CHAPTER 23
Particle Physics

Figure 23.1 Part of the Large Hadron Collider (LHC) at CERN, on the border of Switzerland and France. The LHC is a particle accelerator, designed to study fundamental particles. (credit: Image Editor, Flickr)

Chapter Outline

INTRODUCTION Following ideas remarkably similar to those of the ancient Greeks, we continue to look for smaller and smaller structures in nature, hoping ultimately to find and understand the most fundamental building blocks that exist. Atomic physics deals with the smallest units of elements and compounds. In its study, we have found a relatively small number of atoms with systematic properties, and these properties have explained a tremendous range of phenomena. Nuclear physics is concerned with the nuclei of atoms and their substructures. Here, a smaller number of components—the proton and neutron—make up all nuclei. Exploring the systematic behavior of their interactions has revealed even more about matter, forces, and energy. **Particle physics** deals with the substructures of atoms and nuclei and is particularly aimed at finding those truly fundamental particles that have no further substructure. Just as in atomic and nuclear physics, we have found a complex array of particles and properties with systematic characteristics analogous to the periodic table and the chart of nuclides. An underlying structure is apparent, and there is some reason to think that we *are* finding particles that have no substructure. Of course, we have been in similar situations before. For example, atoms were once thought to be the ultimate substructures. It is possible that we could continue to find deeper and deeper structures without ever discovering the ultimate substructure—in science there is never complete certainty. See Figure 23.2.

The properties of matter are based on substructures called molecules and atoms. Each atom has the substructure of a nucleus surrounded by electrons, and their interactions explain atomic properties. Protons and neutrons—and the interactions between them—explain the stability and abundance of elements and form the substructure of nuclei. Protons and neutrons are not fundamental—they are composed of quarks. Like electrons and a few other particles, quarks may be the fundamental building blocks of all matter, lacking any further substructure. But the story is not complete because quarks and electrons may have substructures smaller than details that are presently observable.

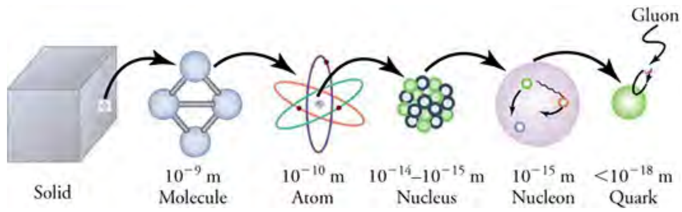

Figure 23.2 A solid, a molecule, an atom, a nucleus, a nucleon (a particle that makes up the nucleus—either a proton or a neutron), and a quark.

This chapter covers the basics of particle physics as we know it today. An amazing convergence of topics is evolving in particle physics. We find that some particles are intimately related to forces and that nature on the smallest scale may have its greatest influence on the large scale character of the universe. It is an adventure exceeding the best science fiction because it is not only fantastic but also real.

23.1 The Four Fundamental Forces

Section Learning Objectives

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

- Define, describe, and differentiate the four fundamental forces
- Describe the carrier particles and explain how their exchange transmits force
- Explain how particle accelerators work to gather evidence about particle physics

Section Key Terms

carrier particle	colliding beam	cyclotron	Feynman diagram	graviton
particle physics	pion	quantum electrodynamics	synchrotron	W^- boson
W^+ boson	weak nuclear force	Z^0 boson		

Despite the apparent complexity within the universe, there remain just four basic forces. These forces are responsible for all interactions known to science: from the very small to the very large to those that we experience in our day-to-day lives. These forces describe the movement of galaxies, the chemical reactions in our laboratories, the structure within atomic nuclei, and the cause of radioactive decay. They describe the true cause behind familiar terms like friction and the normal force. These four basic forces are known as fundamental because they alone are responsible for all observations of forces in nature. The four fundamental forces are gravity, electromagnetism, **weak nuclear force**, and strong nuclear force.

Understanding the Four Forces

The gravitational force is most familiar to us because it describes so many of our common observations. It explains why a dropped ball falls to the ground and why our planet orbits the Sun. It gives us the property of weight and determines much about the motion of objects in our daily lives. Because gravitational force acts between all objects of mass and has the ability to act over large distances, the gravitational force can be used to explain much of what we observe and can even describe the motion of objects on astronomical scales! That said, gravity is incredibly weak compared to the other fundamental forces and is the weakest of all of the fundamental forces. Consider this: The entire mass of Earth is needed to hold an iron nail to the ground. Yet with a simple magnet, the force of gravity can be overcome, allowing the nail to accelerate upward through space.

The electromagnetic force is responsible for both electrostatic interactions and the magnetic force seen between bar magnets. When focusing on the electrostatic relationship between two charged particles, the electromagnetic force is known as the coulomb force. The electromagnetic force is an important force in the chemical and biological sciences, as it is responsible for molecular connections like ionic bonding and hydrogen bonding. Additionally, the electromagnetic force is behind the common physics forces of friction and the normal force. Like the gravitational force, the electromagnetic force is an inverse square law. However, the electromagnetic force does not exist between any two objects of mass, only those that are charged.

When considering the structure of an atom, the electromagnetic force is somewhat apparent. After all, the electrons are held in place by an attractive force from the nucleus. But what causes the nucleus to remain intact? After all, if all protons are positive, it makes sense that the coulomb force between the protons would repel the nucleus apart immediately. Scientists theorized that another force must exist within the nucleus to keep it together. They further theorized that this nuclear force must be significantly stronger than gravity, which has been observed and measured for centuries, and also stronger than the electromagnetic force, which would cause the protons to want to accelerate away from each other.

The strong nuclear force is an attractive force that exists between all nucleons. This force, which acts equally between proton-proton connections, proton-neutron connections, and neutron-neutron connections, is the strongest of all forces at short ranges. However, at a distance of 10^{-13} cm, or the diameter of a single proton, the force dissipates to zero. If the nucleus is large (it has many nucleons), then the distance between each nucleon could be much larger than the diameter of a single proton.

The weak nuclear force is responsible for beta decay, as seen in the equation $^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e + v$. Recall that beta decay is when a beta particle is ejected from an atom. In order to accelerate away from the nucleus, the particle must be acted on by a force. Enrico Fermi was the first to envision this type of force. While this force is appropriately labeled, it remains stronger than the gravitational force. However, its range is even smaller than that of the strong force, as can be seen in Table 23.1. The weak nuclear force is more important than it may appear at this time, as will be addressed when we discuss quarks.

Force	Approximate Relative Strength[1]	Range
Gravity	10^{-38}	∞
Weak	10^{-13}	$< 10^{-18}$ m
Electromagnetic	10^{-2}	∞
Strong	1	$< 10^{-15}$ m

[1]Relative strength is based on the strong force felt by a proton–proton pair.

Table 23.1 Relative strength and range of the four fundamental forces

Transmitting the Four Fundamental Forces

Just as it troubled Einstein prior to formulating the gravitational field theory, the concept of forces acting over a distance had greatly troubled particle physicists. That is, how does one proton *know* that another exists? Furthermore, what causes one proton to make a second proton repel? Or, for that matter, what is it about a proton that causes a neutron to attract? These mysterious interactions were first considered by Hideki Yukawa in 1935 and laid the foundation for much of what we now understand about particle physics.

Hideki Yukawa's focus was on the strong nuclear force and, in particular, its incredibly short range. His idea was a blend of particles, relativity, and quantum mechanics that was applicable to all four forces. Yukawa proposed that the nuclear force is actually transmitted by the exchange of particles, called **carrier particles**, and that what we commonly refer to as the force's field consists of these carrier particles. Specifically for the strong nuclear force, Yukawa proposed that a previously unknown particle, called a **pion**, is exchanged between nucleons, transmitting the force between them. Figure 23.3 illustrates how a pion would carry a force between a proton and a neutron.

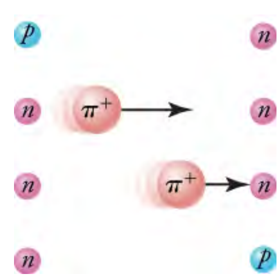

Figure 23.3 The strong nuclear force is transmitted between a proton and neutron by the creation and exchange of a pion. The pion, created through a temporary violation of conservation of mass-energy, travels from the proton to the neutron and is recaptured. It is not

directly observable and is called a virtual particle. Note that the proton and neutron change identity in the process. The range of the force is limited by the fact that the pion can exist for only the short time allowed by the Heisenberg uncertainty principle. Yukawa used the finite range of the strong nuclear force to estimate the mass of the pion; the shorter the range, the larger the mass of the carrier particle.

In Yukawa's strong force, the carrier particle is assumed to be transmitted at the speed of light and is continually transferred between the two nucleons shown. The particle that Yukawa predicted was finally discovered within cosmic rays in 1947. Its name, the pion, stands for pi meson, where meson means *medium mass*; it's a medium mass because it is smaller than a nucleon but larger than an electron. Yukawa launched the field that is now called quantum chromodynamics, and the carrier particles are now called gluons due to their strong binding power. The reason for the change in the particle name will be explained when quarks are discussed later in this section.

As you may assume, the strong force is not the only force with a carrier particle. Nuclear decay from the weak force also requires a particle transfer. In the weak force are the following three: the weak negative carrier, W^-; the weak positive carrier, W^+; and the zero charge carrier, Z°. As we will see, Fermi inferred that these particles must carry mass, as the total mass of the products of nuclear decay is slightly larger than the total mass of all reactants after nuclear decay.

The carrier particle for the electromagnetic force is, not surprisingly, the photon. After all, just as a lightbulb can emit photons from a charged tungsten filament, the photon can be used to transfer information from one electrically charged particle to another. Finally, the **graviton** is the proposed carrier particle for gravity. While it has not yet been found, scientists are currently looking for evidence of its existence (see Boundless Physics: Searching for the Graviton).

So how does a carrier particle transmit a fundamental force? Figure 23.4 shows a virtual photon transmitted from one positively charged particle to another. The transmitted photon is referred to as a virtual particle because it cannot be directly observed while transmitting the force. Figure 23.5 shows a way of graphing the exchange of a virtual photon between the two positively charged particles. This graph of time versus position is called a **Feynman diagram**, after the brilliant American physicist Richard Feynman (1918–1988), who developed it.

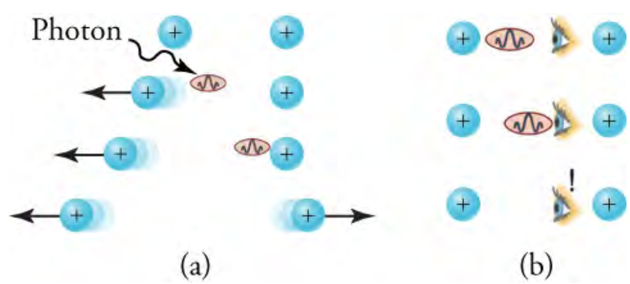

Figure 23.4 The image in part (a) shows the exchange of a virtual photon transmitting the electromagnetic force between charges, just as virtual pion exchange carries the strong nuclear force between nucleons. The image in part (b) shows that the photon cannot be directly observed in its passage because this would disrupt it and alter the force. In this case, the photon does not reach the other charge.

The Feynman diagram should be read from the bottom up to show the movement of particles over time. In it, you can see that the left proton is propelled leftward from the photon emission, while the right proton feels an impulse to the right when the photon is received. In addition to the Feynman diagram, Richard Feynman was one of the theorists who developed the field of **quantum electrodynamics** (QED), which further describes electromagnetic interactions on the submicroscopic scale. For this work, he shared the 1965 Nobel Prize with Julian Schwinger and S.I. Tomonaga. A Feynman diagram explaining the strong force interaction hypothesized by Yukawa can be seen in Figure 23.6. Here, you can see the change in particle type due to the exchange of the pi meson.

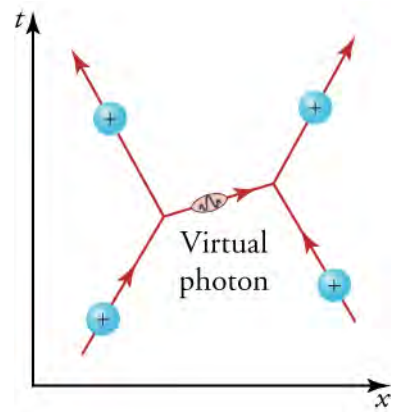

Figure 23.5 The Feynman diagram for the exchange of a virtual photon between two positively charged particles illustrates how electromagnetic force is transmitted on a quantum mechanical scale. Time is graphed vertically, while the distance is graphed horizontally. The two positively charged particles are seen to repel each other by the photon exchange.

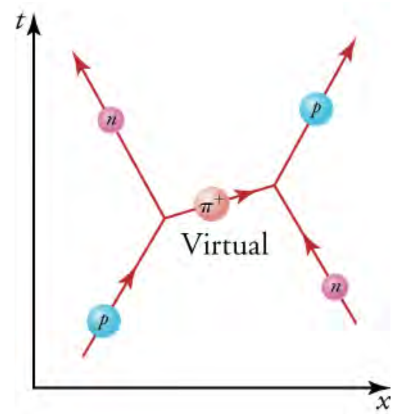

Figure 23.6 The image shows a Feynman diagram for the exchange of a π+ (pion) between a proton and a neutron, carrying the strong nuclear force between them. This diagram represents the situation shown more pictorially in Figure 23.3.

The relative masses of the listed carrier particles describe something valuable about the four fundamental forces, as can be seen in Table 23.2. **W bosons** (consisting of W^- and W^+ bosons) and **Z bosons** (Z^0 bosons), carriers of the weak nuclear force, are nearly 1,000 times more massive than pions, carriers of the strong nuclear force. Simultaneously, the distance that the weak nuclear force can be transmitted is approximately $\frac{1}{1{,}000}$ times the strong force transmission distance. Unlike carrier particles, which have a limited range, the photon is a massless particle that has no limit to the transmission distance of the electromagnetic force. This relationship leads scientists to understand that the yet-unfound graviton is likely massless as well.

Force	Carrier Particle	Range	Relative Strength[1]
Gravity	Graviton (theorized)	∞	10^{-38}
Weak	W and Z bosons	∞	10^{-2}
Electromagnetic	Photon	$< 10^{-18}\,\text{m}$	10^{-13}
Strong	Pi mesons or pions (now known as gluons)	$< 10^{-15}\,\text{m}$	1

[1]Relative strength is based on the strong force felt by a proton-proton pair.

Table 23.2 Carrier particles and their relative masses compared to pions for the four fundamental forces

BOUNDLESS PHYSICS

Searching for the Graviton

From Newton's Universal Law of Gravitation to Einstein's field equations, gravitation has held the focus of scientists for centuries. Given the discovery of carrier particles during the twentieth century, the importance of understanding gravitation has yet again gained the interest of prominent physicists everywhere.

With carrier particles discovered for three of the four fundamental forces, it is sensible to scientists that a similar particle, titled the **graviton**, must exist for the gravitational force. While evidence of this particle is yet to be uncovered, scientists are working diligently to discover its existence.

So what do scientists think about the unfound particle? For starters, the graviton (like the photon) should be a massless particle traveling at the speed of light. This is assumed because, like the electromagnetic force, gravity is an inverse square law, $F \approx \frac{1}{r^2}$. Scientists also theorize that the graviton is an electrically neutral particle, as an empty space within the influence of gravity is chargeless.

However, because gravity is such a weak force, searching for the graviton has resulted in some unique methods. LIGO, the Laser Interferometer Gravitational-Wave Observatory, is one tool currently being utilized (see Figure 23.7). While searching for a gravitational wave to find a carrier particle may seem counterintuitive, it is similar to the approach taken by Planck and Einstein to learn more about the photon. According to wave-particle duality, if a gravitational wave can be found, the graviton should be present along with it. Predicted by Einstein's theory of general relativity, scientists have been monitoring binary star systems for evidence of these gravitational waves.

Figure 23.7 In searching for gravitational waves, scientists are using the Laser Interferometer Gravitational-Wave Observatory (LIGO). Here we see the control room of LIGO in Hanford, Washington.

Particle accelerators like the Large Hadron Collider (LHC) are being used to search for the graviton through high-energy collisions. While scientists at the LHC speculate that the particle may not exist long enough to be seen, evidence of its prior existence, like footprints in the sand, can be found through gaps in projected energy and momentum.

Some scientists are even searching the remnants of the Big Bang in an attempt to find the graviton. By observing the cosmic background radiation, they are looking for anomalies in gravitational waves that would provide information about the gravity particles that existed at the start of our universe.

Regardless of the method used, scientists should know the graviton once they find it. A massless, chargeless particle with a spin of 2 and traveling at the speed of light—there is no other particle like it. Should it be found, its discovery would surely be considered by future generations to be on par with those of Newton and Einstein.

GRASP CHECK

Why are binary star systems used by LIGO to find gravitational waves?

a. Binary star systems have high temperature.
b. Binary star systems have low density.
c. Binary star systems contain a large amount of mass, but because they are orbiting each other, the gravitational field between the two is much less.
d. Binary star systems contain a large amount of mass. As a result, the gravitational field between the two is great.

Accelerators Create Matter From Energy

Before looking at all the particles that make up our universe, let us first examine some of the machines that create them. The fundamental process in creating unknown particles is to accelerate known particles, such as protons or electrons, and direct a beam of them toward a target. Collisions with target nuclei provide a wealth of information, such as information obtained by Rutherford in the gold foil experiment. If the energy of the incoming particles is large enough, new matter can even be created in the collision. The more energy input or ΔE, the more matter m can be created, according to mass energy equivalence $m = \Delta E/c^2$. Limitations are placed on what can occur by known conservation laws, such as conservation of mass-energy, momentum, and charge. Even more interesting are the unknown limitations provided by nature. While some expected reactions do occur, others do not, and still other unexpected reactions may appear. New laws are revealed, and the vast majority of what we know about particle physics has come from accelerator laboratories. It is the particle physicist's favorite indoor sport.

Our earliest model of a particle accelerator comes from the Van de Graaff generator. The relatively simple device, which you have likely seen in physics demonstrations, can be manipulated to produce potentials as great as 50 million volts. While these machines do not have energies large enough to produce new particles, analysis of their accelerated ions was instrumental in exploring several aspects of the nucleus.

Another equally famous early accelerator is the **cyclotron**, invented in 1930 by the American physicist, E.O. Lawrence (1901–1958). Figure 23.8 is a visual representation with more detail. Cyclotrons use fixed-frequency alternating electric fields to accelerate particles. The particles spiral outward in a magnetic field, making increasingly larger radius orbits during acceleration. This clever arrangement allows the successive addition of electric potential energy with each loop. As a result, greater particle energies are possible than in a Van de Graaff generator.

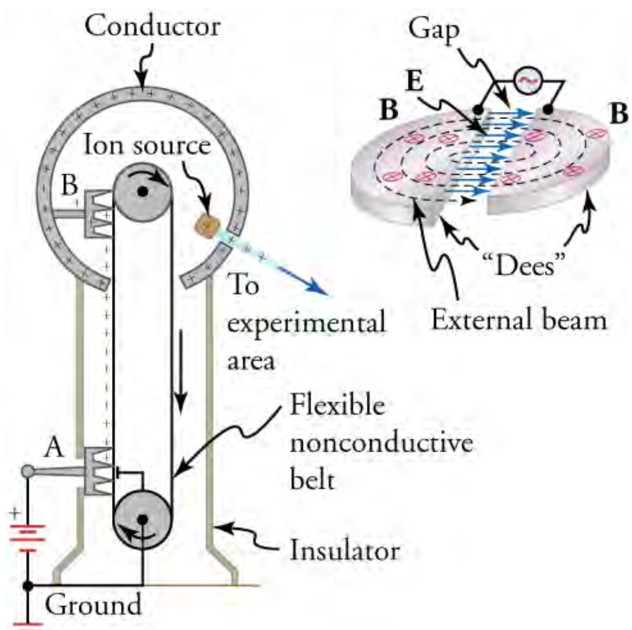

Figure 23.8 On the left is an artist's rendition of the popular physics demonstration tool, the Van de Graaff generator. A battery (A) supplies excess positive charge to a pointed conductor, the points of which spray the charge onto a moving insulating belt near the bottom. The pointed conductor (B) on top in the large sphere picks up the charge. (The induced electric field at the points is so large that it removes the charge from the belt.) This can be done because the charge does not remain inside the conducting sphere but moves to its outer surface. An ion source inside the sphere produces positive ions, which are accelerated away from the positive sphere to high velocities. On the right is a cyclotron. Cyclotrons use a magnetic field to cause particles to move in circular orbits. As the particles pass between the plates of the Dees, the voltage across the gap is oscillated to accelerate them twice in each orbit.

A **synchrotron** is a modification of the cyclotron in which particles continually travel in a fixed-radius orbit, increasing speed each time. Accelerating voltages are synchronized with the particles to accelerate them, hence the name. Additionally, magnetic field strength is increased to keep the orbital radius constant as energy increases. A ring of magnets and accelerating tubes, as shown in Figure 23.9, are the major components of synchrotrons. High-energy particles require strong magnetic fields to steer them, so superconducting magnets are commonly employed. Still limited by achievable magnetic field strengths, synchrotrons need to be very large at very high energies since the radius of a high-energy particle's orbit is very large.

To further probe the nucleus, physicists need accelerators of greater energy and detectors of shorter wavelength. To do so requires not only greater funding but greater ingenuity as well. **Colliding beams** used at both the Fermi National Accelerator Laboratory (Fermilab; see Figure 23.11) near Chicago and the LHC in Switzerland are designed to reduce energy loss in particle collisions. Typical stationary particle detectors lose a large amount of energy to the recoiling target struck by the accelerating particle. By providing head-on collisions between particles moving in opposite directions, colliding beams make it possible to create particles with momenta and kinetic energies near zero. This allows for particles of greater energy and mass to be created. Figure 23.10 is a schematic representation of this effect. In addition to circular accelerators, linear accelerators can be used to reduce energy radiation losses. The Stanford Linear Accelerator Center (now called the SLAC National Accelerator Laboratory) in California is home to the largest such accelerator in the world.

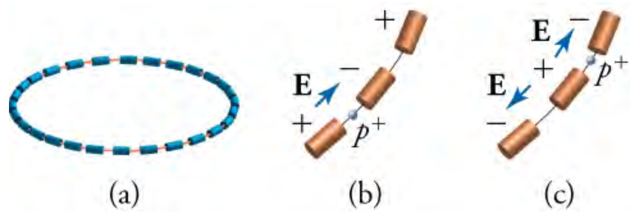

Figure 23.9 (a) A synchrotron has a ring of magnets and accelerating tubes. The frequency of the accelerating voltages is increased to cause the beam particles to travel the same distance in a shorter time. The magnetic field should also be increased to keep each beam burst traveling in a fixed-radius path. Limits on magnetic field strength require these machines to be very large in order to accelerate particles to very high energies. (b) A positively charged particle is shown in the gap between accelerating tubes. (c) While the particle passes through the tube, the potentials are reversed so that there is another acceleration at the next gap. The frequency of the reversals needs to be varied as the particle is accelerated to achieve successive accelerations in each gap.

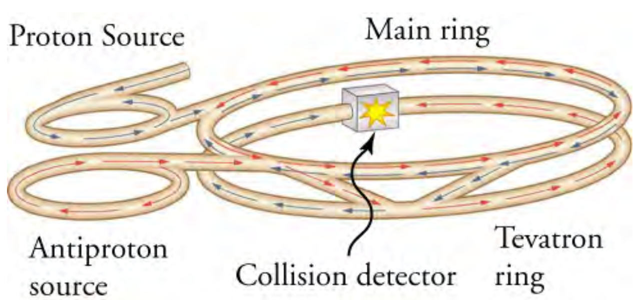

Figure 23.10 This schematic shows the two rings of Fermilab's accelerator and the scheme for colliding protons and antiprotons (not to scale).

Figure 23.11 The Fermi National Accelerator Laboratory, near Batavia, Illinois, was a subatomic particle collider that accelerated protons and antiprotons to attain energies up to 1 Tev (a trillion electronvolts). The circular ponds near the rings were built to dissipate waste heat. This accelerator was shut down in September 2011. (credit: Fermilab, Reidar Hahn)

Check Your Understanding

1. Which of the four forces is responsible for radioactive decay?

  a. the electromagnetic force

   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