b. the gravitational force
c. the strong nuclear force
d. the weak nuclear force

2. What force or forces exist between an electron and a proton?
   a. the strong nuclear force, the electromagnetic force, and gravity
   b. the weak nuclear force, the strong nuclear force, and gravity
   c. the weak nuclear force, the strong nuclear force, and the electromagnetic force
   d. the weak nuclear force, the electromagnetic force, and gravity

3. What is the proposed carrier particle for the gravitational force?
   a. boson
   b. graviton
   c. gluon
   d. photon

4. What is the relationship between the mass and range of a carrier particle?
   a. Range of a carrier particle is inversely proportional to its mass.
   b. Range of a carrier particle is inversely proportional to square of its mass.
   c. Range of a carrier particle is directly proportional to its mass.
   d. Range of a carrier particle is directly proportional to square of its mass.

5. What type of particle accelerator uses fixed-frequency oscillating electric fields to accelerate particles?
   a. cyclotron
   b. synchrotron
   c. betatron
   d. Van de Graaff accelerator

6. How does the expanding radius of the cyclotron provide evidence of particle acceleration?
   a. A constant magnetic force is exerted on particles at all radii. As the radius increases, the velocity of the particle must increase to maintain this constant force.
   b. A constant centripetal force is exerted on particles at all radii. As the radius increases, the velocity of the particle must decrease to maintain this constant force.
   c. A constant magnetic force is exerted on particles at all radii. As the radius increases, the velocity of the particle must decrease to maintain this constant force.
   d. A constant centripetal force is exerted on particles at all radii. As the radius increases, the velocity of the particle must increase to maintain this constant force.

7. Which of the four forces is responsible for the structure of galaxies?
   a. electromagnetic force
   b. gravity
   c. strong nuclear force
   d. weak nuclear force

23.2 Quarks

Section Learning Objectives

By the end of the section, you will be able to do the following:

- Describe quarks and their relationship to other particles
- Distinguish hadrons from leptons
- Distinguish matter from antimatter
- Describe the standard model of the atom
- Define a Higgs boson and its importance to particle physics

Section Key Terms

annihilation	antimatter	baryon	bottom quark	charmed quark
color	down quark	flavor	gluon	hadron
Higgs boson	Higgs field	lepton	meson	pair production
positron	quantum chromodynamics	quark	Standard Model	strange quark
top quark	up quark			

Quarks

"The first principles of the universe are atoms and empty space. Everything else is merely thought to exist…"

"… Further, the atoms are unlimited in size and number, and they are borne along with the whole universe in a vortex, and thereby generate all composite things—fire, water, air, earth. For even these are conglomerations of given atoms. And it because of their solidity that these atoms are impassive and unalterable."

—Diogenes Laertius (summarizing the views of Democritus, circa 460–370 B.C.)

The search for fundamental particles is nothing new. Atomists of the Greek and Indian empires, like Democritus of fifth century B.C., openly wondered about the most finite components of our universe. Though dormant for centuries, curiosity about the atomic nature of matter was reinvigorated by Rutherford's gold foil experiment and the discovery of the nucleus. By the early 1930s, scientists believed they had fully determined the tiniest constituents of matter—in the form of the proton, neutron, and electron.

This would be only partially true. At present, scientists know that there are hundreds of particles not unlike our electron and nucleons, all making up what some have termed the *particle zoo*. While we are confident that the electron remains fundamental, it is surrounded by a plethora of similar sounding terms, like leptons, hadrons, baryons, and mesons. Even though not every particle is considered fundamental, they all play a vital role in understanding the intricate structure of our universe.

A fundamental particle is defined as a particle with no substructure and no finite size. According to the **Standard Model**, there are three types of fundamental particles: leptons, quarks, and carrier particles. As you may recall, carrier particles are responsible for transmitting fundamental forces between their interacting masses. **Leptons** are a group of six particles not bound by the strong nuclear force, of which the electron is one. As for quarks, they are the fundamental building blocks of a group of particles called **hadrons**, a group that includes both the proton and the neutron.

Now for a brief history of **quarks**. Quarks were first proposed independently by American physicists Murray Gell-Mann and George Zweig in 1963. Originally, three quark types—or **flavors**—were proposed with the names **up** (u), **down** (d), and **strange** (s).

At first, physicists expected that, with sufficient energy, we should be able to free quarks and observe them directly. However, this has not proved possible, as the current understanding is that the force holding quarks together is incredibly great and, much like a spring, increases in magnitude as the quarks are separated. As a result, when large energies are put into collisions, other particles are created—but no quarks emerge. With that in mind, there is compelling evidence for the existence of quarks. By 1967, experiments at the SLAC National Accelerator Laboratory scattering 20-GeV electrons from protons produced results like Rutherford had obtained for the nucleus nearly 60 years earlier. The SLAC scattering experiments showed unambiguously that there were three point-like (meaning they had sizes considerably smaller than the probe's wavelength) charges inside the proton as seen in Figure 23.12. This evidence made all but the most skeptical admit that there was validity to the quark substructure of hadrons.

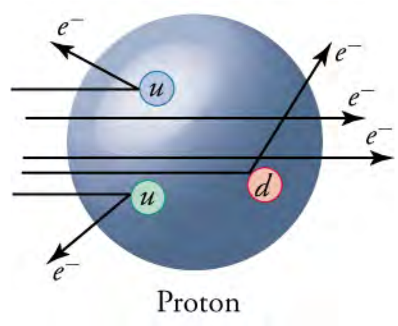

Figure 23.12 Scattering of high-energy electrons from protons at facilities like SLAC produces evidence of three point-like charges consistent with proposed quark properties. This experiment is analogous to Rutherford's discovery of the small size of the nucleus by scattering α particles. High-energy electrons are used so that the probe wavelength is small enough to see details smaller than the proton.

The inclusion of the strange quark with Zweig and Gell-Mann's model concerned physicists. While the up and down quarks demonstrated fairly clear symmetry and were present in common fundamental particles like protons and neutrons, the strange quark did not have a counterpart of its own. This thought, coupled with the four known leptons at the time, caused scientists to predict that a fourth quark, yet to be found, also existed.

In 1974, two groups of physicists independently discovered a particle with this new quark, labeled **charmed**. This completed the second *exotic* quark pair, strange (s) and charmed (c). A final pair of quarks was proposed when a third pair of leptons was discovered in 1975. The existence of the **bottom** (b) quark and the **top** (t) quark was verified through experimentation in 1976 and 1995, respectively. While it may seem odd that so much time would elapse between the original quark discovery in 1967 and the verification of the top quark in 1995, keep in mind that each quark discovered had a progressively larger mass. As a result, each new quark has required more energy to discover.

TIPS FOR SUCCESS

Note that a very important tenet of science occurred throughout the period of quark discovery. The charmed, bottom, and top quarks were all speculated on, and then were discovered some time later. Each of their discoveries helped to verify and strengthen the quark model. This process of speculation and verification continues to take place today and is part of what drives physicists to search for evidence of the graviton and Grand Unified Theory.

One of the most confounding traits of quarks is their electric charge. Long assumed to be discrete, and specifically a multiple of the elementary charge of the electron, the electric charge of an individual quark is fractional and thus seems to violate a presumed tenet of particle physics. The fractional charge of quarks, which are $\pm\left(\frac{2}{3}\right) q_e$ and $\pm\left(\frac{1}{3}\right) q_e$, are the only structures found in nature with a nonintegral number of charge q . However, note that despite this odd construction, the fractional value of the quark does not violate the quantum nature of the charge. After all, free quarks cannot be found in nature, and all quarks are bound into arrangements in which an integer number of charge is constructed. Table 23.3 shows the six known quarks, in addition to their antiquark components, as will be discussed later in this section.

Flavor	Symbol	Antiparticle	Charge[1][2]
Up	u	$\overline{u}$	$\pm\frac{2}{3}q_e$
Down	d	$\overline{d}$	$\mp\frac{1}{3}q_e$
Strange	s	$\overline{s}$	$\mp\frac{1}{3}q_e$
Charmed	c	$\overline{c}$	$\pm\frac{2}{3}q_e$

[1]The lower of the $\pm$ symbols are the values for antiquarks.
[2]There are further qualities that differentiate between quarks. However, they are beyond the discussion in this text.

Table 23.3 Quarks and Antiquarks

Flavor	Symbol	Antiparticle	Charge[1][2]
Bottom	b	$\overline{b}$	$\mp\frac{1}{3}q_e$
Top	t	$\overline{t}$	$\pm\frac{2}{3}q_e$

[1]The lower of the $\pm$ symbols are the values for antiquarks.
[2]There are further qualities that differentiate between quarks. However, they are beyond the discussion in this text.

Table 23.3 Quarks and Antiquarks

While the term *flavor* is used to differentiate between types of quarks, the concept of **color** is more analogous to the electric charge in that it is primarily responsible for the force interactions between quarks. Note—Take a moment to think about the electrostatic force. It is the electric charge that causes attraction and repulsion. It is the same case here but with a *color* charge. The three colors available to a quark are red, green, and blue, with antiquarks having colors of anti-red (or cyan), anti-green (or magenta), and anti-blue (or yellow).

Why use colors when discussing quarks? After all, the quarks are not actually colored with visible light. The reason colors are used is because the properties of a quark are analogous to the three primary and secondary colors mentioned above. Just as different colors of light can be combined to create white, different *colors* of quark may be combined to construct a particle like a proton or neutron. In fact, for each hadron, the quarks must combine such that their color sums to white! Recall that two up quarks and one down quark construct a proton, as seen in Figure 23.12. The sum of the three quarks' colors—red, green, and blue—yields the color white. This theory of color interaction within particles is called **quantum chromodynamics**, or QCD. As part of QCD, the strong nuclear force can be explained using color. In fact, some scientists refer to the color force, not the strong force, as one of the four fundamental forces. Figure 23.13 is a Feynman diagram showing the interaction between two quarks by using the transmission of a colored **gluon**. Note that the gluon is also considered the charge carrier for the strong nuclear force.

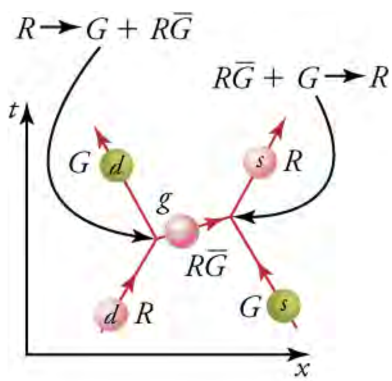

Figure 23.13 The exchange of gluons between quarks carries the strong force and may change the color of the interacting quarks. While the colors of the individual quarks change, their flavors do not.

Note that quark flavor may have any color. For instance, in Figure 23.13, the down quark has a red color and a green color. In other words, colors are not specific to a particle quark flavor.

Hadrons and Leptons

Particles can be revealingly grouped according to what forces they feel between them. All particles (even those that are massless) are affected by gravity since gravity affects the space and time in which particles exist. All charged particles are affected by the electromagnetic force, as are neutral particles that have an internal distribution of charge (such as the neutron with its magnetic moment). Special names are given to particles that feel the strong and weak nuclear forces. Hadrons are particles that feel the strong nuclear force, whereas leptons are particles that do not. All particles feel the weak nuclear force. This means that hadrons are distinguished by being able to feel both the strong and weak nuclear forces. Leptons and hadrons are distinguished in other ways as well. Leptons are fundamental particles that have no measurable size, while hadrons are composed of quarks and have a diameter on the order of 10 to 15 m. Six particles, including the electron and neutrino, make up the list of known leptons. There are hundreds of complex particles in the hadron class, a few of which (including the proton and neutron) are listed in Table 23.4.

Category	Particle Name	Symbol	Antiparticle	Rest Mass $\left(\mathrm{MeV/c^2}\right)$	Mean Lifetime (s)
Leptons	Electron	e^-	e^+	0.511	Stable
	Neutrino (e)	ν_e	$\overline{\nu}_e$	$0\ (7.0\,\mathrm{eV})$ [1]	Stable
	Muon	μ^-	μ^+	105.7	2.20×10^{-6}
	Neutrino (μ)	ν_μ	$\overline{\nu}_\mu$	$0\ (<0.27)$ [1]	Stable
	Tau	τ^-	τ^+	1,777	2.91×10^{-6}
	Neutrino (τ)	ν_τ	$\overline{\nu}_\tau$	$0\ (<31)$ [1]	Stable
Hadrons – Mesons[2]	Pion	π^+	π^-	139.6	2.60×10^{-8}
		π^0	Self	135.0	8.40×10^{-17}
	Kaon	K^+	K^-	493.7	1.24×10^{-8}
		K^0	K^0	497.6	0.90×10^{-10}
	Eta	η^0	Self	547.9	2.53×10^{-19}
Hadrons – Baryons[3]	Proton	p	$\overline{p}$	938.3	Stable
	Neutron	n	$\overline{n}$	939.6	882
	Lambda	Λ^0	$\overline{\Lambda}^0$	1,115.7	2.63×10^{-10}
	Omega	Ω^-	Ω^+	1,672.5	0.82×10^{-10}

[1]Neutrino masses may be zero. Experimental upper limits are given in parentheses.
[2]Many other mesons known
[3]Many other baryons known

Table 23.4 List of Leptons and Hadrons.

There are many more leptons, mesons, and baryons yet to be discovered and measured. The purpose of trying to uncover the smallest indivisible things in existence is to explain the world around us through forces and the interactions between particles, galaxies and objects. This is why a handful of scientists devote their life's work to smashing together small particles.

What internal structure makes a proton so different from an electron? The proton, like all hadrons, is made up of quarks. A few examples of hadron quark composition can be seen in Figure 23.14. As shown, each hadron is constructed of multiple quarks. As mentioned previously, the fractional quark charge in all four hadrons sums to the particle's integral value. Also, notice that the color composition for each of the four particles adds to white. Each of the particles shown is constructed of up, down, and their antiquarks. This is not surprising, as the quarks strange, charmed, top, and bottom are found in only our most exotic particles.

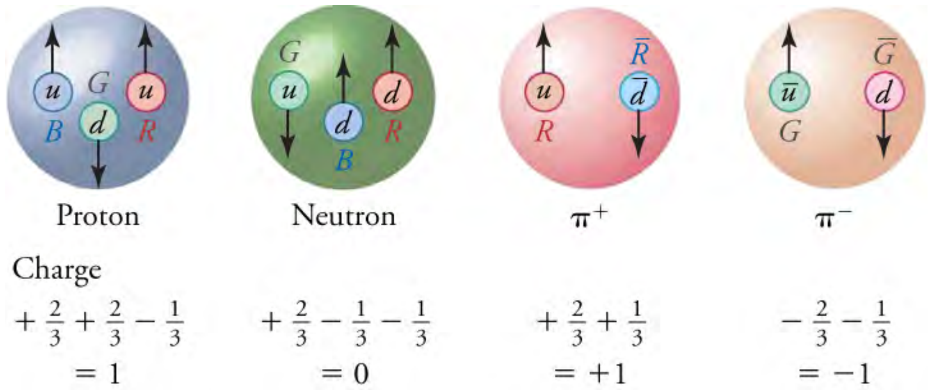

Figure 23.14 All baryons, such as the proton and neutron shown here, are composed of three quarks. All mesons, such as the pions shown here, are composed of a quark–antiquark pair. Arrows represent the spins of the quarks. The colors are such that they need to add to white for any possible combination of quarks.

You may have noticed that while the proton and neutron in Figure 23.14 are composed of three quarks, both pions are comprised of only two quarks. This refers to a final delineation in particle structure. Particles with three quarks are called **baryons**. These are heavy particles that can decay into another baryon. Particles with only two quarks—a-quark–anti-quark pair—are called **mesons**. These are particles of moderate mass that cannot decay into the more massive baryons.

Before continuing, take a moment to view Figure 23.15. In this figure, you can see the strong force reimagined as a color force. The particles interacting in this figure are the proton and neutron, just as they were in Figure 23.6. This reenvisioning of the strong force as an interaction between colored quarks is the critical concept behind quantum chromodynamics.

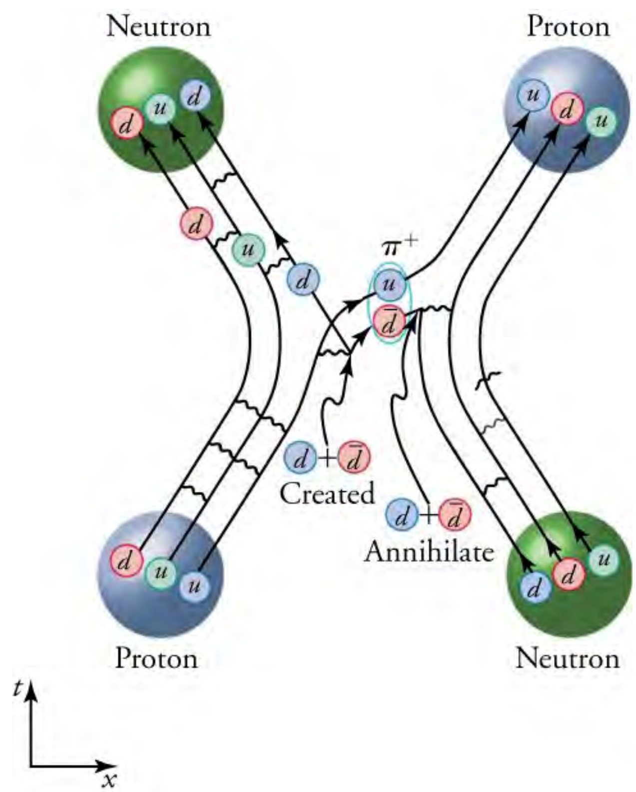

Figure 23.15 This Feynman diagram shows the interaction between a proton and a neutron, corresponding to the interaction shown in Figure 23.6. This diagram, however, shows the quark and gluon details of the strong nuclear force interaction.

Matter and Antimatter

Antimatter was first discovered in the form of the **positron**, the positively charged electron. In 1932, American physicist Carl Anderson discovered the positron in cosmic ray studies. Through a cloud chamber modified to curve the trajectories of cosmic rays, Anderson noticed that the curves of some particles followed that of a negative charge, while others curved like a positive charge. However, the positive curve showed not the mass of a proton but the mass of an electron. This outcome is shown in Figure 23.16 and suggests the existence of a positively charged version of the electron, created by the destruction of solar photons.

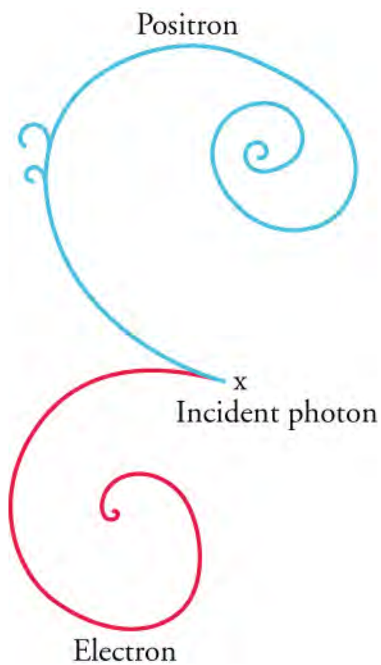

Figure 23.16 The image above is from the Fermilab *15 foot bubble chamber* and shows the production of an electron and positron (or antielectron) from an incident photon. This event is titled **pair production** and provides evidence of antimatter, as the two repel each other.

Antimatter is considered the opposite of matter. For most antiparticles, this means that they share the same properties as their original particles with the exception of their charge. This is why the positron can be considered a positive electron while the antiproton is considered a negative proton. The idea of an opposite charge for neutral particles (like the neutron) can be confusing, but it makes sense when considered from the quark perspective. Just as the neutron is composed of one up quark and two down quarks (of charge $+\frac{2}{3}$ and $-\frac{1}{3}$, respectively), the antineutron is composed of one anti–up quark and two anti–down quarks (of charge $-\frac{2}{3}$ and $+\frac{1}{3}$, respectively). While the overall charge of the neutron remains the same, its constituent particles do not!

A word about antiparticles: Like regular particles, antiparticles could function just fine on their own. In fact, a universe made up of antimatter may operate just as our own matter-based universe does. However, we do not know fully whether this is the case. The reason for this is **annihilation**. Annihilation is the process of destruction that occurs when a particle and its antiparticle interact. As soon as two particles (like a positron and an electron) coincide, they convert their masses to energy through the equation $E = mc^2$. This mass-to-energy conversion, which typically results in photon release, happens instantaneously and makes it very difficult for scientists to study antimatter. That said, scientists have had success creating antimatter through high-energy particle collisions. Both antineutrons and antiprotons were created through accelerator experiments in 1956, and an anti–hydrogen atom was even created at CERN in 1995! As referenced in , the annihilation of antiparticles is currently used in medical studies to determine the location of radioisotopes.

Completing the Standard Model of the Atom

The Standard Model of the atom refers to the current scientific view of the fundamental components and interacting forces of matter. The Standard Model (Figure 23.17) shows the six quarks that bind to form all hadrons, the six lepton particles already considered fundamental, the four carrier particles (or gauge bosons) that transmit forces between the leptons and quarks, and the recently added **Higgs boson** (which will be discussed shortly). This totals 17 fundamental particles, combinations of which are responsible for all known matter in our entire universe! When adding the antiquarks and antileptons, 31 components make up the Standard Model.

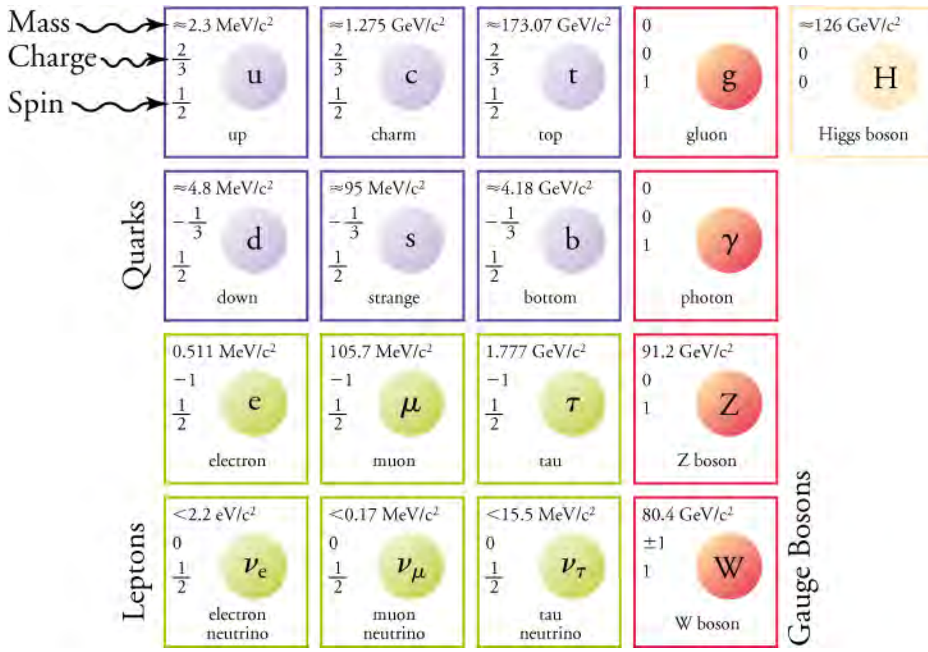

Figure 23.17 The Standard Model of elementary particles shows an organized view of all fundamental particles, as currently known: six quarks, six leptons, and four gauge bosons (or carrier particles). The Higgs boson, first observed in 2012, is a new addition to the Standard Model.

Figure 23.17 shows all particles within the Standard Model of the atom. Not only does this chart divide all known particles by color-coded group, but it also provides information on particle stability. Note that the color-coding system in this chart is separate from the red, green, and blue color labeling system of quarks. The first three columns represent the three *families* of matter. The first column, considered Family 1, represents particles that make up normal matter, constructing the protons, neutrons, and electrons that make up the common world. Family 2, represented from the charm quark to the muon neutrino, is comprised of particles that are more massive. The leptons in this group are less stable and more likely to decay. Family 3, represented by the third column, are more massive still and decay more quickly. The order of these families also conveniently represents the order in which these particles were discovered.

TIPS FOR SUCCESS

Look for trends that exist within the Standard Model. Compare the charge of each particle. Compare the spin. How does mass relate to the model structure? Recognizing each of these trends and asking questions will yield more insight into the organization of particles and the forces that dictate particle relationships. Our understanding of the Standard Model is still young, and the questions you may have in analyzing the Standard Model may be some of the same questions that particle physicists are searching for answers to today!

The Standard Model also summarizes the fundamental forces that exist as particles interact. A closer look at the Standard Model, as shown in Figure 23.18, reveals that the arrangement of carrier particles describes these interactions.

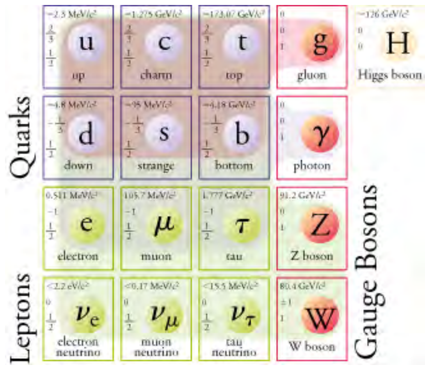

Figure 23.18 The revised Standard Model shows the interaction between gauge bosons and other fundamental particles. These interactions are responsible for the fundamental forces, three of which are described through the chart's shaded areas.

Each of the shaded areas represents a fundamental force and its constituent particles. The red shaded area shows all particles involved in the strong nuclear force, which we now know is due to quantum chromodynamics. The blue shaded area corresponds to the electromagnetic force, while the green shaded area corresponds to the weak nuclear force, which affects all quarks and leptons. The electromagnetic force and weak nuclear force are considered united by the electroweak force within the Standard Model. Also, because definitive evidence of the graviton is yet to be found, it is not included in the Standard Model.

The Higgs Boson

One interesting feature of the Standard Model shown in Figure 23.18 is that, while the gluon and photon have no mass, the Z and W bosons are very massive. What supplies these quickly moving particles with mass and not the gluons and photons? Furthermore, what causes some quarks to have more mass than others?

In the 1960s, British physicist Peter Higgs and others speculated that the W and Z bosons were actually just as massless as the gluon and photon. However, as the W and Z bosons traveled from one particle to another, they were slowed down by the presence of a **Higgs field**, much like a fish swimming through water. The thinking was that the existence of the Higgs field would slow down the bosons, causing them to decrease in energy and thereby transfer this energy to mass. Under this theory, all particles pass through the Higgs field, which exists throughout the universe. The gluon and photon travel through this field as well but are able to do so unaffected.

The presence of a force from the Higgs field suggests the existence of its own carrier particle, the Higgs boson. This theorized boson interacts with all particles but gluons and photons, transferring force from the Higgs field. Particles with large mass (like the top quark) are more likely to receive force from the Higgs boson.

While it is difficult to examine a field, it is somewhat simpler to find evidence of its carrier. On July 4, 2012, two groups of scientists at the LHC independently confirmed the existence of a Higgs-like particle. By examining trillions of proton–proton collisions at energies of 7 to 8 TeV, LHC scientists were able to determine the constituent particles that created the protons. In this data, scientists found a particle with similar mass, spin, parity, and interactions with other particles that matched the Higgs boson predicted decades prior. On March 13, 2013, the existence of the Higgs boson was tentatively confirmed by CERN. Peter Higgs and Francois Englert received the Nobel Prize in 2013 for the "theoretical discovery of a mechanism that contributes to our understanding of the origin and mass of subatomic particles."

WORK IN PHYSICS

Particle Physicist

If you have an innate desire to unravel life's great mysteries and further understand the nature of the physical world, a career in particle physics may be for you!

Particle physicists have played a critical role in much of society's technological progress. From lasers to computers, televisions to space missions, splitting the atom to understanding the DNA molecule to MRIs and PET scans, much of our modern society is based on the work done by particle physicists.

While many particle physicists focus on specialized tasks in the fields of astronomy and medicine, the main goal of particle physics is to further scientists' understanding of the Standard Model. This may mean work in government, industry, or academics. Within the government, jobs in particle physics can be found within the National Institute for Standards and Technology, Department of Energy, NASA, and Department of Defense. Both the electronics and computer industries rely on the expertise of particle physicists. College teaching and research positions can also be potential career opportunities for particle physicists, though they often require some postgraduate work as a prerequisite. In addition, many particle physicists are employed to work on high-energy colliders. Domestic collider labs include the Brookhaven National Laboratory in New York, the Fermi National Accelerator Laboratory near Chicago, and the SLAC National Accelerator Laboratory operated by Stanford University. For those who like to travel, work at international collider labs can be found at the CERN facility in Switzerland in addition to institutes like the Budker Institute of Nuclear Physics in Russia, DESY in Germany, and KEK in Japan.

Shirley Jackson became the first African American woman to earn a Ph.D. from MIT back in 1973, and she went on to lead a highly successful career in the field of particle physics. Like Dr. Jackson, successful students of particle physics grow up with a strong curiosity in the world around them and a drive to continually learn more. If you are interested in exploring a career in particle physics, work to achieve good grades and SAT scores, and find time to read popular books on physics topics that interest you. While some math may be challenging, recognize that this is only a tool of physics and should not be considered prohibitive to the field. High-level work in particle physics often requires a Ph.D.; however, it is possible to find work with a master's degree. Additionally, jobs in industry and teaching can be achieved with solely an undergraduate degree.

GRASP CHECK

What is the primary goal of all work in particle physics?

a. The primary goal is to further our understanding of the Standard Model.
b. The primary goal is to further our understanding of Rutherford's model.
c. The primary goal is to further our understanding of Bohr's model.
d. The primary goal is to further our understanding of Thomson's model.

Check Your Understanding

8. In what particle were quarks originally discovered?

a. the electron
b. the neutron
c. the proton
d. the photon

9. Why was the existence of the charm quark speculated, even though no direct evidence of it existed?

a. The existence of the charm quark was symmetrical with up and down quarks. Additionally, there were two known leptons at the time and only two quarks.
b. The strange particle lacked the symmetry that existed with the up and down quarks. Additionally, there were four known leptons at the time and only three quarks.
c. The bottom particle lacked the symmetry that existed with the up and down quarks. Additionally, there were two known leptons at the time and only two quarks.
d. The existence of charm quarks was symmetrical with up and down quarks. Additionally, there were four known leptons at the time and only three quarks.

10. What type of particle is the electron?

a. The electron is a lepton.
b. The electron is a hadron.
c. The electron is a baryon.
d. The electron is an antibaryon.

11. How do the number of fundamental particles differ between hadrons and leptons?

a. Hadrons are constructed of at least three fundamental quark particles, while leptons are fundamental particles.
b. Hadrons are constructed of at least three fundamental quark particles, while leptons are constructed of two fundamental particles.
c. Hadrons are constructed of at least two fundamental quark particles, while leptons are constructed of three

fundamental particles.
d. Hadrons are constructed of at least two fundamental quark particles, while leptons are fundamental particles.

12. Does antimatter exist?
a. no
b. yes

13. How does the deconstruction of a photon into an electron and a positron uphold the principles of mass and charge conservation?
a. The sum of the masses of an electron and a positron is equal to the mass of the photon before pair production. The sum of the charges on an electron and a positron is equal to the zero charge of the photon.
b. The sum of the masses of an electron and a positron is equal to the mass of the photon before pair production. The sum of the same charges on an electron and a positron is equal to the charge on a photon.
c. During the particle production the total energy of the photon is converted to the mass of an electron and a positron. The sum of the opposite charges on the electron and positron is equal to the zero charge of the photon.
d. During particle production, the total energy of the photon is converted to the mass of an electron and a positron. The sum of the same charges on an electron and a positron is equal to the charge on a photon.

14. How many fundamental particles exist in the Standard Model, including the Higgs boson and the graviton (not yet observed)?
a. 12
b. 15
c. 13
d. 19

15. Why do gluons interact only with particles in the first two rows of the Standard Model?
a. The leptons in the third and fourth rows do not have mass, but the gluons can interact between the quarks through gravity only.
b. The leptons in the third and fourth rows do not have color, but the gluons can interact between quarks through color interactions only.
c. The leptons in the third and fourth rows do not have spin, but the gluons can interact between quarks through spin interactions only.
d. The leptons in the third and fourth rows do not have charge, but the gluons can interact between quarks through charge interactions only.

16. What fundamental property is provided by particle interaction with the Higgs boson?
a. charge
b. mass
c. spin
d. color

17. Considering the Higgs field, what differentiates more massive particles from less massive particles?
a. More massive particles interact more with the Higgs field than the less massive particles.
b. More massive particles interact less with the Higgs field than the less massive particles.

18. What particles were launched into the proton during the original discovery of the quark?
a. bosons
b. electrons
c. neutrons
d. photons

23.3 The Unification of Forces

Section Learning Objectives

By the end of the section, you will be able to do the following:

- Define a grand unified theory and its importance
- Explain the evolution of the four fundamental forces from the Big Bang onward
- Explain how grand unification theories can be tested

Section Key Terms

Big Bang	Electroweak Epoch	electroweak theory	Grand Unification Epoch	Grand Unified Theory
Inflationary Epoch	Planck Epoch	Quark Era	superforce	Theory of Everything

Understanding the Grand Unified Theory

Present quests to show that the four basic forces are different manifestations of a single unified force that follow a long tradition. In the nineteenth century, the distinct electric and magnetic forces were shown to be intimately connected and are now collectively called the electromagnetic force. More recently, the weak nuclear force was united with the electromagnetic force. As shown in Figure 23.19, carrier particles transmit three of the four fundamental forces in very similar ways. With these considerations in mind, it is natural to suggest that a theory may be constructed in which the strong nuclear, weak nuclear, and electromagnetic forces are all unified. The search for a correct theory linking the forces, called the **Grand Unified Theory (GUT)**, is explored in this section.

In the 1960s, the **electroweak theory** was developed by Steven Weinberg, Sheldon Glashow, and Abdus Salam. This theory proposed that the electromagnetic and weak nuclear forces are identical at sufficiently high energies. At lower energies, like those in our present-day universe, the two forces remain united but manifest themselves in different ways. One of the main consequences of the electroweak theory was the prediction of three short-range carrier particles, now known as the W^+, W^-, and Z^0 bosons. Not only were three particles predicted, but the mass of each W^+ and W^- boson was predicted to be 81 GeV/c^2, and that of the Z^0 boson was predicted to be 90 GeV/c^2. In 1983, these carrier particles were observed at CERN with the predicted characteristics, including masses having those predicted values as given in .

How can forces be unified? They are definitely distinct under most circumstances. For example, they are carried by different particles and have greatly different strengths. But experiments show that at extremely short distances and at extremely high energies, the strengths of the forces begin to become more similar, as seen in Figure 23.20.

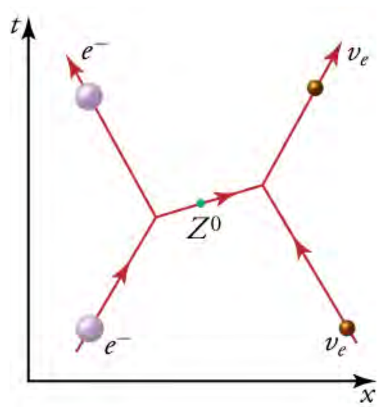

Figure 23.19 The exchange of a virtual Z^0 particle (boson) carries the weak nuclear force between an electron and a neutrino in this Feynman diagram. This diagram is similar to the diagrams in Figure 23.6 and for the electromagnetic and strong nuclear forces.

As discussed earlier, the short ranges and large masses of the weak carrier bosons require correspondingly high energies to create them. Thus, the energy scale on the horizontal axis of Figure 23.20 also corresponds to shorter and shorter distances