electrons is far greater than for a light beam in a light microscope $(\lambda \approx 500\,\text{nm})$.

EXERCISE A What is the wavelength of a proton with $\text{KE} = 1.00\,\text{TeV}$?

A major reason today for building high-energy accelerators is that new particles of greater mass can be produced at higher collision energies, transforming the kinetic energy of the colliding particles into massive particles by $E = mc^2$, as we will discuss shortly. Now we look at particle accelerators.

Cyclotron

The cyclotron was developed in 1930 by E. O. Lawrence (1901–1958; Fig. 32–1) at the University of California, Berkeley. It uses a magnetic field to maintain charged ions—usually protons—in nearly circular paths. Although particle physicists no longer use simple cyclotrons, they are used in medicine for treating cancer, and their operating principles are useful for understanding modern accelerators.

FIGURE 32–1 Ernest O. Lawrence, left, with Donald Cooksey and the "dees" of an early cyclotron.

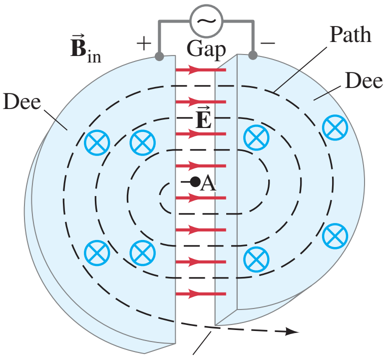


FIGURE 32–2 Diagram of a cyclotron. The magnetic field, applied by a large electromagnet, points into the page. The protons start at A, the ion source. The red electric field lines shown are for the alternating electric field in the gap at a certain moment.

The protons move in a vacuum inside two D-shaped cavities, as shown in Fig. 32–2. Each time they pass into the gap between the "dees," a voltage accelerates them (the electric force), increasing their speed and increasing the radius of curvature of their path in the magnetic field. After many revolutions, the protons acquire high kinetic energy and reach the outer edge of the cyclotron where they strike a target. The protons speed up only when they are in the gap *between* the dees, and the voltage must be alternating. When protons are moving to the right across the gap in Fig. 32–2, the right dee must be electrically negative and the left one positive. A half-cycle later, the protons are moving to the left, so the left dee must be negative in order to accelerate them.

The frequency, f, of the applied voltage must be equal to the frequency of the circulating protons. When ions of charge q are circulating *within* the hollow dees, the net force F on each ion is due to the magnetic field B, so $F = qvB$, where v is the speed of the ion at a given moment (Eq. 20–4). The magnetic force is perpendicular to both $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$, and does not speed up the ions but causes them to move in circles; the acceleration within the dees is centripetal and equals v^2/r, where r is the radius of the ion's path at a given moment. We use Newton's second law, $F = ma$, and find that

$$F = ma$$

$$qvB = \frac{mv^2}{r}$$

when the protons are within the dees (not the gap), so their (constant) speed at radius r is

$$v = \frac{qBr}{m}.$$

The time required for a complete revolution is the period T and is equal to

$$T = \frac{\text{distance}}{\text{speed}} = \frac{2\pi r}{qBr/m} = \frac{2\pi m}{qB}.$$

Hence the frequency of revolution f is

$$f = \frac{1}{T} = \frac{qB}{2\pi m}. \qquad \textbf{(32–2)}$$

This is known as the **cyclotron frequency**.

EXAMPLE 32–2 **Cyclotron.** A small cyclotron of maximum radius $R = 0.25\,\text{m}$ accelerates protons in a 1.7 T magnetic field. Calculate (*a*) the frequency needed for the applied alternating voltage, and (*b*) the kinetic energy of protons when they leave the cyclotron.

APPROACH The frequency of the protons revolving within the dees (Eq. 32–2) must equal the frequency of the voltage applied across the gap if the protons are going to increase in speed.

SOLUTION (*a*) From Eq. 32–2,

$$f = \frac{qB}{2\pi m} = \frac{(1.6 \times 10^{-19}\,\text{C})(1.7\,\text{T})}{(6.28)(1.67 \times 10^{-27}\,\text{kg})} = 2.6 \times 10^{7}\,\text{Hz} = 26\,\text{MHz},$$

which is in the radio-wave region of the EM spectrum (Fig. 22–8).

(*b*) The protons leave the cyclotron at $r = R = 0.25\,\text{m}$. From $qvB = mv^2/r$ (see above), we have $v = qBr/m$, so their kinetic energy is

$$\text{KE} = \frac{1}{2}mv^2 = \frac{1}{2}m\frac{q^2B^2R^2}{m^2} = \frac{q^2B^2R^2}{2m}$$

$$= \frac{(1.6 \times 10^{-19}\,\text{C})^2(1.7\,\text{T})^2(0.25\,\text{m})^2}{(2)(1.67 \times 10^{-27}\,\text{kg})} = 1.4 \times 10^{-12}\,\text{J} = 8.7\,\text{MeV}.$$

NOTE The kinetic energy is much less than the rest energy of the proton (938 MeV), so relativity is not needed.

NOTE The magnitude of the voltage applied to the dees does not appear in the formula for KE, and so does not affect the final energy. But the higher this voltage, the fewer the revolutions required to bring the protons to full energy.

An important aspect of the cyclotron is that the frequency of the applied voltage, as given by Eq. 32–2, does not depend on the radius r of the particle's path. Thus the frequency does not have to be changed as the protons or ions start from the source and are accelerated to paths of larger and larger radii. But this is only true at nonrelativistic energies. At higher speeds, the momentum (Eq. 26–4) is $p = \gamma mv = mv/\sqrt{1 - v^2/c^2}$, so m in Eq. 32–2 has to be replaced by γm and the cyclotron frequency f (Eq. 32–2) depends on speed v because γ does. To keep the particles in sync, machines called **synchrocyclotrons** reduce the frequency in time to correspond to the increase of γm (in Eq. 32–2) as a packet of charged particles increases in speed more slowly at larger orbits.

Synchrotron

Another way to accelerate relativistic particles is to increase the magnetic field B in time so as to keep f (Eq. 32–2) constant as the particles speed up. Such devices are called **synchrotrons**; the particles move in a circle of fixed radius, which can be very large. The larger the radius, the greater the KE of the particles can be for a given magnetic field strength (see argument on previous page). The biggest synchrotron of all is at the European Center for Nuclear Research (CERN) in Geneva, Switzerland, the Large Hadron Collider (LHC). It is 4.3 km in radius, and 27 km in circumference, and accelerates protons to 4 TeV (soon to be 7 TeV).

FIGURE 32–3 The interior of the tunnel of the main accelerator at Fermilab, showing (red) the ring of superconducting magnets used to keep particles moving in a circular path at the 1-TeV Tevatron.

The *Tevatron* accelerator at Fermilab (Fermi National Accelerator Laboratory, near Chicago, Illinois, has a radius of 1.0 km.[†] The Tevatron accelerated protons to about 1000 GeV = 1 TeV (hence its name, 1 TeV = 10^{12} eV). It was shut down in 2011.

These large synchrotrons use a narrow ring of magnets (see Fig. 32–3) with each magnet placed at the same radius from the center of the circle. The magnets are interrupted by gaps where high voltage accelerates the particles to higher speeds. Another way to describe the acceleration is to say the particles "surf" on a traveling electromagnetic wave within radiofrequency (RF) cavities. (The particles are first given considerable energy in smaller accelerators, "injectors," before being injected into the large ring of the large synchrotron.)

One problem of any accelerator is that accelerating electric charges radiate electromagnetic energy (see Chapter 22). Since ions or electrons are accelerated in an accelerator, we can expect considerable energy to be lost by radiation. The effect increases with energy and is especially important in circular machines where centripetal acceleration is present, such as synchrotrons, and hence is called **synchrotron radiation**. Synchrotron radiation can be useful, however. Intense beams of photons (γ rays) are sometimes needed, and they are often obtained from an electron synchrotron. Strong sources of such photons are referred to as **light sources**.

[†] Robert Wilson, who helped design the Tevatron, and founded the field of proton therapy (Section 31–6), expressed his views on accelerators and national security in this exchange with Senator John Pastore during testimony before a Congressional Committee in 1969:

> Pastore: "Is there anything connected with the hopes of this accelerator [the Tevatron] that in any way involves the security of the country?"
>
> Robert Wilson: "No sir, I don't believe so."
>
> Pastore: "Nothing at all?"
>
> Wilson: "Nothing at all. … "
>
> Pastore: "It has no value in that respect?"
>
> Wilson: "It has only to do with the respect with which we regard one another, the dignity of men, our love of culture. … It has to do with are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about … it has nothing to do directly with defending our country except to make it worth defending."

Linear Accelerators

In a **linear accelerator** (linac), electrons or ions are accelerated along a straight-line path, Fig. 32–4, passing through a series of tubular conductors. Voltage applied to the tubes is alternating so that when electrons (say) reach a gap, the tube in front of them is positive and the one they just left is negative. At low speeds, the particles cover less distance in the same amount of time, so the tubes are shorter at first. Electrons, with their small mass, get close to the speed of light quickly, $v \approx c$, and the tubes are nearly equal in length. Linear accelerators are particularly important for accelerating electrons to avoid loss of energy due to synchrotron radiation. The largest electron linear accelerator has been at Stanford University (Stanford Linear Accelerator Center, or SLAC), about 3 km (2 mi) long, accelerating electrons to 50 GeV. Linacs accelerating protons are used as injectors into circular machines to provide initial kinetic energy. Many hospitals have 10-MeV electron linacs that strike a metal foil to produce γ ray photons to irradiate tumors.

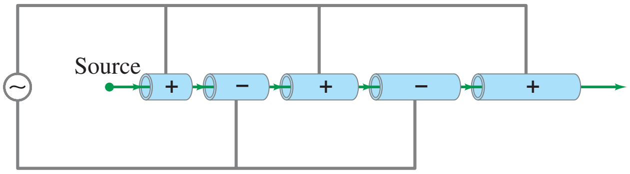


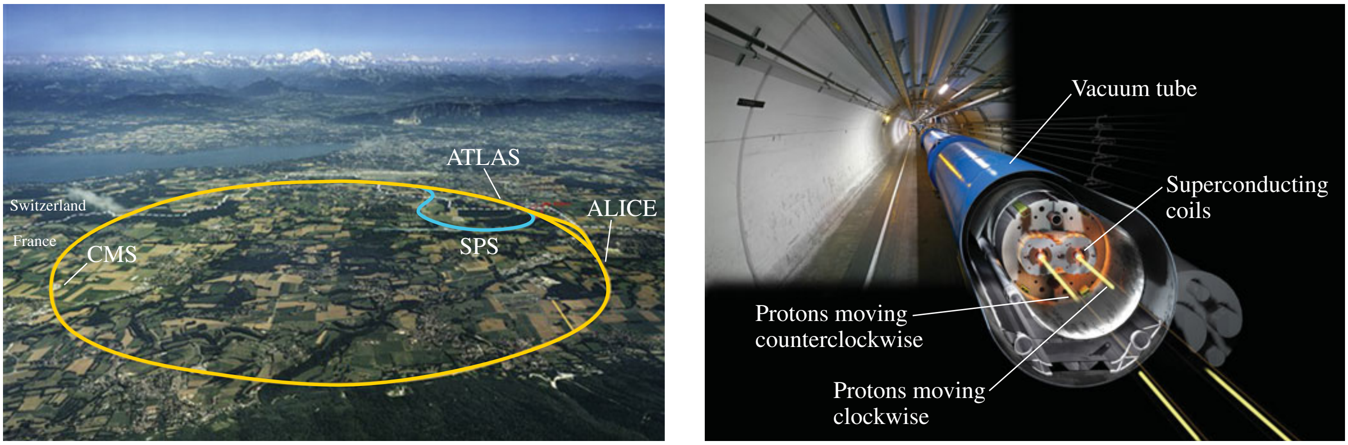
FIGURE 32–4 Diagram of a simple linear accelerator.

Colliding Beams

High-energy physics experiments were once done by aiming a beam of particles from an accelerator at a stationary target. But to obtain the maximum possible collision energy from a given accelerator, two beams of particles are now accelerated to very high energy and are steered so that they collide head-on. One way to accomplish such **colliding beams** with a single accelerator is through the use of **storage rings**, in which oppositely circulating beams can be repeatedly brought into collision with one another at particular points. For example, in the experiments that provided strong evidence for the top quark (Section 32–9 and Fig. 32–15), the Fermilab Tevatron accelerated protons and antiprotons each to 900 GeV, so that the combined energy of head-on collisions was 1.8 TeV.

The largest collider is the Large Hadron Collider (LHC) at CERN, with a circumference of 26.7 km (Fig. 32–5). The two colliding beams are designed to each carry 7-TeV protons for a total interaction energy of 14 TeV. For the experiments in 2011 and 2012 the total interaction energy was 7 TeV and 8 TeV. The protons for each of the beams, moving in opposite directions, are accelerated in several stages. The penultimate is SPS (Super Proton Synchrotron), seen in Fig. 32–5a which accelerates protons from 28 GeV to the 450 GeV at which they are injected into the LHC itself.

FIGURE 32–5 (a) The large circle represents the position of the tunnel, about 100 m below the ground at CERN (near Geneva) on the French–Swiss border, which houses the LHC. The smaller circle shows the position of the Super Proton Synchrotron used for accelerating protons prior to injection into the LHC. (b) Circulating proton beams, in opposite directions, inside the vacuum tube within the LHC tunnel.



(a)

(b)

Figure 32–6 shows part of one of the detectors (ATLAS) as it was being constructed at the LHC. The detectors within ATLAS include silicon semiconductor detectors with huge numbers of pixels used to track particle paths and find their point of interaction, and to measure their radius of curvature in a magnetic field and thus determine their momentum (Section 20–4). Their energy is determined in "calorimeters" utilizing plastic, liquid, or dense metal compound crystal scintillators (Section 30–13).

In the planning stage is the International Linear Collider (ILC) which would have colliding beams of e^- and e^+ at around 0.3 to 1 TeV. It would utilize semiconductor detectors using CMOS (Section 25–1) with embedded transistors to allow fast readout.

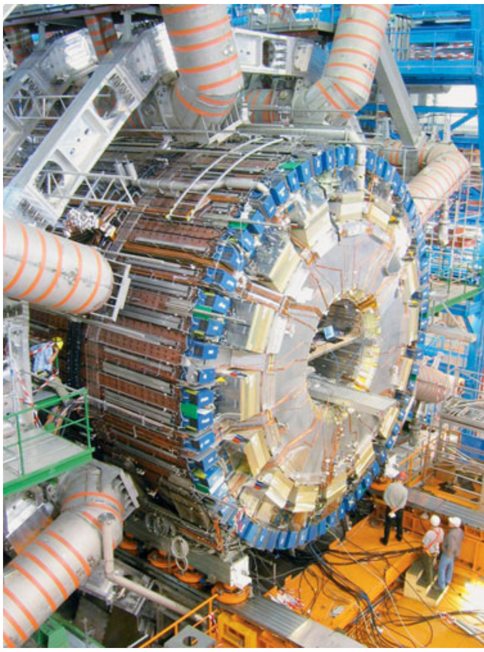


FIGURE 32–6 ATLAS, one of the large complex detectors at the LHC, is shown here as it was being built. In 2012 it was used to provide evidence for the Higgs boson. Note the people near the bottom. From the outside, the CMS detector at the LHC looks similar.

EXAMPLE 32–3 **Protons at relativistic speeds.** Determine the energy required to accelerate a proton in a high-energy accelerator (*a*) from rest to $v = 0.900c$, and (*b*) from $v = 0.900c$ to $v = 0.999c$. (*c*) What is the kinetic energy achieved by the proton in each case?

APPROACH We use the work-energy principle, which is still valid relativistically as mentioned in Section 26–9: $W = \Delta\text{KE}$.

SOLUTION The kinetic energy of a proton of mass m is given by Eq. 26–5,

$$\text{KE} = (\gamma - 1)mc^2,$$

where the relativistic factor γ is

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

The work-energy theorem becomes

$$W = \Delta\text{KE} = (\gamma_2 - 1)mc^2 - (\gamma_1 - 1)mc^2 = (\gamma_2 - \gamma_1)mc^2$$

where γ_1 and γ_2 are for the initial and final speeds, $v_1 = 0$, $v_2 = 0.900c$.

(*a*) For $v = v_1 = 0$, $\gamma_1 = 1$; and for $v_2 = 0.900c$

$$\gamma_2 = \frac{1}{\sqrt{1 - (0.900)^2}} = 2.29.$$

For a proton, $mc^2 = 938\text{ MeV}$, so the work (or energy) needed to accelerate it from rest to $v_2 = 0.900c$ is

$$\begin{aligned} W = \Delta\text{KE} &= (\gamma_2 - \gamma_1)mc^2 \\ &= (2.29 - 1.00)(938\text{ MeV}) = 1.21\text{ GeV}. \end{aligned}$$

(*b*) To go from $v_2 = 0.900c$ to $v_3 = 0.999c$, we need

$$\gamma_3 = \frac{1}{\sqrt{1 - (0.999)^2}} = 22.4.$$

So the work needed to accelerate a proton from $0.900c$ to $0.999c$ is

$$\begin{aligned} W = \Delta\text{KE} &= (\gamma_3 - \gamma_2)mc^2 \\ &= (22.4 - 2.29)(938\text{ MeV}) = 18.9\text{ GeV}, \end{aligned}$$

which is 15 times as much.

(*c*) The kinetic energy reached by the proton in (*a*) is just equal to the work done on it, $\text{KE} = 1.21\text{ GeV}$. The final kinetic energy of the proton in (*b*), moving at $v_3 = 0.999c$, is

$$\text{KE} = (\gamma_3 - 1)mc^2 = (21.4)(938\text{ MeV}) = 20.1\text{ GeV}.$$

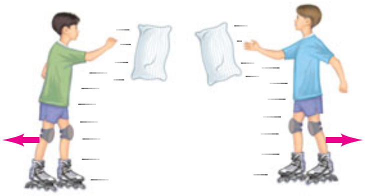
NOTE This result makes sense because, starting from rest, we did work

$$W = 1.21\text{ GeV} + 18.9\text{ GeV} = 20.1\text{ GeV}$$

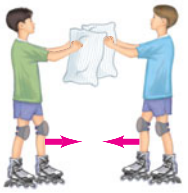
on it.

32–2 Beginnings of Elementary Particle Physics—Particle Exchange

The accepted model for elementary particles today views *quarks* and *leptons* as the fundamental constituents of ordinary matter. To understand our present-day view of elementary particles, it is necessary to understand the ideas leading up to its formulation.



(a) Repulsive force (children throwing pillows)



(b) Attractive force (children grabbing pillows from each other's hands)

FIGURE 32–7 Forces equivalent to particle exchange. (a) Repulsive force (children on roller skates throwing pillows at each other). (b) Attractive force (children grabbing pillows from each other's hands).

Elementary particle physics might be said to have begun in 1935 when the Japanese physicist Hideki Yukawa (1907–1981) predicted the existence of a new particle that would in some way mediate the strong nuclear force. To understand Yukawa's idea, we first consider the electromagnetic force. When we first discussed electricity, we saw that the electric force acts over a distance, without contact. To better perceive how a force can act over a distance, we used the idea of a **field**. The force that one charged particle exerts on a second can be said to be due to the electric field set up by the first. Similarly, the magnetic field can be said to carry the magnetic force. Later (Chapter 22), we saw that electromagnetic (EM) fields can travel through space as waves. Finally, in Chapter 27, we saw that electromagnetic radiation (light) can be considered as either a wave or as a collection of particles called *photons*. Because of this wave–particle duality, it is possible to imagine that the electromagnetic force between charged particles is due to

(1) the EM field set up by one charged particle and felt by the other, or

(2) an exchange of photons (γ particles) between them.

It is (2) that we want to concentrate on here, and a crude analogy for how an exchange of particles could give rise to a force is suggested in Fig. 32–7. In part (a), two children start throwing heavy pillows at each other; each throw and each catch results in the child being pushed backward by the impulse. This is the equivalent of a repulsive force. On the other hand, if the two children exchange pillows by grabbing them out of the other person's hand, they will be pulled toward each other, as when an attractive force acts.

For the electromagnetic force, it is photons exchanged between two charged particles that give rise to the force between them. A simple diagram describing this photon exchange is shown in Fig. 32–8. Such a diagram, called a **Feynman diagram** after its inventor, the American physicist Richard Feynman (1918–1988), is based on the theory of **quantum electrodynamics** (QED).

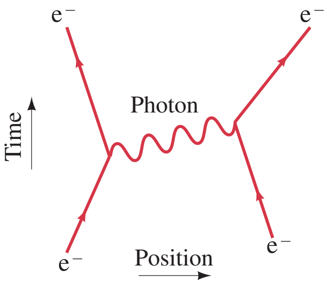


FIGURE 32–8 Feynman diagram showing a photon acting as the carrier of the electromagnetic force between two electrons. This is sort of an x vs. t graph, with t increasing upward. Starting at the bottom, two electrons approach each other. As they get close, momentum and energy get transferred from one to the other, carried by a photon (or more than one), and the two electrons bounce apart.

Figure 32–8 represents the simplest case in QED, in which a single photon is exchanged. One of the charged particles emits the photon and recoils somewhat as a result; and the second particle absorbs the photon. In such a collision or *interaction*, energy and momentum are transferred from one charged particle to the other, carried by the photon. The photon is absorbed by the second particle after it is emitted by the first particle and is not observable. Hence the photon is referred to as a **virtual** photon, in contrast to one that is free and can be detected by instruments. The photon is said to **mediate**, or **carry**, the electromagnetic force.

By analogy with photon exchange that mediates the electromagnetic force, Yukawa argued that there ought to be a particle that mediates the strong nuclear force—the force that holds nucleons together in the nucleus. Yukawa called this predicted particle a **meson** (meaning "medium mass"). Figure 32–9 is a Feynman diagram showing the original model of meson exchange: a meson carrying the strong force between a neutron and a proton.

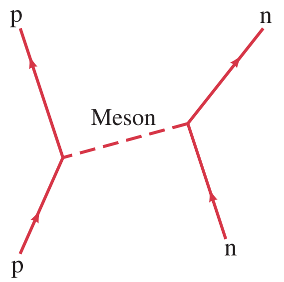


FIGURE 32–9 Early model showing meson exchange when a proton and neutron interact via the strong nuclear force. (Today, as we shall see shortly, we view the strong force as carried by gluons between quarks.)

A rough estimate of the mass of the meson can be made as follows. Suppose the proton on the left in Fig. 32–9 is at rest. For it to emit a meson would require energy (to make the meson's mass) which, coming from nowhere, would violate conservation of energy. But the uncertainty principle allows nonconservation of energy by an amount ΔE if it occurs only for a time Δt given by $(\Delta E)(\Delta t) \approx h/2\pi$. We set ΔE equal to the energy needed to create the mass m of the meson: $\Delta E = mc^2$. Conservation of energy is violated only as long as the meson exists, which is the time Δt required for the meson to pass from one nucleon to the other, where it is absorbed and disappears. If we assume the meson travels at relativistic speed, close to the speed of light c, then Δt need be at most about $\Delta t = d/c$, where d is the maximum distance that can separate the interacting nucleons. Thus we can write

$$\Delta E\,\Delta t \approx \frac{h}{2\pi}$$

$$mc^2\left(\frac{d}{c}\right) \approx \frac{h}{2\pi}$$

or

$$mc^2 \approx \frac{hc}{2\pi d}. \tag{32–3}$$

The range of the strong nuclear force (the maximum distance away it can be felt) is small—not much more than the size of a nucleon or small nucleus (see Eq. 30–1)—so let us take $d \approx 1.5 \times 10^{-15}$ m. Then from Eq. 32–3,

$$mc^2 \approx \frac{hc}{2\pi d} = \frac{(6.6\times10^{-34}\,\mathrm{J\cdot s})(3.0\times10^{8}\,\mathrm{m/s})}{(6.28)(1.5\times10^{-15}\,\mathrm{m})} \approx 2.1\times10^{-11}\,\mathrm{J} = 130\,\mathrm{MeV}.$$

The mass of the predicted meson, roughly 130 MeV/c^2, is about 250 times the electron mass of 0.51 MeV/c^2.

EXERCISE B What effect does an increase in the mass of the virtual exchange particle have on the range of the force it mediates? (*a*) Decreases it; (*b*) increases it; (*c*) has no appreciable effect; (*d*) decreases the range for charged particles and increases the range for neutral particles.

Note that since the electromagnetic force has infinite range, Eq. 32–3 with $d = \infty$ tells us that the exchanged particle for the electromagnetic force, the photon, will have zero mass, which it does.

The particle predicted by Yukawa was discovered in cosmic rays by C. F. Powell and G. Occhialini in 1947, and is called the "π" or pi meson, or simply the **pion**. It comes in three charge states: $+e$, $-e$, or 0, where $e = 1.6 \times 10^{-19}$ C. The π^+ and π^- have mass of 139.6 MeV/c^2 and the π^0 a mass of 135.0 MeV/c^2, all close to Yukawa's prediction. All three interact strongly with matter. Reactions observed in the laboratory, using a particle accelerator, include

$$\begin{aligned} \mathrm{p} + \mathrm{p} &\rightarrow \mathrm{p} + \mathrm{p} + \pi^0, \\ \mathrm{p} + \mathrm{p} &\rightarrow \mathrm{p} + \mathrm{n} + \pi^+. \end{aligned} \tag{32–4}$$

The incident proton from the accelerator must have sufficient energy to produce the additional mass of the free pion.

Yukawa's theory of pion exchange as carrier of the strong force has been superseded by *quantum chromodynamics* in which protons, neutrons, and other strongly interacting particles are made up of basic entities called *quarks*, and the basic carriers of the strong force are *gluons*, as we shall discuss shortly. But the basic idea of the earlier theory, that forces can be understood as the exchange of particles, remains valid.

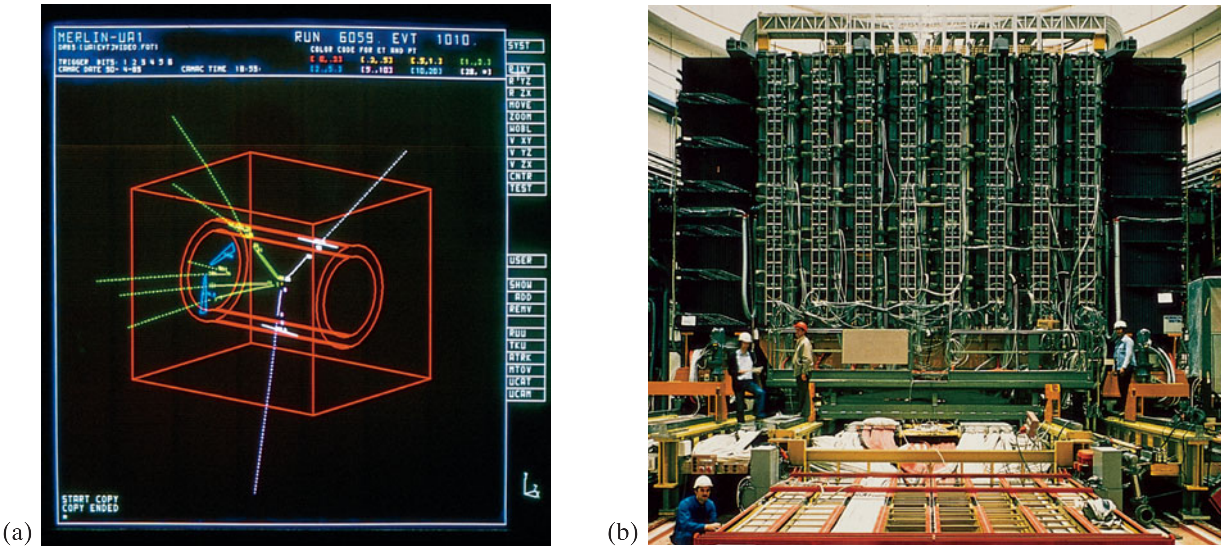


FIGURE 32–10 (a) Computer reconstruction of a Z-particle decay into an electron and a positron $(Z^0 \rightarrow e^+ + e^-)$ whose tracks are shown in white, which took place in the UA1 detector at CERN. (b) Photo of the UA1 detector at CERN as it was being built. 1980s.

There are four known types of force—or interactions—in nature. The electromagnetic force is carried by the photon, the strong force by gluons. What about the other two: the weak force and gravity? These too are believed to be mediated by particles. The particles that transmit the weak force are referred to as the W^+, W^-, and Z^0, and were detected in 1983 (Fig. 32–10). The quantum (or carrier) of the gravitational force has been named the **graviton**, but its existence has not been detected and it may not be detectable.

A comparison of the four forces is given in Table 32–1, where they are listed according to their (approximate) relative strengths. Although gravity may be the most obvious force in daily life (because of the huge mass of the Earth), on a nuclear scale gravity is by far the weakest of the four forces and its effect at the particle level can nearly always be ignored.

TABLE 32–1 The Four Forces in Nature

Type	Relative Strength (approx., for 2 protons in nucleus)	Field Particle
Strong	1	Gluons (= g)
Electromagnetic	10^{-2}	Photon (= γ)
Weak	10^{-6}	$W^\pm$ and Z^0
Gravitational	10^{-38}	Graviton (?)

32–3 Particles and Antiparticles

The positron, as we discussed in Sections 27–6 (pair production) and 30–5 (β^+ decay), is basically a positive electron. That is, many of its properties are the same as for the electron, such as mass, but it has the opposite electric charge $(+e)$. Other quantum numbers that we will discuss shortly are also reversed. The positron is said to be the **antiparticle** to the electron.

The positron was first detected as a curved path in a cloud chamber in a magnetic field by Carl Anderson in 1932. It was predicted that other particles also would have antiparticles. It was decades before another type was found.

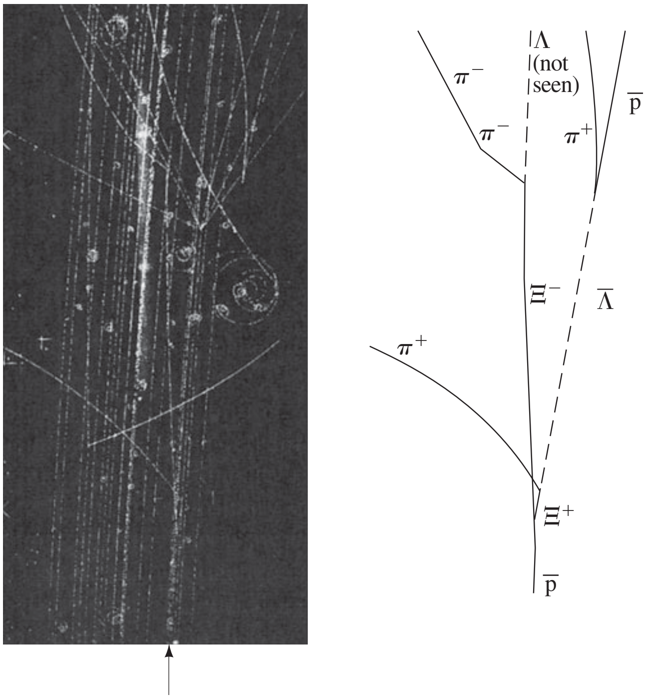


FIGURE 32–11 Liquid-hydrogen bubble-chamber photograph of an antiproton ($\overline{\text{p}}$) colliding with a proton at rest, producing a Xi—anti-Xi pair $\left(\overline{\text{p}} + \text{p} \rightarrow \Xi^- + \Xi^+\right)$ that subsequently decay into other particles. The drawing indicates the assignment of particles to each track, which is based on how or if that particle decays, and on mass values estimated from measurement of momentum (curvature of track in magnetic field) and energy (thickness of track, for example). Neutral particle paths are shown by dashed lines since neutral particles rarely ionize atoms, around which bubbles form, and hence leave no tracks. 1950s.

Finally, in 1955 the antiparticle to the proton, the **antiproton** ($\overline{\text{p}}$), which carries a negative charge (Fig. 32–11), was discovered at the University of California, Berkeley, by Emilio Segrè (1905–1989, Fig. 32–12) and Owen Chamberlain (1920–2006). A bar, such as over the p, is used to indicate the antiparticle ($\overline{\text{p}}$). Soon after, the antineutron ($\overline{\text{n}}$) was found. All particles have antiparticles. But a few, like the photon, the π^0, and the Higgs, do not have distinct antiparticles—we say that they are their own antiparticles.

Antiparticles are produced in nuclear reactions when there is sufficient energy available to produce the required mass, and they do not live very long in the presence of matter. For example, a positron is stable when by itself but rarely survives for long; as soon as it encounters an electron, the two annihilate each other. The energy of their vanished mass, plus any kinetic energy they possessed, is usually converted into the energy of two γ rays. Annihilation also occurs for all other particle–antiparticle pairs.

Antimatter is a term referring to material that would be made up of "antiatoms" in which antiprotons and antineutrons would form the nucleus around which positrons (antielectrons) would move. The term is also used for antiparticles in general. If there were pockets of antimatter in the universe, a huge explosion would occur if it should encounter normal matter. It is believed that antimatter was prevalent in the very early universe (Section 33–7).

FIGURE 32–12 Emilio Segrè: he worked with Fermi in the 1930s, later discovered the first "man-made" element, technetium, and other elements, and then the antiproton. The inscription below the photo is from a book by Segrè given to this book's author.

Emilio Segrè.
Feb 20 1985
To enlist the help of the subjects of this book for the next edition of Giancoli's texts

* Negative Sea of Electrons; Vacuum State

The original idea for antiparticles came from a relativistic wave equation developed in 1928 by the Englishman P. A. M. Dirac (1902–1984). Recall that, as we saw in Chapter 26, the total energy E of a particle with mass m and momentum p and zero potential energy is given by Eq. 26–9, $E^2 = p^2c^2 + m^2c^4$. Thus

$$E = \pm\sqrt{p^2c^2 + m^2c^4}.$$

Dirac applied his new equation and found that it included solutions with both + and − signs. He could not ignore the solution with the negative sign, which we might have thought unphysical. If those negative energy states are real, then we would expect normal free electrons to drop down into those states, emitting

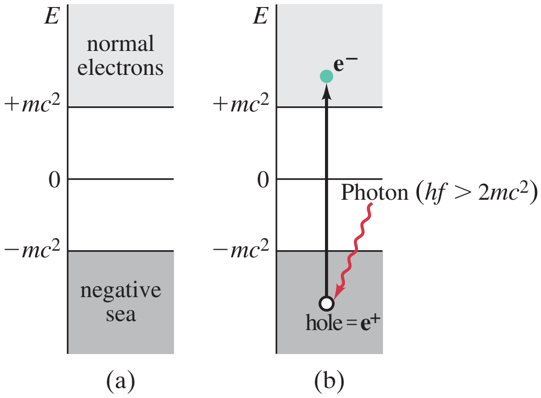


FIGURE 32–13 (a) Possible energy states for an electron. Note the vast sea of fully occupied electron states at $E < -mc^2$. (b) An electron in the negative sea is hit by a photon $(E > 2mc^2)$ and knocks it up to a normal positive energy state. The positive "hole" left behind acts like a positive electron—it is a positron.

photons—never experimentally seen. To deal with this difficulty, Dirac postulated that all those negative energy states are *normally occupied*. That is, what we thought was the **vacuum** is instead a vast **sea of electrons** in negative energy states (Fig. 32–13a). These electrons are not normally observable. But if a photon strikes one of these negative energy electrons, that electron can be knocked up to a normal $(E > mc^2)$ energy state as shown in Fig. 32–13b. Note in Fig. 32–13 that there are no energy states between $E = -mc^2$ and $E = +mc^2$ (because p^2 cannot be negative in the equation $E = \pm\sqrt{p^2c^2 + m^2c^4}$). The photon that knocks an e^- from the negative sea up to a normal state (Fig. 32–13b) must have an energy greater than $2mc^2$. What is left behind is a hole (as in semiconductors, Sections 29–7 and 29–8) with positive charge. We call that "hole" a **positron**, and it can move around as a free particle with positive energy. Thus Fig. 32–13b represents (Section 27–6) **pair production**: $\gamma \rightarrow e^-e^+$.

The vast sea of electrons with negative energy in Fig. 32–13 is the vacuum (or **vacuum state**). According to quantum mechanics, the vacuum is not empty, but contains electrons and other particles as well. The uncertainty principle allows a particle to jump briefly up to a normal energy, thus creating a **particle–antiparticle** pair. It is possible that they could be the source of the recently discovered *dark energy* that fills the universe (Chapter 33). We still have a lot to learn.

32–4 Particle Interactions and Conservation Laws

One of the important uses of high-energy accelerators and colliders is to study the interactions of elementary particles with each other. As a means of ordering this subnuclear world, the conservation laws are indispensable. The laws of conservation of energy, of momentum, of angular momentum, and of electric charge are found to hold precisely in all particle interactions.

A study of particle interactions has revealed a number of new conservation laws which (just like the old ones) are ordering principles: they help to explain why some reactions occur and others do not. For example, the following reaction has never been observed:

$$\mathrm{p} + \mathrm{n} \nrightarrow \mathrm{p} + \mathrm{p} + \bar{\mathrm{p}}$$

even though charge, energy, and so on, are conserved ($\nrightarrow$ means the reaction does not occur). To understand why such a reaction does not occur, physicists hypothesized a new conservation law, the conservation of **baryon number**. (Baryon number is a generalization of nucleon number, which we saw earlier is conserved in nuclear reactions and decays.) All nucleons are defined to have baryon number $B = +1$, and all antinucleons (antiprotons, antineutrons) have $B = -1$. All other types of particles, such as photons, mesons, and electrons and other leptons, have $B = 0$. The reaction shown at the start of this paragraph does not conserve baryon number since the left side has $B = (+1) + (+1) = +2$, and the right has $B = (+1) + (+1) + (-1) = +1$. On the other hand, the following reaction does conserve B and *does* occur if the incoming proton has sufficient energy:

$$\begin{aligned} \mathrm{p} + \mathrm{p} &\rightarrow \mathrm{p} + \mathrm{p} + \bar{\mathrm{p}} + \mathrm{p}, \\ B = +1 + 1 &= +1 + 1 - 1 + 1. \end{aligned}$$

As indicated, $B = +2$ on both sides of this equation. From these and other reactions, the **conservation of baryon number** has been established as a basic principle of physics.

Also useful are conservation laws for the three **lepton numbers**, associated with weak interactions including decays. In ordinary β decay, an electron or positron is emitted along with a neutrino or antineutrino. In another type of decay, a particle known as a "μ" or **muon**, can be emitted instead of an electron. The muon (discovered in 1937) seems to be much like an electron, except its mass is 207 times larger $(106\,\mathrm{MeV}/c^2)$. The neutrino (ν_e) that accompanies an emitted electron is found to be different from the neutrino (ν_μ) that accompanies an emitted muon. Each of these neutrinos has an antiparticle: $\bar{\nu}_\mathrm{e}$ and $\bar{\nu}_\mu$. In ordinary β decay we have, for example,

CAUTION

The different types of neutrinos are not identical

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

but not $\mathrm{n} \not\rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mu$. To explain why these do not occur, the concept of **electron lepton number**, L_e, was invented. If the electron (e^-) and the electron neutrino (ν_e) are assigned $L_\mathrm{e} = +1$, and e^+ and $\bar{\nu}_\mathrm{e}$ are assigned $L_\mathrm{e} = -1$, whereas all other particles have $L_\mathrm{e} = 0$, then all observed decays conserve L_e. For example, in $\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$, initially $L_\mathrm{e} = 0$, and afterward $L_\mathrm{e} = 0 + (+1) + (-1) = 0$. Decays that do not conserve L_e, even though they would obey the other conservation laws, are not observed to occur.

In a decay involving muons, such as

$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

a second quantum number, **muon lepton number** (L_μ), is conserved. The μ^- and ν_μ are assigned $L_\mu = +1$, and their antiparticles μ^+ and $\bar{\nu}_\mu$ have $L_\mu = -1$, whereas all other particles have $L_\mu = 0$. L_μ too is conserved in interactions and decays. Similar assignments can be made for the **tau lepton number**, L_τ, associated with the τ lepton (discovered in 1976 with mass more than 3000 times the electron mass) and its neutrino, ν_τ.

Antiparticles have not only opposite electric charge from their particles, but also opposite B, L_e, L_μ, and L_τ. For example, a neutron has $B = +1$, an antineutron has $B = -1$ (and all the L's are zero).

CONCEPTUAL EXAMPLE 32–4 **Lepton number in muon decay.** Which of the following decay schemes is possible for muon decay: (*a*) $\mu^- \rightarrow \mathrm{e}^- + \bar{\nu}_\mathrm{e}$; (*b*) $\mu^- \rightarrow \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \nu_\mu$; (*c*) $\mu^- \rightarrow \mathrm{e}^- + \nu_\mathrm{e}$? All of these particles have $L_\tau = 0$.

RESPONSE A μ^- has $L_\mu = +1$ and $L_\mathrm{e} = 0$. This is the initial state for all decays given, and the final state must also have $L_\mu = +1$, $L_\mathrm{e} = 0$. In (*a*), the final state has $L_\mu = 0 + 0 = 0$, and $L_\mathrm{e} = +1 - 1 = 0$; L_μ would not be conserved and indeed this decay is not observed to occur. The final state of (*b*) has $L_\mu = 0 + 0 + 1 = +1$ and $L_\mathrm{e} = +1 - 1 + 0 = 0$, so both L_μ and L_e are conserved. This is in fact the most common decay mode of the μ^-. Lastly, (*c*) does not occur because L_e $(= +2$ in the final state$)$ is not conserved, nor is L_μ.

EXAMPLE 32–5 **Energy and momentum are conserved.** In addition to the "number" conservation laws which help explain the decay schemes of particles, we can also apply the laws of conservation of energy and momentum. The decay of a Σ^+ particle at rest with mass $1189\,\mathrm{MeV}/c^2$ (Table 32–2 in Section 32–6) can yield a proton $(m_\mathrm{p} = 938\,\mathrm{MeV}/c^2)$ and a neutral pion, π^0 $(m_{\pi^0} = 135\,\mathrm{MeV}/c^2)$:

$$\Sigma^+ \rightarrow \mathrm{p} + \pi^0.$$

Determine the kinetic energies of the proton and π^0.

APPROACH We find the energy release from the change in mass $(E = mc^2)$ as we did for nuclear processes (Eq. 30–2 or 31–2a). Then we apply conservation of energy and momentum, using relativistic formulas as the energies are large.

SOLUTION The energy released, $Q = \text{KE}_\mathrm{p} + \text{KE}_{\pi^0}$, is the change in mass $\times\, c^2$:

$$Q = \left[m_{\Sigma^+} - \left(m_\mathrm{p} + m_{\pi^0}\right)\right]c^2 = \left[1189 - (938 + 135)\right]\mathrm{MeV} = 116\,\mathrm{MeV}.$$

Next we apply conservation of momentum: the initial particle Σ^+ is at rest, so the π^0 and p have opposite momentum but are equal in magnitude: $p_{\pi^0} = p_\mathrm{p}$. We square this equation, $p_{\pi^0}^2 = p_\mathrm{p}^2$, which becomes, using Eq. 26–9 $(p^2c^2 = E^2 - m^2c^4)$,

$$E_{\pi^0}^2 - m_{\pi^0}^2c^4 = E_\mathrm{p}^2 - m_\mathrm{p}^2c^4.$$

Solving for $E_{\pi^0}^2$:

$$E_{\pi^0}^2 = E_\mathrm{p}^2 - m_\mathrm{p}^2c^4 + m_{\pi^0}^2c^4.$$

We substitute Eq. 26–6a, $E = \text{KE} + mc^2$, for both the π^0 and the p:

$$\left(\text{KE}_{\pi^0} + m_{\pi^0}c^2\right)^2 = \left(\text{KE}_\mathrm{p} + m_\mathrm{p}c^2\right)^2 - m_\mathrm{p}^2c^4 + m_{\pi^0}^2c^4$$

$$\text{KE}_{\pi^0}^2 + 2\text{KE}_{\pi^0}m_{\pi^0}c^2 + \cancel{m_{\pi^0}^2c^4} = \text{KE}_\mathrm{p}^2 + 2\text{KE}_\mathrm{p}m_\mathrm{p}c^2 + \cancel{m_\mathrm{p}^2c^4} - \cancel{m_\mathrm{p}^2c^4} + \cancel{m_{\pi^0}^2c^4}.$$

Next (after cancelling as shown) we substitute $\text{KE}_\mathrm{p} = Q - \text{KE}_{\pi^0}$:

$$\cancel{\text{KE}_{\pi^0}^2} + 2\text{KE}_{\pi^0}m_{\pi^0}c^2 = Q^2 - 2Q\text{KE}_{\pi^0} + \cancel{\text{KE}_{\pi^0}^2} + 2Qm_\mathrm{p}c^2 - 2\text{KE}_{\pi^0}m_\mathrm{p}c^2.$$

After cancelling as shown, we solve for KE_{π^0}:

$$\text{KE}_{\pi^0} = \frac{Q^2 + 2Qm_\mathrm{p}c^2}{2m_{\pi^0}c^2 + 2Q + 2m_\mathrm{p}c^2} = \frac{(116\,\mathrm{MeV})^2 + 2(116\,\mathrm{MeV})(938\,\mathrm{MeV})}{2(135\,\mathrm{MeV}) + 2(116\,\mathrm{MeV}) + 2(938\,\mathrm{MeV})}$$

which gives $\text{KE}_{\pi^0} = 97\,\mathrm{MeV}$. Then $\text{KE}_\mathrm{p} = 116\,\mathrm{MeV} - 97\,\mathrm{MeV} = 19\,\mathrm{MeV}$.

32–5 Neutrinos

We first met neutrinos with regard to β decay in Section 30–5. The study of neutrinos is a "hot" subject today. Experiments are being carried out in deep underground laboratories, sometimes in deep mine shafts. The thick layer of earth above is meant to filter out all other "background" particles, leaving mainly the very weakly interacting neutrinos to arrive at the detectors.

Some very important results have come to the fore in recent years. First there was the **solar neutrino problem**. The energy output of the Sun is believed to be due to the nuclear fusion reactions discussed in Chapter 31, Eqs. 31–6 and 31–7. The neutrinos emitted in these reactions are all ν_e (accompanied by e^+). But the rate at which ν_e arrive at Earth was measured starting in the late 1960s to be much less than expected based on the power output of the Sun. It was then proposed that, on the long trip between Sun and Earth, ν_e might turn into ν_μ or ν_τ. Subsequent experiments, definitive only in 2001, confirmed this hypothesis. Thus the three neutrinos, $\nu_\mathrm{e}, \nu_\mu, \nu_\tau$, can change into one another in certain circumstances, a phenomenon called **neutrino flavor oscillation**[†]. (Each of the three neutrino types is called, whimsically, a different "flavor.") This result suggests that the lepton numbers L_e, L_μ, and L_τ are not perfectly conserved. But the sum, $L_\mathrm{e} + L_\mu + L_\tau$, is believed to be always conserved.

[†] Neutrino oscillations had first been proposed in 1957 by Bruno Pontecorvo. He also proposed that the electron and muon neutrinos are different species; and he also suggested a way to confirm the existence of neutrinos by detecting $\bar{\nu}_\mathrm{e}$ emitted in huge numbers by a nuclear reactor, an experiment carried out by Frederick Reines and Clyde Cowan in the 1950s. The experimentalists who confirmed these two predictions were awarded the Nobel Prize, but not the theorist who proposed them.

The second exceptional result has long been speculated on: are neutrinos massless as originally thought, or do they have a nonzero mass? Rough upper limits on the masses have been made. Today astrophysical experiments show that the sum of all three neutrino masses combined is less than about $0.14\ \mathrm{eV}/c^2$. But can all the masses be zero? Not if there are the flavor oscillations discussed above. It seems that at most, one type could have zero mass, and it is likely that at least one neutrino type has a mass of at least $0.04\ \mathrm{eV}/c^2$.

As a result of neutrino oscillations, the three types of neutrino may not be exactly what we thought they were (e, μ, τ). If not, the three basic neutrinos, called 1, 2, and 3, are combinations of ν_e, ν_μ, and ν_τ.

Another outstanding question is whether or not neutrinos are in the category called **Majorana particles**,[†] meaning they would be their own antiparticles, like γ, π^0, and Higgs. If so, a lot of other questions (and answers) would appear.

*Neutrino Mass Estimate from a Supernova

The explosion of a supernova in the outer parts of our Galaxy in 1987 (Section 33–2) released lots of neutrinos and offered an opportunity to estimate electron neutrino mass. If neutrinos do have mass, then their speed would be less than c, and neutrinos of different energy would take different times to travel the 170,000 light-years from the supernova to Earth. To get an idea of how such a measurement could be done, suppose two neutrinos from “SN1987A” were emitted at the same time and were actually detected on Earth (via the reaction $\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$) 10 seconds apart, with measured kinetic energies of about 20 MeV and 10 MeV. From other laboratory measurements we expect the neutrino mass to be less than 100 eV; and since our neutrinos have kinetic energy of 20 MeV and 10 MeV, we can make the approximation $m_\nu c^2 \ll E$, so that E (the total energy) is essentially equal to the kinetic energy. We use Eq. 26–6b, which tells us

$$E = \frac{m_\nu c^2}{\sqrt{1 - v^2/c^2}}.$$

We solve this for v, the velocity of a neutrino with energy E:

$$v = c\left(1 - \frac{m_\nu^2 c^4}{E^2}\right)^{\frac{1}{2}} = c\left(1 - \frac{m_\nu^2 c^4}{2E^2} + \cdots\right),$$

where we have used the binomial expansion $(1 - x)^{\frac{1}{2}} = 1 - \frac{1}{2}x + \cdots$, and we ignore higher-order terms since $m_\nu^2 c^4 \ll E^2$. The time t for a neutrino to travel a distance d $(= 170{,}000\ \mathrm{ly})$ is

$$t = \frac{d}{v} = \frac{d}{c\left(1 - \dfrac{m_\nu^2 c^4}{2E^2}\right)} \approx \frac{d}{c}\left(1 + \frac{m_\nu^2 c^4}{2E^2}\right),$$

where again we used the binomial expansion $\left[(1 - x)^{-1} = 1 + x + \cdots\right]$. The difference in arrival times for our two neutrinos of energies $E_1 = 20\ \mathrm{MeV}$ and $E_2 = 10\ \mathrm{MeV}$ is

$$t_2 - t_1 = \frac{d}{c}\frac{m_\nu^2 c^4}{2}\left(\frac{1}{E_2^2} - \frac{1}{E_1^2}\right).$$

We solve this for $m_\nu c^2$ and set $t_2 - t_1 = 10\ \mathrm{s}$:

$$m_\nu c^2 = \left[\frac{2c(t_2 - t_1)}{d}\frac{E_1^2 E_2^2}{E_1^2 - E_2^2}\right]^{\frac{1}{2}} = 22 \times 10^{-6}\ \mathrm{MeV} = 22\ \mathrm{eV}.$$

This calculation, with its optimistic assumptions, estimates the mass of the neutrino to be $22\ \mathrm{eV}/c^2$. But there would be experimental uncertainties, and even worse there is the unwarranted assumption that the two neutrinos were emitted at the same time.

[†] The brilliant young physicist Ettore Majorana (1906–1938) disappeared from a ship under mysterious circumstances in 1938 at the age of 31.

Theoretical models of supernova explosions suggest that the neutrinos are emitted in a burst that lasts from a second or two up to perhaps 10 s. If we assume the neutrinos are not emitted simultaneously but rather at any time over a 10-s interval, then that 10-s difference in arrival times could be due to a 10-s difference in their emission time. In this case the data would be consistent with zero neutrino mass, and it put an approximate *upper limit* of $22\,\mathrm{eV}/c^2$.

The actual detection of these neutrinos was brilliant—it was a rare event that allowed us to detect something other than EM radiation from beyond the solar system, and was an exceptional confirmation of theory. In the experiments, the most sensitive detector consisted of several thousand tons of water in an underground chamber. It detected 11 events in 12 seconds, probably via the reaction $\bar{\nu}_{\mathrm{e}} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$. There was not a clear correlation between energy and time of arrival. Nonetheless, a careful analysis of that experiment set a rough upper limit on the electron antineutrino mass of about $4\,\mathrm{eV}/c^2$. The more recent results mentioned above are much more definitive—they provide evidence that mass is much smaller, and that it is *not zero*—but precise neutrino masses still elude us.

32–6 Particle Classification

In the decades after the discovery of the π meson in the late 1940s, hundreds of other subnuclear particles were discovered. One way to categorize the particles is according to their interactions, since not all particles interact via all four of the forces known in nature (though all interact via gravity). Table 32–2 (next page) lists some of the more common particles classified in this way along with many of their properties. At the top of Table 32–2 are the so-called "fundamental" particles which we believe have no internal structure. Below them are some of the "composite" particles which are made up of quarks, according to the Standard Model.

The **fundamental particles** include the **gauge bosons** (so-named after the theory that describes them, *gauge theory*), which include the gluons, the photon, and the W and Z particles; these are the particles that mediate (or "carry") the strong, electromagnetic, and weak interactions, respectively.

Also fundamental are the **leptons**, which are particles that do not interact via the strong force but do interact via the weak nuclear force. Leptons that carry electric charge also interact via the electromagnetic force. The leptons include the electron, the muon, and the tau, and three types of neutrino: the electron neutrino (ν_{e}), the muon neutrino (ν_μ), and the tau neutrino (ν_τ). Each lepton has an antiparticle. Finally, the recently detected Higgs boson is also considered to be fundamental, with no internal structure.

The second category of particle in Table 32–2 is the **hadrons**, which are **composite** particles (made up of quarks as we will discuss shortly). Hadrons are particles that interact via the strong nuclear force and are said to be **strongly interacting particles**. They also interact via the other forces, but the strong force predominates at short distances. The hadrons include the proton, neutron, pion, and many other particles. They are divided into two subgroups: **baryons**, which are particles that have baryon number $+1$ (or -1 in the case of their antiparticles) and, as we shall see, are each made up of three quarks; and **mesons**, which have baryon number $= 0$, and are made up of a quark and an antiquark.

Only a few of the hundreds of hadrons (a veritable "zoo") are included in Table 32–2. Notice that the baryons Λ, Σ, Ξ, and Ω all decay to lighter-mass baryons, and eventually to a proton or neutron. All these processes conserve baryon number. Since there is no particle lighter than the proton with $B = +1$, if baryon number is strictly conserved, the proton itself cannot decay and is stable. (But see Section 32–11.) Note that Table 32–2 gives the **mean life** (τ) of each particle (as is done in particle physics), not the half-life $(T_{\frac{1}{2}})$. Recall that they differ by a factor 0.693: $\tau = T_{\frac{1}{2}}/\ln 2 = T_{\frac{1}{2}}/0.693$, Eq. 30–7. The term **lifetime** in particle physics means the mean life τ (= mean lifetime).

The baryon and lepton numbers $(B,\ L_{\mathrm{e}}, L_\mu, L_\tau)$, as well as strangeness S (Section 32–8), as given in Table 32–2 are for particles; their antiparticles have opposite sign for these numbers.

TABLE 32–2 Particles (selected)†

Category	Forces involved	Particle name	Symbol	Anti-particle	Spin	Mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Mean life (s)	Principal Decay Modes
							[antiparticles have opposite sign]						
Fundamental													
Gauge bosons (force carriers)	str	Gluons	g	Self	1	0	0	0	0	0	0	Stable	
	em	Photon	γ	Self	1	0	0	0	0	0	0	Stable	
	w, em	W	W^+	W^-	1	80.385×10^3	0	0	0	0	0	3×10^{-25}	$e\nu_e$, $\mu\nu_\mu$, $\tau\nu_\tau$, hadrons
	w	Z	Z^0	Self	1	91.19×10^3	0	0	0	0	0	3×10^{-25}	e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, hadrons
Higgs boson	w, str	Higgs	H^0	Self	0	125×10^3	0	0	0	0	0	1.6×10^{-22}	$b\bar{b}$, Z^0Z^0, W^+W^-, $g\bar{g}$, $\tau\bar{\tau}$, $\gamma\gamma$
Leptons	w, em‡	Electron	e^-	e^+	$\frac{1}{2}$	0.511	0	+1	0	0	0	Stable	
		Neutrino (e)	ν_e	$\bar{\nu}_e$	$\frac{1}{2}$	0 (<0.14 eV/c^2)‡	0	+1	0	0	0	Stable	
		Muon	μ^-	μ^+	$\frac{1}{2}$	105.7	0	0	+1	0	0	2.20×10^{-6}	$e^-\bar{\nu}_e\nu_\mu$
		Neutrino (μ)	ν_μ	$\bar{\nu}_\mu$	$\frac{1}{2}$	0 (<0.14 eV/c^2)‡	0	0	+1	0	0	Stable	
		Tau	τ^-	τ^+	$\frac{1}{2}$	1777	0	0	0	+1	0	2.91×10^{-13}	$\mu^-\bar{\nu}_\mu\nu_\tau$, $e^-\bar{\nu}_e\nu_\tau$, hadrons $+\nu_\tau$
		Neutrino (τ)	ν_τ	$\bar{\nu}_\tau$	$\frac{1}{2}$	0 (<0.14 eV/c^2)‡	0	0	0	+1	0	Stable	
Quarks	w, em, str	(see Table 32–3)											
Hadrons (composite), selected													
Mesons (quark–antiquark)	str, em, w	Pion	π^+	π^-	0	139.6	0	0	0	0	0	2.60×10^{-8}	$\mu^+\nu_\mu$
			π^0	Self	0	135.0	0	0	0	0	0	0.85×10^{-16}	2γ
		Kaon	K^+	K^-	0	493.7	0	0	0	0	+1	1.24×10^{-8}	$\mu^+\nu_\mu$, $\pi^+\pi^0$
			K^0_S	$\overline{K}^0_S$	0	497.6	0	0	0	0	+1	0.895×10^{-10}	$\pi^+\pi^-$, $2\pi^0$
			K^0_L	$\overline{K}^0_L$	0	497.6	0	0	0	0	+1	5.12×10^{-8}	$\pi^\pm e^\mp \overset{(-)}{\nu}_e$, $\pi^\pm\mu^\mp\overset{(-)}{\nu}_\mu$, 3π
		Eta	η^0	Self	0	547.9	0	0	0	0	0	5.1×10^{-19}	2γ, $3\pi^0$, $\pi^+\pi^-\pi^0$
		Rho	ρ^0	Self	1	775	0	0	0	0	0	4.4×10^{-24}	$\pi^+\pi^-$, $2\pi^0$
			ρ^+	ρ^-	1	775	0	0	0	0	0	4.4×10^{-24}	$\pi^+\pi^0$
		and others											
Baryons (3 quarks)	str, em, w	Proton	p	$\bar{p}$	$\frac{1}{2}$	938.3	+1	0	0	0	0	Stable	
		Neutron	n	$\bar{n}$	$\frac{1}{2}$	939.6	+1	0	0	0	0	882	$pe^-\bar{\nu}_e$
		Lambda	Λ^0	$\overline{\Lambda}^0$	$\frac{1}{2}$	1115.7	+1	0	0	0	−1	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
		Sigma	Σ^+	$\overline{\Sigma}^-$	$\frac{1}{2}$	1189.4	+1	0	0	0	−1	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
			Σ^0	$\overline{\Sigma}^0$	$\frac{1}{2}$	1192.6	+1	0	0	0	−1	7.4×10^{-20}	$\Lambda^0\gamma$
			Σ^-	$\overline{\Sigma}^+$	$\frac{1}{2}$	1197.4	+1	0	0	0	−1	1.48×10^{-10}	$n\pi^-$
		Xi	Ξ^0	$\overline{\Xi}^0$	$\frac{1}{2}$	1314.9	+1	0	0	0	−2	2.90×10^{-10}	$\Lambda^0\pi^0$
			Ξ^-	$\overline{\Xi}^+$	$\frac{1}{2}$	1321.7	+1	0	0	0	−2	1.64×10^{-10}	$\Lambda^0\pi^-$
		Omega	Ω^-	Ω^+	$\frac{3}{2}$	1672.5	+1	0	0	0	−3	0.82×10^{-10}	$\Xi^0\pi^-$, Λ^0K^-, $\Xi^-\pi^0$
		and others											

† See also Table 32–4 for particles with charm and bottom. S in this Table stands for "strangeness" (see Section 32–8). More detail online at: pdg.lbl.gov.

‡ Neutrinos partake only in the weak interaction. Experimental upper limits on neutrino masses are given in parentheses, as obtained mainly from the WMAP survey (Chapter 33). Detection of neutrino oscillations suggests that at least one type of neutrino has a nonzero mass greater than 0.04 eV/c^2.

EXAMPLE 32–6 **Baryon decay.** Show that the decay modes of the Σ^+ baryon given in Table 32–2 do not violate the conservation laws we have studied up to now: energy, charge, baryon number, lepton numbers.

APPROACH Table 32–2 shows two possible decay modes, (*a*) $\Sigma^+ \rightarrow p + \pi^0$, (*b*) $\Sigma^+ \rightarrow n + \pi^+$. All the particles have lepton numbers equal to zero.

SOLUTION (*a*) Energy: for $\Sigma^+ \rightarrow p + \pi^0$ the change in mass-energy is

$$\begin{aligned} \Delta(Mc^2) &= m_\Sigma c^2 - m_p c^2 - m_{\pi^0} c^2 \\ &= 1189.4\,\text{MeV} - 938.3\,\text{MeV} - 135.0\,\text{MeV} = +116.1\,\text{MeV}, \end{aligned}$$

so energy can be conserved with the resulting particles having kinetic energy.

Charge: $+e = +e + 0$, so charge is conserved.

Baryon number: $+1 = +1 + 0$, so baryon number is conserved.

(*b*) Energy: for $\Sigma^+ \rightarrow n + \pi^+$, the mass-energy change is

$$\begin{aligned} \Delta(Mc^2) &= m_\Sigma c^2 - m_n c^2 - m_{\pi^+} c^2 \\ &= 1189.4\,\text{MeV} - 939.6\,\text{MeV} - 139.6\,\text{MeV} = +110.2\,\text{MeV}. \end{aligned}$$

This reaction releases 110.2 MeV of energy as kinetic energy of the products.

Charge: $+e = 0 + e$, so charge is conserved.

Baryon number: $+1 = +1 + 0$, so baryon number is conserved.

32–7 Particle Stability and Resonances

Many particles listed in Table 32–2 are unstable. The lifetime of an unstable particle depends on which force is most active in causing the decay. When a stronger force influences a decay, that decay occurs more quickly. Decays caused by the weak force typically have lifetimes of 10^{-13} s or longer (W and Z decay directly and more quickly). Decays via the electromagnetic force have much shorter lifetimes, typically about 10^{-16} to 10^{-19} s, and normally involve a γ (photon). Most of the unstable particles included in Table 32–2 decay either via the weak or the electromagnetic interaction.

Many particles have been found that decay via the strong interaction, with very short lifetimes, typically about 10^{-23} s. Their lifetimes are so short they do not travel far enough to be detected before decaying. The existence of such short-lived particles is inferred from their decay products. Consider the first such particle discovered (by Fermi), using a beam of π^+ particles with varying amounts of energy directed through a hydrogen target (protons). The number of interactions (π^+ scattered) plotted versus the pion's kinetic energy is shown in Fig. 32–14. The large number of interactions around 200 MeV led Fermi to conclude that the π^+ and proton combined momentarily to form a short-lived particle before coming apart again, or at least that they resonated together for a short time. Indeed, the large peak in Fig. 32–14 resembles a resonance curve (see Figs. 11–18 and 21–46), and this new "particle"—now called the Δ—is referred to as a **resonance**. Hundreds of other resonances have been found, and are regarded as excited states of lighter mass particles such as a nucleon.

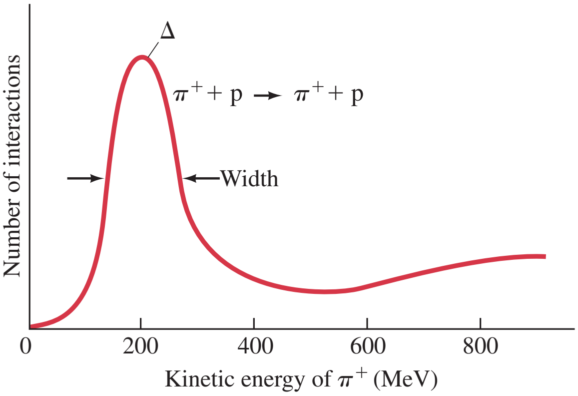


FIGURE 32–14 Number of π^+ particles scattered elastically by a proton target as a function of the incident π^+ kinetic energy. The resonance shape represents the formation of a short-lived particle, the Δ, which has a charge in this case of $+2e$ (Δ^{++}).

The **width** of a resonance—in Fig. 32–14 the full width of the Δ peak at half the maximum is on the order of 100 MeV—is an interesting application of the uncertainty principle. If a particle lives only 10^{-23} s, then its mass (i.e., its rest energy) will be uncertain by an amount

$$\Delta E \approx \frac{h}{2\pi\,\Delta t} \approx \frac{(6.6\times10^{-34}\,\mathrm{J\cdot s})}{(6)(10^{-23}\,\mathrm{s})} \approx 10^{-11}\,\mathrm{J} \approx 100\,\mathrm{MeV},$$

which is what is observed. Actually, the lifetimes of $\approx 10^{-23}$ s for such resonances are inferred by the reverse process: from the measured width being $\approx$ 100 MeV.

32–8 Strangeness? Charm? Towards a New Model

In the early 1950s, the newly found particles K, Λ, and Σ were found to behave rather strangely in two ways. First, they were always produced in pairs. For example, the reaction

$$\pi^- + p \rightarrow K^0 + \Lambda^0$$

occurred with high probability, but the similar reaction $\pi^- + p \not\rightarrow K^0 + n$ was never observed to occur even though it did not violate any known conservation law. The second feature of these **strange particles**, as they came to be called, was that they were produced via the strong interaction (that is, at a high interaction rate), but did not decay at a fast rate characteristic of the strong interaction (even though they decayed into strongly interacting particles).

To explain these observations, a new quantum number, **strangeness**, and a new conservation law, **conservation of strangeness**, were introduced. By assigning the strangeness numbers (S) indicated in Table 32–2, the production of strange particles in pairs was explained. Antiparticles were assigned opposite strangeness from their particles. For example, in the reaction $\pi^- + \mathrm{p} \rightarrow \mathrm{K}^0 + \Lambda^0$, the initial state has strangeness $S = 0 + 0 = 0$, and the final state has $S = +1 - 1 = 0$, so strangeness is conserved. But for $\pi^- + \mathrm{p} \nrightarrow \mathrm{K}^0 + \mathrm{n}$, the initial state has $S = 0$ and the final state has $S = +1 + 0 = +1$, so strangeness would not be conserved; and this reaction is not observed.

CAUTION
Partially conserved quantities

To explain the decay of strange particles, it is assumed that strangeness is conserved in the strong interaction but is *not conserved in the weak interaction*. Thus, strange particles were forbidden by strangeness conservation to decay to nonstrange particles of lower mass via the strong interaction, but could decay by means of the weak interaction at the observed longer lifetimes of 10^{-10} to 10^{-8} s.

The conservation of strangeness was the first example of a **partially conserved** quantity. In this case, the quantity strangeness is conserved by strong interactions but not by weak.

CONCEPTUAL EXAMPLE 32–7 **Guess the missing particle.** Using the conservation laws for particle interactions, determine the possibilities for the missing particle in the reaction

$$\pi^- + \mathrm{p} \rightarrow \mathrm{K}^0 + ?$$

in addition to $\mathrm{K}^0 + \Lambda^0$ mentioned above.

RESPONSE We write equations for the conserved numbers in this reaction, with B, L_e, S, and Q as unknowns whose determination will reveal what the possible particle might be:

$$\begin{aligned}
&\text{Baryon number:} && 0 + 1 = 0 + B\\
&\text{Lepton number:} && 0 + 0 = 0 + L_e\\
&\text{Charge:} && -1 + 1 = 0 + Q\\
&\text{Strangeness:} && 0 + 0 = 1 + S.
\end{aligned}$$

The unknown product particle would have to have these characteristics:

$$B = +1 \qquad L_e = 0 \qquad Q = 0 \qquad S = -1.$$

In addition to Λ^0, a neutral sigma particle, Σ^0, is also consistent with these numbers.

In the next Section we will discuss another partially conserved quantity which was given the name **charm**. The discovery in 1974 of a particle with charm helped solidify a new theory involving quarks, which we now discuss.

32–9 Quarks

One difference between leptons and hadrons is that the hadrons interact via the strong interaction, whereas the leptons do not. There is an even more fundamental difference. The six leptons $(e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau)$ are considered to be truly fundamental particles because they do not show any internal structure, and have no measurable size. (Attempts to determine the size of leptons have put an upper limit of about 10^{-18} m.) On the other hand, there are hundreds of hadrons, and experiments indicate they do have an internal structure. When an electron collides with another electron, it scatters off as per Coulomb's law. But electrons scattering off a proton reveal a more complex pattern, implying internal parts within the proton (= quarks).

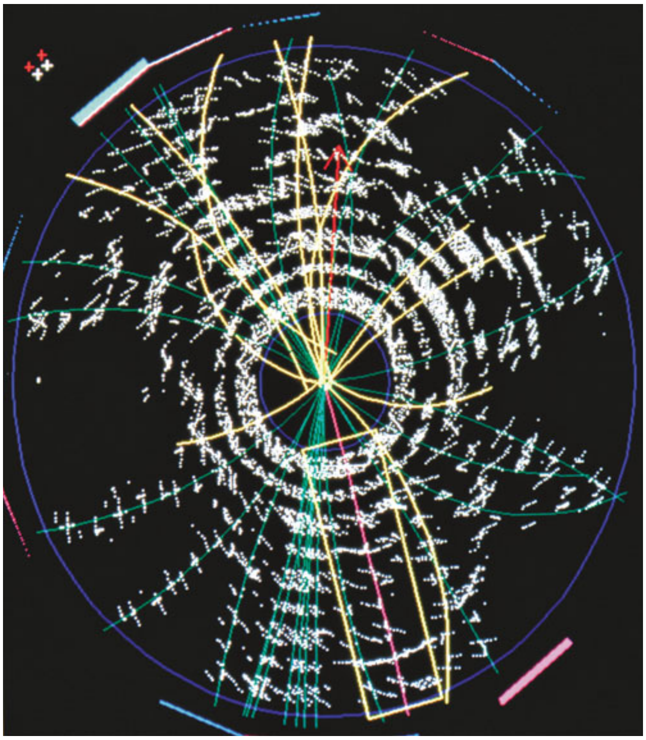


FIGURE 32–15 This computer-generated reconstruction of a proton–antiproton collision at Fermilab occurred at an energy of nearly 2 TeV. It is one of the events that provided evidence for the top quark (1995). The multiwire chamber (Section 30–13) is in a magnetic field, and the radius of curvature of the charged particle tracks is a measure of each particle's momentum (Chapter 20). The white dots represent signals seen on the electric wires of the multiwire chamber. The colored lines are particle paths. The top quark (t) has too brief a lifetime $(\approx 10^{-23}\ \mathrm{s})$ to be detected itself, so we look for its possible decay products. Analysis indicates the following interaction and subsequent decays:

$\mathrm{p} + \bar{\mathrm{p}} \longrightarrow \mathrm{t} + \bar{\mathrm{t}}$
$\quad\quad \hookrightarrow \mathrm{W}^- + \bar{\mathrm{b}}$
$\quad\quad\quad\quad \hookrightarrow \text{jet}$
$\quad\quad\quad \longrightarrow \mu^- + \bar{\nu}_\mu$
$\quad \longrightarrow \mathrm{W}^+ + \mathrm{b}$
$\quad\quad\quad \hookrightarrow \text{jet}$
$\quad\quad \hookrightarrow \mathrm{u} + \bar{\mathrm{d}}$
$\quad\quad\quad\quad \hookrightarrow \text{jet}$
$\quad\quad\quad \longrightarrow \text{jet}$

The tracks in the photo include jets (groups of particles moving in roughly the same direction), and a muon (μ^-) whose track is the pink one enclosed by a yellow rectangle to make it stand out.

In 1963, M. Gell-Mann and G. Zweig proposed that none of the hadrons, not even the proton and neutron, are truly fundamental, but instead are made up of combinations of three more fundamental pointlike entities called (somewhat whimsically) **quarks**.[†] Today, the quark theory is well-accepted, and quarks are considered truly fundamental particles, like leptons. The three quarks originally proposed were named **up**, **down**, and **strange**, with abbreviations u, d, s. The theory today has six quarks, just as there are six leptons—based on a presumed *symmetry* in nature. The other three quarks are called **charm**, **bottom**, and **top** (c, b, t). The names apply also to new properties of each quark (quantum numbers c, b, t) that distinguish these new quarks from the 3 original quarks (see Table 32–3). These properties (like strangeness) are conserved in strong, but not weak, interactions. Figure 32–15 shows one of the events that provided evidence for the top quark.

All quarks have spin $\frac{1}{2}$ and an electric charge of either $+\frac{2}{3}e$ or $-\frac{1}{3}e$ (that is, a fraction of the previously thought smallest charge e). Antiquarks have opposite sign of electric charge Q, baryon number B, strangeness S, charm c, bottom b, and top t. Other properties of quarks are shown in Table 32–3.

[†] Gell-Mann chose the word from a phrase in James Joyce's *Finnegans Wake*.

TABLE 32–3 Properties of Quarks (Antiquarks have opposite sign Q, B, S, c, b, t)

				Quarks				
Name	**Symbol**	**Mass (MeV/c^2)**	**Charge Q**	**Baryon Number B**	**Strangeness S**	**Charm c**	**Bottom b**	**Top t**
Up	u	2.3	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	0
Down	d	4.8	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	0	0
Strange	s	95	$-\frac{1}{3}e$	$\frac{1}{3}$	−1	0	0	0
Charm	c	1275	$+\frac{2}{3}e$	$\frac{1}{3}$	0	+1	0	0
Bottom	b	4180	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	−1	0
Top[†]	t	173,500	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	+1

[†] The top quark, with its extremely short lifetime of 5×10^{-25} s, does not live long enough to form hadrons.

TABLE 32–4 Partial List of Heavy Hadrons, with Charm and Bottom ($L_e = L_\mu = L_\tau = 0$)

Category	Particle	Anti-particle	Spin	Mass (MeV/c^2)	Baryon Number B	Strangeness S	Charm c	Bottom b	Mean life (s)	Principal Decay Modes
Mesons	D^+	D^-	0	1869.6	0	0	+1	0	10.4×10^{-13}	K + others, e + others
	D^0	$\overline{D}^0$	0	1864.9	0	0	+1	0	4.1×10^{-13}	K + others, μ or e + others
	D_S^+	D_S^-	0	1968.5	0	+1	+1	0	5.0×10^{-13}	K + others
	J/ψ (3097)	Self	1	3096.9	0	0	0	0	0.71×10^{-20}	Hadrons, e^+e^-, $\mu^+\mu^-$
	Υ (9460)	Self	1	9460.3	0	0	0	0	1.2×10^{-20}	Hadrons, $\mu^+\mu^-$, e^+e^-, $\tau^+\tau^-$
	B^-	B^+	0	5279.3	0	0	0	−1	1.6×10^{-12}	D^0 + others
	B^0	$\overline{B}^0$	0	5279.6	0	0	0	−1	1.5×10^{-12}	D^0 + others
Baryons	Λ_c^+	Λ_c^-	$\frac{1}{2}$	2286	+1	0	+1	0	2.0×10^{-13}	Hadrons (e.g., Λ + others)
	Σ_c^{++}	Σ_c^{--}	$\frac{1}{2}$	2454	+1	0	+1	0	2.9×10^{-22}	$\Lambda_c^+\pi^+$
	Σ_c^+	Σ_c^-	$\frac{1}{2}$	2453	+1	0	+1	0	$>1.4 \times 10^{-22}$	$\Lambda_c^+\pi^0$
	Σ_c^0	$\overline{\Sigma}_c^0$	$\frac{1}{2}$	2454	+1	0	+1	0	3.0×10^{-22}	$\Lambda_c^+\pi^-$
	Λ_b^0	$\overline{\Lambda}_b^0$	$\frac{1}{2}$	5619	+1	0	0	−1	1.4×10^{-12}	$J/\psi\Lambda^0$, $pD^0\pi^-$, $\Lambda_c^+\pi^+\pi^-\pi^-$

All hadrons are considered to be made up of combinations of quarks (plus the gluons that hold them together), and their properties are described by looking at their quark content. Mesons consist of a quark–antiquark pair. For example, a π^+ meson is a $u\bar{d}$ combination: note that for the $u\bar{d}$ pair (Table 32–3), $Q = \frac{2}{3}e + \frac{1}{3}e = +1e$, $B = \frac{1}{3} - \frac{1}{3} = 0$, $S = 0 + 0 = 0$, as they must for a π^+; and a $K^+ = u\bar{s}$, with $Q = +1$, $B = 0$, $S = +1$. A π^0 can be made of $u\bar{u}$ or $d\bar{d}$.

Baryons, on the other hand, consist of three quarks. For example, a neutron is $n = ddu$, whereas an antiproton is $\bar{p} = \bar{u}\,\bar{u}\,\bar{d}$. See Fig. 32–16. Strange particles all contain an s or $\bar{s}$ quark, whereas charm particles contain a c or $\bar{c}$ quark. A few of these hadrons are listed in Table 32–4.

Current models suggest that quarks may be so tightly bound together that they may not ever exist singly in the free state. But quarks can be detected indirectly when they turn into narrow **jets** of other particles, as in Fig. 32–15. Also, observations of very high energy electrons scattered off protons suggest that protons are indeed made up of constituents.

Today, the truly **fundamental particles** are considered to be the six quarks, the six leptons, the gauge bosons that carry the fundamental forces, and the Higgs (page 939). See Table 32–5, where the quarks and leptons are arranged in three “families” or “generations.” Ordinary matter—atoms made of protons, neutrons, and electrons—is contained in the “first generation.” The others are thought to have existed in the very early universe, but are seen by us today only at powerful colliders or in cosmic rays. All of the hundreds of hadrons can be accounted for by combinations of the six quarks and six antiquarks.

EXERCISE C Return to the Chapter-Opening Questions, page 915, and answer them again now. Try to explain why you may have answered differently the first time.

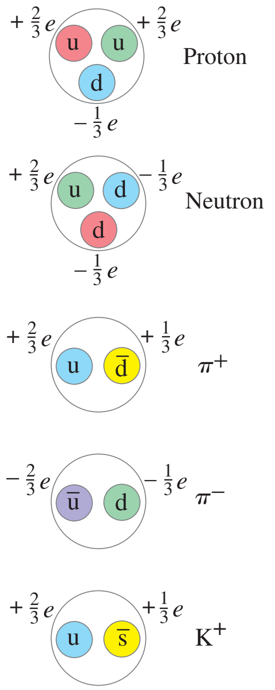


FIGURE 32–16 Quark compositions for several particles.

TABLE 32–5 The Fundamental Particles[†] of the Standard Model

Gauge bosons	γ	g	Z^0	$W^\pm$
Higgs boson	H^0			
	Quarks		Leptons	
First generation	u	d	e	ν_e
Second generation	s	c	μ	ν_μ
Third generation	b	t	τ	ν_τ

[†] The graviton (G^0) has been hypothesized but not detected and may not be detectable. It is not part of the Standard Model.

CONCEPTUAL EXAMPLE 32–8 **Quark combinations.** Find the baryon number, charge, and strangeness for the following quark combinations, and identify the hadron particle that is made up of these quark combinations: (*a*) udd, (*b*) $u\bar{u}$, (*c*) uss, (*d*) sdd, and (*e*) $b\bar{u}$.

RESPONSE We use Table 32–3 to get the properties of the quarks, then Table 32–2 or 32–4 to find the particle that has these properties.

(*a*) udd has

$$\begin{aligned} Q &= +\tfrac{2}{3}e - \tfrac{1}{3}e - \tfrac{1}{3}e = 0, \\ B &= \tfrac{1}{3} + \tfrac{1}{3} + \tfrac{1}{3} = 1, \\ S &= 0 + 0 + 0 = 0, \end{aligned}$$

as well as $c = 0$, bottom $= 0$, top $= 0$. The only baryon $(B = +1)$ that has $Q = 0$, $S = 0$, etc., is the neutron (Table 32–2).

(*b*) $u\bar{u}$ has $Q = \frac{2}{3}e - \frac{2}{3}e = 0$, $B = \frac{1}{3} - \frac{1}{3} = 0$, and all other quantum numbers $= 0$. Sounds like a π^0 ($d\bar{d}$ also gives a π^0).

(*c*) uss has $Q = 0$, $B = +1$, $S = -2$, others $= 0$. This is a Ξ^0.

(*d*) sdd has $Q = -1$, $B = +1$, $S = -1$, so must be a Σ^-.

(*e*) $b\bar{u}$ has $Q = -1$, $B = 0$, $S = 0$, $c = 0$, bottom $= -1$, top $= 0$. This must be a B^- meson (Table 32–4).

EXERCISE D What is the quark composition of a K^- meson?

32–10 The Standard Model: QCD and Electroweak Theory

Not long after the quark theory was proposed, it was suggested that quarks have another property (or quality) called **color**, or "color charge" (analogous to electric charge). The distinction between the six types of quark (u, d, s, c, b, t) was referred to as **flavor**. According to theory, each flavor of quark can have one of three colors, usually designated red, green, and blue. (These are the three primary colors which, when added together in appropriate amounts, as on a TV screen, produce white.) Note that the names "color" and "flavor" have nothing to do with our senses, but are purely whimsical—as are other names, such as charm, in this new field. (We did, however, "color" the quarks in Fig. 32–16.) The antiquarks are colored antired, antigreen, and antiblue. Baryons are made up of three quarks, one of each color. Mesons consist of a quark–antiquark pair of a particular color and its anticolor. Both baryons and mesons are thus colorless or white.

Originally, the idea of quark color was proposed to preserve the Pauli exclusion principle (Section 28–7). Not all particles obey the exclusion principle. Those that do, such as electrons, protons, and neutrons, are called **fermions**. Those that don't are called **bosons**. These two categories are distinguished also in their spin: bosons have integer spin (0, 1, 2, etc.) whereas fermions have half-integer spin, usually $\frac{1}{2}$ as for electrons and nucleons, but other fermions have spin $\frac{3}{2}, \frac{5}{2}$, etc. Matter is made up mainly of fermions, but the carriers of the forces (γ, W, Z, and gluons) are all bosons. Quarks are fermions (they have spin $\frac{1}{2}$) and therefore should obey the exclusion principle. Yet for three particular baryons (uuu, ddd, and sss), all three quarks would have the same quantum numbers, and at least two quarks have their spin in the same direction (since there are only two choices, spin up $\left[m_s = +\frac{1}{2}\right]$ or spin down $\left[m_s = -\frac{1}{2}\right]$). This would seem to violate the exclusion principle; but if quarks have that additional quantum number *color*, which is different for each quark, it would serve to distinguish them and allow the exclusion principle to hold. Although quark color, and the resulting threefold increase in the number of quarks, was originally an *ad hoc* idea, it also served to bring the theory into better agreement with experiment, such as predicting the correct lifetime of the π^0 meson, and the measured rate of hadron production in observed e^+e^- collisions at accelerators. The idea of color soon became a central feature of the theory as determining the force binding quarks together in a hadron.

Each quark is assumed to carry a *color charge*, analogous to electric charge, and the strong force between quarks is referred to as the **color force**. This theory of the strong force is called **quantum chromodynamics** (*chroma* = color in Greek), or **QCD**, to indicate that the force acts between color charges (and not between, say, electric charges). The strong force between two hadrons is considered to be a force between the quarks that make them up, as suggested in Fig. 32–17.

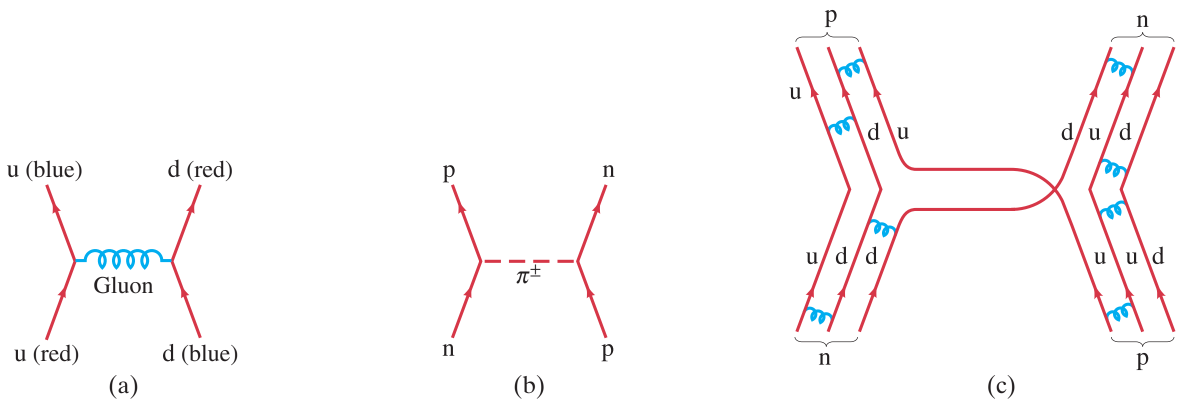


FIGURE 32–17 (a) The force between two quarks holding them together as part of a proton, for example, is carried by a gluon, which in this case involves a change in color. (b) Strong interaction $n + p \rightarrow n + p$ with the exchange of a charged π meson (+ or −, depending on whether it is considered moving to the left or to the right). (c) Quark representation of the same interaction $n + p \rightarrow n + p$. The blue coiled lines between quarks represent gluon exchanges holding the hadrons together. (The exchanged meson may be regarded as $\bar{u}d$ emitted by the n and absorbed by the p, or as $u\bar{d}$ emitted by p and absorbed by n, because a u (or d) quark going to the left in the diagram is equivalent to a $\bar{u}$ (or $\bar{d}$) going to the right.)

The particles that transmit the color force (analogous to photons for the EM force) are called **gluons** (a play on "glue"). They are included in Tables 32–2 and 32–5. There are eight gluons, according to the theory, all massless and all have color charge.[†]

You might ask what would happen if we try to see a single quark with color by reaching deep inside a hadron and extracting a single quark. Quarks are so tightly bound to other quarks that extracting one would require a tremendous amount of energy, so much that it would be sufficient to create more quarks $(E = mc^2)$. Indeed, such experiments are done at modern particle colliders and all we get is more hadrons (quark–antiquark pairs, or triplets, which we observe as mesons or baryons), never an isolated quark. This property of quarks, that they are always bound in groups that are colorless, is called **confinement**.

The color force has the interesting property that, as two quarks approach each other very closely (equivalently, have high energy), the force between them becomes small. This aspect is referred to as **asymptotic freedom**.

The weak force, as we have seen, is thought to be mediated by the W^+, W^-, and Z^0 particles. It acts between the "weak charges" that each particle has. Each fundamental particle can thus have electric charge, weak charge, color charge, and gravitational mass, although one or more of these could be zero. For example, all leptons have color charge of zero, so they do not interact via the strong force.

[†] Compare to the EM interaction, where the photon has no electric charge. Because gluons have color charge, they could attract each other and form composite particles (photons cannot). Such "glueballs" are being searched for.

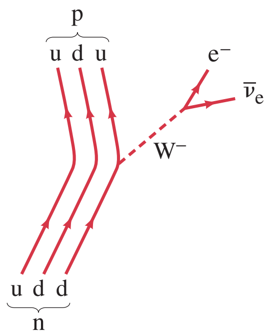


FIGURE 32–18 Quark representation of the Feynman diagram for β decay of a neutron into a proton. Example 23–9.

CONCEPTUAL EXAMPLE 32–9 **Beta decay.** Draw a Feynman diagram, showing what happens in beta decay using quarks.

RESPONSE Beta decay is a result of the weak interaction, and the mediator is either a $W^{\pm}$ or Z^0 particle. What happens, in part, is that a neutron (udd quarks) decays into a proton (uud). Apparently a d quark (charge $-\frac{1}{3}e$) has turned into a u quark (charge $+\frac{2}{3}e$). Charge conservation means that a negatively charged particle, namely a W^-, was emitted by the d quark. Since an electron and an antineutrino appear in the final state, they must have come from the decay of the virtual W^-, as shown in Fig. 32–18.

To summarize, the Standard Model says that the truly fundamental particles (Table 32–5) are the leptons, the quarks, the gauge bosons (photon, W and Z, and the gluons), and the Higgs boson. The photon, leptons, W^+, W^-, and Z^0 have all been observed in experiments. But only combinations of quarks (baryons and mesons) have been observed in the free state, and it seems likely that free quarks and gluons cannot be observed in isolation.

One important aspect of theoretical work is the attempt to find a **unified** basis for the different forces in nature. This was a long-held hope of Einstein, which he was never able to fulfill. A so-called **gauge theory** that unifies the weak and electromagnetic interactions was put forward in the 1960s by S. Weinberg, S. Glashow, and A. Salam. In this **electroweak theory**, the weak and electromagnetic forces are seen as two different manifestations of a single, more fundamental, *electroweak* interaction. The electroweak theory has had many successes, including the prediction of the $W^{\pm}$ particles as carriers of the weak force, with masses of $80.38 \pm 0.02\,\mathrm{GeV}/c^2$ in excellent agreement with the measured values of $80.385 \pm 0.015\,\mathrm{GeV}/c^2$ (and similar accuracy for the Z^0).

The combination of electroweak theory plus QCD for the strong interaction is referred to today as the **Standard Model** (**SM**) of fundamental particles.

EXAMPLE 32–10 **ESTIMATE** **Range of weak force.** The weak nuclear force is of very short range, meaning it acts over only a very short distance. Estimate its range using the masses (Table 32–2) of the $W^{\pm}$ and Z: $m \approx 80$ or $90\,\mathrm{GeV}/c^2 \approx 10^2\,\mathrm{GeV}/c^2$.

APPROACH We assume the $W^{\pm}$ or Z^0 exchange particles can exist for a time Δt given by the uncertainty principle (Section 28–3), $\Delta t \approx \hbar/\Delta E$, where $\Delta E \approx mc^2$ is the energy needed to create the virtual particle $(W^{\pm},\ Z)$ that carries the weak force.

SOLUTION Let Δx be the distance the virtual W or Z can move before it must be reabsorbed within the time $\Delta t \approx \hbar/\Delta E$. To find an upper limit on Δx, and hence the maximum range of the weak force, we let the W or Z travel close to the speed of light, so $\Delta x \lesssim c\,\Delta t$. Recalling that $1\,\mathrm{GeV} = 1.6 \times 10^{-10}\,\mathrm{J}$, then

$$\Delta x \lesssim c\,\Delta t \approx \frac{c\hbar}{\Delta E} \approx \frac{(3 \times 10^8\,\mathrm{m/s})(10^{-34}\,\mathrm{J \cdot s})}{(10^2\,\mathrm{GeV})(1.6 \times 10^{-10}\,\mathrm{J/GeV})} \approx 10^{-18}\,\mathrm{m}.$$

This is indeed a very small range.

NOTE Compare this to the range of the electromagnetic force whose range is infinite ($1/r^2$ never becomes zero for any finite r), which makes sense because the mass of its virtual exchange particle, the photon, is zero (in the denominator of the above equation).

[We did a similar calculation for the strong force in Section 32–2, estimating the mass of the π meson as exchange particle. In our deeper view of the strong force, namely the color force between quarks within a nucleon, the gluons have zero mass, which implies infinite range (see formula in Example 32–10). We might have expected a range of about 10^{-15} m (nuclear size). But according to the Standard Model, the color force is weak at very close distances and increases greatly with distance (causing quark confinement). Thus its range could be infinite.]

Theoreticians have wondered why the W and Z have large masses rather than being massless like the photon. Peter Higgs and others in 1964 used electroweak theory to suggest an explanation by means of a **Higgs field** and its particle, the **Higgs boson**, which interact with the W and Z to "slow them down." In being forced to go slower than the speed of light, they would have to have mass ($m = 0$ only if $v = c$). Indeed, the Higgs field is thought to permeate the vacuum ("empty space") and to perhaps confer mass on particles that now have mass by slowing them down. In 2012 strong evidence was announced at CERN's Large Hadron Collider (Section 32–1) for a particle of mass 125 GeV/c^2 that is thought to be the long-sought Higgs boson of the Standard Model. But intense research continues, not only to better understand this particle, but to search for additional Higgs-like particles suggested by theories that go beyond the Standard Model such as *supersymmetry* (Section 32–12).

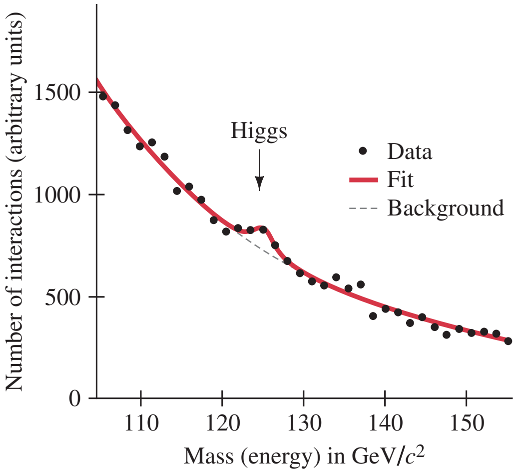


FIGURE 32–19 Evidence for the Higgs boson.

FIGURE 32–20 Fabiola Gianotti, leader of the ATLAS team (3000 physicists), at the LHC with theorist Peter Higgs, July 4, 2012, when the long hoped-for boson was announced.

Figure 32–19 shows the "resonance" bump (Section 32–7) that represents the Higgs boson as detected by the CMS team at the LHC. A second experiment, ATLAS, came up with the same mass. ATLAS is considered the largest scientific experiment ever (see Fig. 32–20).

There is no way to know if the Chapter-Opening Photo of a possible Higgs event, page 915, is actually a Higgs or is a background event. As can be seen in Fig. 32–19, there are many more background events around 125 GeV than there are in the resonance bump representing the Higgs boson.

32–11 Grand Unified Theories

The Standard Model, for all its success, cannot explain some important issues—such as why the charge on the electron has *exactly* the same magnitude as the charge on the proton. This is crucial, because if the charge magnitudes were even a little different, atoms would not be neutral and the resulting large electric forces would surely have made life impossible. Indeed, the Standard Model is now considered to be a low-energy approximation to a more complete theory.

With the success of unified electroweak theory, theorists are trying to incorporate it and QCD for the strong (color) force into a so-called **grand unified theory** (**GUT**).

One type of such a grand unified theory of the electromagnetic, weak, and strong forces has been proposed in which there is only one class of particle—leptons and quarks belong to the same family and are able to change freely from one type to the other—and the three forces are different aspects of a single underlying force. The unity is predicted to occur, however, only on a scale of less than about 10^{-31} m, corresponding to a typical particle energy of about 10^{16} GeV.

If two elementary particles (leptons or quarks) approach each other to within this **unification scale**, the apparently fundamental distinction between them would not exist at this level, and a quark could readily change to a lepton, or vice versa. Baryon and lepton numbers would not be conserved. The weak, electromagnetic, and strong (color) force would blend to a force of a single strength.

What happens between the unification distance of 10^{-31} m and more normal (larger) distances is referred to as **symmetry breaking**. As an analogy, consider an atom in a crystal. Deep within the atom, there is much symmetry—in the innermost regions the electron cloud is spherically symmetric (Chapter 28). Farther out, this symmetry breaks down—the electron clouds are distributed preferentially along the lines (bonds) joining the atoms in the crystal. In a similar way, at 10^{-31} m the force between elementary particles is theorized to be a single force—it is symmetrical and does not single out one type of "charge" over another. But at larger distances, that symmetry is broken and we see three distinct forces. (In the "Standard Model" of electroweak interactions, Section 32–10, the symmetry breaking between the electromagnetic and the weak interactions occurs at about 10^{-18} m.)

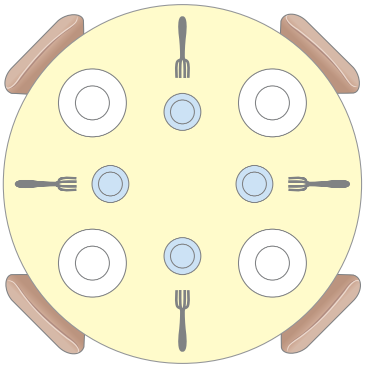


FIGURE 32–21 Symmetry around a table. Example 32–11.

CONCEPTUAL EXAMPLE 32–11 **Symmetry.** The table in Fig. 32–21 has four identical place settings. Four people sit down to eat. Describe the symmetry of this table and what happens to it when someone starts the meal.

RESPONSE The table has several kinds of symmetry. It is symmetric to rotations of 90°: that is, the table will look the same if everyone moved one chair to the left or to the right. It is also north–south symmetric and east–west symmetric, so that swaps across the table don't affect the way the table looks. It also doesn't matter whether any person picks up the fork to the left of the plate or the fork to the right. But once that first person picks up either fork, the choice is set for all the rest at the table as well. The symmetry has been *broken*. The underlying symmetry is still there—the blue glasses could still be chosen either way—but some choice must get made and at that moment the symmetry of the diners is broken.

Another example of symmetry breaking is a pencil standing on its point before falling. Standing, it looks the same from any horizontal direction. From above, it is a tiny circle. But when it falls to the table, it points in one particular direction—the symmetry is broken.

Proton Decay

Since unification is thought to occur at such tiny distances and huge energies, the theory is difficult to test experimentally. But it is not completely impossible. One testable prediction is the idea that the proton might decay (via, for example, $p \rightarrow \pi^0 + e^+$) and violate conservation of baryon number. This could happen if two quarks within a proton approached to within 10^{-31} m of each other. But it is very unlikely at normal temperature and energy, so the decay of a proton can only be an unlikely process. In the simplest form of GUT, the theoretical estimate of the proton mean life for the decay mode $p \rightarrow \pi^0 + e^+$ is about 10^{31} yr, and this is now within the realm of testability.[†] Proton decays have still not been seen, and experiments put the lower limit on the proton mean life for the above mode to be about 10^{33} yr, somewhat greater than this prediction. This may seem a disappointment, but on the other hand, it presents a challenge. Indeed more complex GUTs may resolve this conflict.

[†] This is much larger than the age of the universe ($\approx 14 \times 10^9$ yr). But we don't have to wait 10^{31} yr to see. Instead we can wait for one decay among 10^{31} protons over a year (see Eqs. 30–3a and 30–7, $\Delta N = \lambda N\,\Delta t = N\,\Delta t/\tau$, and Example 32–12).

EXAMPLE 32–12 ESTIMATE **Proton decay.** An experiment uses 3300 tons of water waiting to see a proton decay of the type $p \rightarrow \pi^0 + e^+$. If the experiment is run for 4 years without detecting a decay, estimate the lower limit on the proton mean life.

APPROACH As with radioactive decay, the number of decays is proportional to the number of parent species (N), the time interval (Δt), and the decay constant (λ) which is related to the mean life τ by (see Eqs. 30–3 and 30–7):

$$\Delta N = -\lambda N \,\Delta t = -\frac{N\,\Delta t}{\tau}.$$

SOLUTION Dealing only with magnitudes, we solve for τ:

$$\tau = \frac{N\,\Delta t}{\Delta N}.$$

Thus for $\Delta N < 1$ (we don't see even one decay) over the four-year trial,

$$\tau > N(4\text{ yr}),$$

where N is the number of protons in 3300 tons of water. To determine N, we note that each molecule of H_2O contains $2 + 8 = 10$ protons. So one mole of water $(18\text{ g},\ 6 \times 10^{23}\text{ molecules})$ contains $10 \times 6 \times 10^{23} = 6 \times 10^{24}$ protons in 18 g of water ($= 18\text{ g}/1000\text{ g} = 1/56$ of a kg), or about 3×10^{26} protons per kilogram. One ton is 10^3 kg, so the 3300 tons contains $(3.3 \times 10^6\text{ kg})(3 \times 10^{26}\text{ protons/kg}) \approx 1 \times 10^{33}$ protons. Then our very rough estimate for a lower limit on the proton mean life is $\tau > (10^{33})(4\text{ yr}) \approx 4 \times 10^{33}$ yr.

*GUT and Cosmology

An interesting prediction of unified theories relates to cosmology (Chapter 33). It was thought by many theorists that during the first 10^{-35} s after the theorized Big Bang that created the universe, the temperature was so extremely high that particles had energies corresponding to the unification scale. Baryon number would not have been conserved then, perhaps allowing an imbalance that might account for the observed predominance of matter $(B > 0)$ over antimatter $(B < 0)$ in the universe. The fact that we are surrounded by matter, with no significant antimatter in sight, is considered a problem in search of an explanation (not given by the Standard Model). We call this the **matter–antimatter problem**. To understand it may require still undiscovered phenomena—perhaps related to quarks or neutrinos, or the Higgs boson or supersymmetry (next Section).

Many theorists no longer think the Big Bang was sufficiently hot to create unification. Nonetheless we see that there is a deep connection between investigations at either end of the size scale: theories about the tiniest objects (elementary particles) have a strong bearing on the understanding of the universe on a large scale. We look at this more in the next Chapter.

Figure 32–22 is a rough diagram indicating how the four fundamental forces in nature might have "condensed out" (a symmetry was broken) as time went on after the Big Bang (Chapter 33), and as the mean temperature of the universe and the typical particle energy decreased.

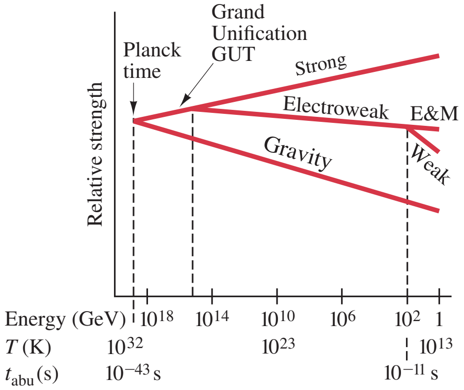


FIGURE 32–22 Time and energy plot of the four fundamental forces, perhaps unified at the "Planck time" (10^{-43} s after the birth of the universe), and how each condensed out, assuming a very hot Big Bang. The symbol t_{abu} means time after the birth of the universe. Note that the typical particle energy (and average temperature of the universe) decreases to the right, as time increases.

32–12 Strings and Supersymmetry

We have seen that the Standard Model is unable to address important experimental issues, and that theoreticians are attacking the problem as experimenters search for new data, new particles, new concepts.

Even more ambitious than grand unified theories are attempts to also incorporate gravity, and thus unify all four forces in nature into a single theory. (Such theories are sometimes referred to misleadingly as **theories of everything**.) A major attempt to unify all four forces is called **string theory**, introduced by Gabriele Veneziano in 1968: Each fundamental particle (Table 32–5) is imagined not as a point but as a one-dimensional **string**, perhaps 10^{-35} m long, which vibrates in a particular standing wave pattern. (You might say each particle is a different note on a tiny stretched string.) More sophisticated theories propose the fundamental entities as being multidimensional **branes** (after 2-D membranes).

A related idea that also goes way beyond the Standard Model is **supersymmetry**, which applied to strings is known as **superstring theory**. Supersymmetry, developed by Bruno Zumino (1923–) and Julius Wess (1934–2007), predicts that interactions exist that would change fermions into bosons and vice versa, and that each known fermion would have a supersymmetric boson partner. Thus, for each quark (a fermion), there would be a **squark** (a boson) or "supersymmetric" quark. For every lepton there would be a **slepton**. Likewise, for every known boson (photons and gluons, for example), there would be a supersymmetric fermion (**photinos** and **gluinos**). Supersymmetry predicts also that a *graviton*, which transmits the gravity force, has a partner, the **gravitino**. Supersymmetry (often abbreviated SUSY) offers solutions to a number of important theoretical problems. Supersymmetric particles are a candidate for the "dark matter" of the universe (discussed in Chapter 33). But why hasn't this "missing part" of the universe ever been detected? The best guess is that supersymmetric particles might be heavier than their conventional counterparts, perhaps too heavy to have been produced in today's accelerators. A search for supersymmetric particles is already being done at CERN's new Large Hadron Collider.

Versions of these theories predict other interesting properties, such as that space has 11 dimensions, but 7 of them are "coiled up" so we normally only notice the 4-D of space–time. We would like to know if and how many extra dimensions there are, and how and why they are hidden. We hope to have some answers from the new LHC (Section 32–1).

Some theorists think SUSY and other theories are approximations to a more fundamental, still undiscovered, **M-theory**. Edward Witten coined the term when proposing an 11 dimensional approximation, but never said what "M" stands for.

The world of elementary particles is opening new vistas. What happens in the future is bound to be exciting.

Summary

Particle accelerators are used to accelerate charged particles, such as electrons and protons, so they can have very high energy collisions with other particles. High-energy particles have short wavelength and so can be used to probe the structure of matter in great detail (very small distances). High kinetic energy also allows the creation of new particles through collisions (via $E = mc^2$).

Cyclotrons and **synchrotrons** use a magnetic field to keep the particles in a circular path and accelerate them at intervals by high voltage. **Linear accelerators** accelerate particles along a line. **Colliding beams** allow higher interaction energy.

An **antiparticle** has the same mass as a particle but opposite charge. Certain other properties may also be opposite: for example, the antiproton has **baryon number** (nucleon number) opposite $(B = -1)$ to that for the proton $(B = +1)$.

In all nuclear and particle reactions, the following conservation laws hold: momentum, angular momentum, mass–energy, electric charge, baryon number, and **lepton numbers**.

Certain particles have a property called **strangeness**, which is conserved by the strong force but not by the weak force. The properties **charm**, **bottom**, and **top** also are conserved by the strong force but not by the weak force.

Just as the electromagnetic force can be said to be due to an exchange of photons, the strong nuclear force is carried by massless **gluons**. The W and Z particles carry the weak force. These fundamental force carriers (photon, W and Z, gluons) are called **gauge bosons**.

Other particles can be classified as either *leptons* or *hadrons*. **Leptons** participate only in gravity, the weak, and the electromagnetic interactions. **Hadrons**, which today are considered **composite** particles, are made up of **quarks**, and participate in all four interactions, including the strong interaction. The hadrons can be classified as **mesons**, with baryon number zero, and **baryons**, with nonzero baryon number.

Most particles, except for the photon, electron, neutrinos, and proton, decay with measurable mean lives varying from 10^{-25} s to 10^3 s. The mean life depends on which force is predominant. Weak decays usually have mean lives greater than about 10^{-13} s. Electromagnetic decays typically have mean lives on the order of 10^{-16} to 10^{-19} s. The shortest lived particles, called **resonances**, decay via the strong interaction and live typically for only about 10^{-23} s.

Today's **Standard Model** of elementary particles considers **quarks** as the basic building blocks of the hadrons. The six quark "flavors" are called **up**, **down**, **strange**, **charm**, **bottom**, and **top**. It is expected that there are the same number of quarks as leptons (six of each), and that quarks and leptons are truly fundamental particles along with the gauge bosons (γ, W, Z, gluons) and the Higgs boson.

Quarks are said to have **color**, and, according to **quantum chromodynamics** (QCD), the strong color force acts between their color charges and is transmitted by **gluons**. **Electroweak theory** views the weak and electromagnetic forces as two aspects of a single underlying interaction. QCD plus the electroweak theory are referred to as the *Standard Model* of the fundamental particles.

Grand unified theories of forces suggest that at very short distance $\left(10^{-31}\,\mathrm{m}\right)$ and very high energy, the weak, electromagnetic, and strong forces would appear as a single force, and the fundamental difference between quarks and leptons would disappear.

According to **string theory**, the fundamental particles may be tiny strings, 10^{-35} m long, distinguished by their standing wave pattern. **Supersymmetry** predicts that each fermion (or boson) has a corresponding boson (or fermion) partner.

Questions

1. Give a reaction between two nucleons, similar to Eq. 32–4, that could produce a π^-.

2. If a proton is moving at very high speed, so that its kinetic energy is much greater than its rest energy $\left(mc^2\right)$, can it then decay via $\mathrm{p} \rightarrow \mathrm{n} + \pi^+$?

3. What would an "antiatom," made up of the antiparticles to the constituents of normal atoms, consist of? What might happen if *antimatter*, made of such antiatoms, came in contact with our normal world of matter?

4. What particle in a decay signals the electromagnetic interaction?

5. (*a*) Does the presence of a neutrino among the decay products of a particle necessarily mean that the decay occurs via the weak interaction? (*b*) Do all decays via the weak interaction produce a neutrino? Explain.

6. Why is it that a neutron decays via the weak interaction even though the neutron and one of its decay products (proton) are strongly interacting?

7. Which of the four interactions (strong, electromagnetic, weak, gravitational) does an electron take part in? A neutrino? A proton?

8. Verify that charge and baryon number are conserved in each of the decays shown in Table 32–2.

9. Which of the particle decays listed in Table 32–2 occur via the electromagnetic interaction?

10. Which of the particle decays listed in Table 32–2 occur by the weak interaction?

11. The Δ baryon has spin $\frac{3}{2}$, baryon number 1, and charge $Q = +2, +1, 0,$ or -1. Why is there no charge state $Q = -2$?

12. Which of the particle decays in Table 32–4 occur via the electromagnetic interaction?

13. Which of the particle decays in Table 32–4 occur by the weak interaction?

14. Quarks have spin $\frac{1}{2}$. How do you account for the fact that baryons have spin $\frac{1}{2}$ or $\frac{3}{2}$, and mesons have spin 0 or 1?

15. Suppose there were a kind of "neutrinolet" that was massless, had no color charge or electrical charge, and did not feel the weak force. Could you say that this particle even exists?

16. Is it possible for a particle to be both (*a*) a lepton and a baryon? (*b*) a baryon and a hadron? (*c*) a meson and a quark? (*d*) a hadron and a lepton? Explain.

17. Using the ideas of quantum chromodynamics, would it be possible to find particles made up of two quarks and no antiquarks? What about two quarks and two antiquarks?

18. Why can neutrons decay when they are free, but not when they are inside a stable nucleus?

19. Is the reaction $\mathrm{e}^- + \mathrm{p} \rightarrow \mathrm{n} + \bar{\nu}_\mathrm{e}$ possible? Explain.

20. Occasionally, the Λ will decay by the following reaction: $\Lambda^0 \rightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$. Which of the four forces in nature is responsible for this decay? How do you know?

MisConceptual Questions

1. There are six kinds (= flavors) of quarks: up, down, strange, charm, bottom, and top. Which flavors make up most of the known matter in the universe?
(*a*) Up and down quarks.
(*b*) Strange and charm quarks.
(*c*) Bottom and top quarks.
(*d*) All of the above.

2. Which of the following particles can not be composed of quarks?
(*a*) Proton.
(*b*) Electron.
(*c*) π meson.
(*d*) Neutron.
(*e*) Higgs boson.

3. If gravity is the weakest force, why is it the one we notice most?
(*a*) Our bodies are not sensitive to the other forces.
(*b*) The other forces act only within atoms and therefore have no effect on us.
(*c*) Gravity may be "very weak" but always attractive, and the Earth has enormous mass. The strong and weak nuclear forces have very short range. The electromagnetic force has a long range, but most matter is electrically neutral.
(*d*) At long distances, the gravitational force is actually stronger than the other forces.
(*e*) The other forces act only on elementary particles, not on objects our size.

4. Is it possible for a tau lepton (whose mass is almost twice that of a proton) to decay into only hadrons?
(*a*) Yes, because it is so massive it could decay into a proton and pions.
(*b*) Yes, it could decay into pions and nothing else.
(*c*) No, such a decay would violate lepton number; all of its decay products must be leptons.
(*d*) No, its decay products must include a tau neutrino but could include hadrons such as pions.
(*e*) No, the tau lepton is too massive to decay.

5. Many particle accelerators are circular because:
(*a*) particles accelerate faster around circles.
(*b*) in order to move in a circle, acceleration is required.
(*c*) a circular accelerator has a shorter length than a square one.
(*d*) the particles can be accelerated through the same potential difference many times, making the accelerator more compact.
(*e*) a particle moving in a circle needs more energy than a particle moving in a straight line.

6. Which of the following are today considered fundamental particles (that is, not composed of smaller components)? Choose as many as apply.
(*a*) Atoms. (*b*) Electrons. (*c*) Protons. (*d*) Neutrons.
(*e*) Quarks. (*f*) Photon. (*g*) Higgs boson.

7. The electron's antiparticle is called the positron. Which of the following properties, if any, are the same for electrons and positrons?
(*a*) Mass.
(*b*) Charge.
(*c*) Lepton number.
(*d*) None of the above.

8. The strong nuclear force between a neutron and a proton is due to
(*a*) the exchange of π mesons between the neutron and the proton.
(*b*) the conservation of baryon number.
(*c*) the beta decay of the neutron into the proton.
(*d*) the exchange of gluons between the quarks within the neutron and the proton.
(*e*) Both (*a*) and (*d*) at different scales.

9. Electrons are still considered fundamental particles (in the group called leptons). But protons and neutrons are no longer considered fundamental; they have substructure and are made up of
(*a*) pions. (*b*) leptons. (*c*) quarks. (*d*) bosons. (*e*) photons.

10. Which of the following will interact via the weak nuclear force *only*?
(*a*) Quarks. (*b*) Gluons. (*c*) Neutrons. (*d*) Neutrinos.
(*e*) Electrons. (*f*) Muons. (*g*) Higgs boson.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

32–1 Particles and Accelerators

1. (I) What is the total energy of a proton whose kinetic energy is 4.65 GeV?

2. (I) Calculate the wavelength of 28-GeV electrons.

3. (I) If α particles are accelerated by the cyclotron of Example 32–2, what must be the frequency of the voltage applied to the dees?

4. (I) What is the time for one complete revolution for a very high-energy proton in the 1.0-km-radius Fermilab accelerator?

5. (II) What strength of magnetic field is used in a cyclotron in which protons make 3.1×10^7 revolutions per second?

6. (II) (*a*) If the cyclotron of Example 32–2 accelerated α particles, what maximum energy could they attain? What would their speed be? (*b*) Repeat for deuterons $\left({}^{2}_{1}\mathrm{H}\right)$. (*c*) In each case, what frequency of voltage is required?

7. (II) Which is better for resolving details of the nucleus: 25-MeV alpha particles or 25-MeV protons? Compare each of their wavelengths with the size of a nucleon in a nucleus.

8. (II) What is the wavelength (= minimum resolvable size) of 7.0-TeV protons at the LHC?

9. (II) The 1.0-km radius Fermilab Tevatron took about 20 seconds to bring the energies of the stored protons from 150 GeV to 1.0 TeV. The acceleration was done once per turn. Estimate the energy given to the protons on each turn. (You can assume that the speed of the protons is essentially *c* the whole time.)

10. (II) A cyclotron with a radius of 1.0 m is to accelerate deuterons $\left({}^{2}_{1}\mathrm{H}\right)$ to an energy of 12 MeV. (*a*) What is the required magnetic field? (*b*) What frequency is needed for the voltage between the dees? (*c*) If the potential difference between the dees averages 22 kV, how many revolutions will the particles make before exiting? (*d*) How much time does it take for one deuteron to go from start to exit? (*e*) Estimate how far it travels during this time.

11. (III) Show that the energy of a particle (charge *e*) in a synchrotron, in the relativistic limit $(v \approx c)$, is given by E (in eV) $= Brc$, where B is the magnetic field and r is the radius of the orbit (SI units).

32–2 to 32–6 Particle Interactions, Particle Exchange

12. (I) About how much energy is released when a Λ^0 decays to $\mathrm{n} + \pi^0$? (See Table 32–2.)

13. (I) How much energy is released in the decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ?$$

See Table 32–2.

14. (I) Estimate the range of the strong force if the mediating particle were the kaon instead of a pion.

15. (I) How much energy is required to produce a neutron–antineutron pair?

16. (II) Determine the total energy released when Σ^0 decays to Λ^0 and then to a proton.

17. (II) Two protons are heading toward each other with equal speeds. What minimum kinetic energy must each have if a π^0 meson is to be created in the process? (See Table 32–2.)

18. (II) What minimum kinetic energy must a proton and an antiproton each have if they are traveling at the same speed toward each other, collide, and produce a K^+K^- pair in addition to themselves? (See Table 32–2.)

19. (II) What are the wavelengths of the two photons produced when a proton and antiproton at rest annihilate?

20. (II) The Λ^0 cannot decay by the following reactions. What conservation laws are violated in each of the reactions?
(*a*) $\Lambda^0 \nrightarrow n + \pi^-$
(*b*) $\Lambda^0 \nrightarrow p + K^-$
(*c*) $\Lambda^0 \nrightarrow \pi^+ + \pi^-$

21. (II) What would be the wavelengths of the two photons produced when an electron and a positron, each with 420 keV of kinetic energy, annihilate in a head-on collision?

22. (II) Which of the following reactions and decays are possible? For those forbidden, explain what laws are violated.
(*a*) $\pi^- + p \rightarrow n + \eta^0$
(*b*) $\pi^+ + p \rightarrow n + \pi^0$
(*c*) $\pi^+ + p \rightarrow p + e^+$
(*d*) $p \rightarrow e^+ + \nu_e$
(*e*) $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu$
(*f*) $p \rightarrow n + e^+ + \nu_e$

23. (II) Antiprotons can be produced when a proton with sufficient energy hits a stationary proton. Even if there is enough energy, which of the following reactions will not happen?

$$p + p \rightarrow p + \bar{p}$$
$$p + p \rightarrow p + p + \bar{p}$$
$$p + p \rightarrow p + p + p + \bar{p}$$
$$p + p \rightarrow p + e^+ + e^+ + \bar{p}$$

24. (III) In the rare decay $\pi^+ \rightarrow e^+ + \nu_e$, what is the kinetic energy of the positron? Assume the π^+ decays from rest and $m_\nu = 0$.

25. (III) For the decay $\Lambda^0 \rightarrow p + \pi^-$, calculate (*a*) the Q-value (energy released), and (*b*) the kinetic energy of the p and π^-, assuming the Λ^0 decays from rest. (Use relativistic formulas.)

26. (III) Calculate the maximum kinetic energy of the electron when a muon decays from rest via $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. [*Hint*: In what direction do the two neutrinos move relative to the electron in order to give the electron the maximum kinetic energy? Both energy and momentum are conserved; use relativistic formulas.]

32–7 to 32–11 Resonances, Standard Model, Quarks, QCD, GUT

27. (I) The mean life of the Σ^0 particle is 7×10^{-20} s. What is the uncertainty in its rest energy? Express your answer in MeV.

28. (I) The measured width of the ψ (3686) meson is about 300 keV. Estimate its mean life.

29. (I) The measured width of the J/ψ meson is 88 keV. Estimate its mean life.

30. (I) The B^- meson is a $b\bar{u}$ quark combination. (*a*) Show that this is consistent for all quantum numbers. (*b*) What are the quark combinations for B^+, B^0, $\bar{B}^0$?

31. (I) What is the energy width (or uncertainty) of (*a*) η^0, and (*b*) ρ^+? See Table 32–2.

32. (II) Which of the following decays are possible? For those that are forbidden, explain which laws are violated.
(*a*) $\Xi^0 \rightarrow \Sigma^+ + \pi^-$
(*b*) $\Omega^- \rightarrow \Sigma^0 + \pi^- + \nu$
(*c*) $\Sigma^0 \rightarrow \Lambda^0 + \gamma + \gamma$

33. (II) In ordinary radioactive decay, a W particle may be created even though the decaying particle has less mass than the W particle. If you assume $\Delta E \approx$ mass of the virtual W, what is the expected lifetime of the W?

34. (II) What quark combinations produce (*a*) a Ξ^0 baryon and (*b*) a Ξ^- baryon?

35. (II) What are the quark combinations that can form (*a*) a neutron, (*b*) an antineutron, (*c*) a Λ^0, (*d*) a $\bar{\Sigma}^0$?

36. (II) What particles do the following quark combinations produce: (*a*) uud, (*b*) $\bar{u}\,\bar{u}\,\bar{s}$, (*c*) $\bar{u}s$, (*d*) $d\bar{u}$, (*e*) $\bar{c}s$?

37. (II) What is the quark combination needed to produce a D^0 meson $(Q = B = S = 0,\ \ c = +1)$?

38. (II) The D_S^+ meson has $S = c = +1$, $B = 0$. What quark combination would produce it?

39. (II) Draw a possible Feynman diagram using quarks (as in Fig. 32–17c) for the reaction $\pi^- + p \rightarrow \pi^0 + n$.

40. (II) Draw a Feynman diagram for the reaction $n + \nu_\mu \rightarrow p + \mu^-$.

General Problems

41. What is the total energy of a proton whose kinetic energy is 15 GeV? What is its wavelength?

42. The mean lifetimes listed in Table 32–2 are in terms of *proper time*, measured in a reference frame where the particle is at rest. If a tau lepton is created with a kinetic energy of 950 MeV, how long would its track be as measured in the lab, on average, ignoring any collisions?

43. (*a*) How much energy is released when an electron and a positron annihilate each other? (*b*) How much energy is released when a proton and an antiproton annihilate each other? (All particles have KE ≈ 0.)

44. If 2×10^{14} protons moving at $v \approx c$, with KE = 4.0 TeV, are stored in the 4.3-km-radius ring of the LHC, (*a*) how much current (amperes) is carried by this beam? (*b*) How fast would a 1500-kg car have to move to carry the same kinetic energy as this beam?

45. Protons are injected into the 4.3-km-radius Large Hadron Collider with an energy of 450 GeV. If they are accelerated by 8.0 MV each revolution, how far do they travel and approximately how much time does it take for them to reach 4.0 TeV?

46. Which of the following reactions are possible, and by what interaction could they occur? For those forbidden, explain why.
(*a*) $\pi^- + \mathrm{p} \rightarrow \mathrm{K}^0 + \mathrm{p} + \pi^0$
(*b*) $\mathrm{K}^- + \mathrm{p} \rightarrow \Lambda^0 + \pi^0$
(*c*) $\mathrm{K}^+ + \mathrm{n} \rightarrow \Sigma^+ + \pi^0 + \gamma$
(*d*) $\mathrm{K}^+ \rightarrow \pi^0 + \pi^0 + \pi^+$
(*e*) $\pi^+ \rightarrow \mathrm{e}^+ + \nu_\mathrm{e}$

47. Which of the following reactions are possible, and by what interaction could they occur? For those forbidden, explain why.
(*a*) $\pi^- + \mathrm{p} \rightarrow \mathrm{K}^+ + \Sigma^-$
(*b*) $\pi^+ + \mathrm{p} \rightarrow \mathrm{K}^+ + \Sigma^+$
(*c*) $\pi^- + \mathrm{p} \rightarrow \Lambda^0 + \mathrm{K}^0 + \pi^0$
(*d*) $\pi^+ + \mathrm{p} \rightarrow \Sigma^0 + \pi^0$
(*e*) $\pi^- + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$

48. One decay mode for a π^+ is $\pi^+ \rightarrow \mu^+ + \nu_\mu$. What would be the equivalent decay for a π^-? Check conservation laws.

49. Symmetry breaking occurs in the electroweak theory at about 10^{-18} m. Show that this corresponds to an energy that is on the order of the mass of the $\mathrm{W}^\pm$.

50. Calculate the Q-value for each of the reactions, Eq. 32–4, for producing a pion.

51. How many fundamental fermions are there in a water molecule?

52. The mass of a π^0 can be measured by observing the reaction $\pi^- + \mathrm{p} \rightarrow \pi^0 + \mathrm{n}$ with initial kinetic energies near zero. The neutron is observed to be emitted with a kinetic energy of 0.60 MeV. Use conservation of energy and momentum to determine the π^0 mass.

53. (*a*) Show that the so-called unification distance of 10^{-31} m in grand unified theory is equivalent to an energy of about 10^{16} GeV. Use the uncertainty principle, and also de Broglie's wavelength formula, and explain how they apply. (*b*) Calculate the temperature corresponding to 10^{16} GeV.

54. Calculate the Q-value for the reaction $\pi^- + \mathrm{p} \rightarrow \Lambda^0 + \mathrm{K}^0$, when negative pions strike stationary protons. Estimate the minimum pion kinetic energy needed to produce this reaction. [*Hint*: Assume Λ^0 and K^0 move off with the same velocity.]

55. A proton and an antiproton annihilate each other at rest and produce two pions, π^- and π^+. What is the kinetic energy of each pion?

56. For the reaction $\mathrm{p} + \mathrm{p} \rightarrow 3\mathrm{p} + \bar{\mathrm{p}}$, where one of the initial protons is at rest, use relativistic formulas to show that the threshold energy is $6m_\mathrm{p}c^2$, equal to three times the magnitude of the Q-value of the reaction, where m_p is the proton mass. [*Hint*: Assume all final particles have the same velocity.]

57. At about what kinetic energy (in eV) can the rest energy of a proton be ignored when calculating its wavelength, if the wavelength is to be within 1.0% of its true value? What are the corresponding wavelength and speed of the proton?

58. Use the quark model to describe the reaction

$$\bar{\mathrm{p}} + \mathrm{n} \rightarrow \pi^- + \pi^0.$$

59. Identify the missing particle in the following reactions.
(*a*) $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{n} + \pi^+ + ?$ (*b*) $\mathrm{p} + ? \rightarrow \mathrm{n} + \mu^+$

60. What fraction of the speed of light c is the speed of a 7.0-TeV proton?

61. Using the information in Section 32–1, show that the Large Hadron Collider's two colliding proton beams can resolve details that are less than 1/10,000 the size of a nucleus.

62. Searches are underway for a process called **neutrinoless double beta decay**, in which a nucleus decays by emitting two electrons. (*a*) If the parent nucleus is ${}^{96}_{40}\mathrm{Zr}$, what would the daughter nucleus be? (*b*) What conservation laws would be violated during this decay? (*c*) How could ${}^{96}_{40}\mathrm{Zr}$ decay to the same daughter nucleus without violating any conservation laws?

63. Estimate the lifetime of the Higgs boson from the width of the "bump" in Fig. 32–19, using the uncertainty principle. [Note: This is not a realistic estimate because the underlying processes are very complicated.]

Search and Learn

1. (*a*) What are the two major classes of particles that make up the matter of the universe? (*b*) Name six types, or flavors, of each class of particles. (*c*) What are the four known fundamental forces in the universe? (*d*) Name the particles that carry the forces in part *c*. Which force is much weaker than the other three?

2. (*a*) What property characterizes all hadrons? (*b*) What property characterizes all baryons? (*c*) What property characterizes all mesons?

3. Show that all conservation laws hold for all the decays described in Fig. 32–15 for the decays of the top quark.

4. The Higgs boson, Section 32–10, has very probably been detected at the CERN LHC. (*a*) If a Higgs boson at rest decays into two tau leptons, what is the kinetic energy of each tau? Follow the analysis of Example 32–5. See Table 32–2. (*b*) What are the signs of the electric charges of the two tau leptons? (*c*) Could a Higgs boson decay into two Z bosons (Table 32–2)?

5. (*a*) Show, by conserving momentum and energy, that it is impossible for an isolated electron to radiate only a single photon. (*b*) With this result in mind, how can you defend the photon exchange diagram in Fig. 32–8?

6. What magnetic field is required for the 4.25-km-radius Large Hadron Collider (LHC) to accelerate protons to 7.0 TeV? [*Hint*: Use relativity, Chapter 26.]

ANSWERS TO EXERCISES

A: 1.24×10^{-18} m = 1.24 am.
B: (*a*).

C: (*c*); (*d*).
D: $\mathrm{s}\bar{\mathrm{u}}$.