11 | PARTICLE PHYSICS AND COSMOLOGY

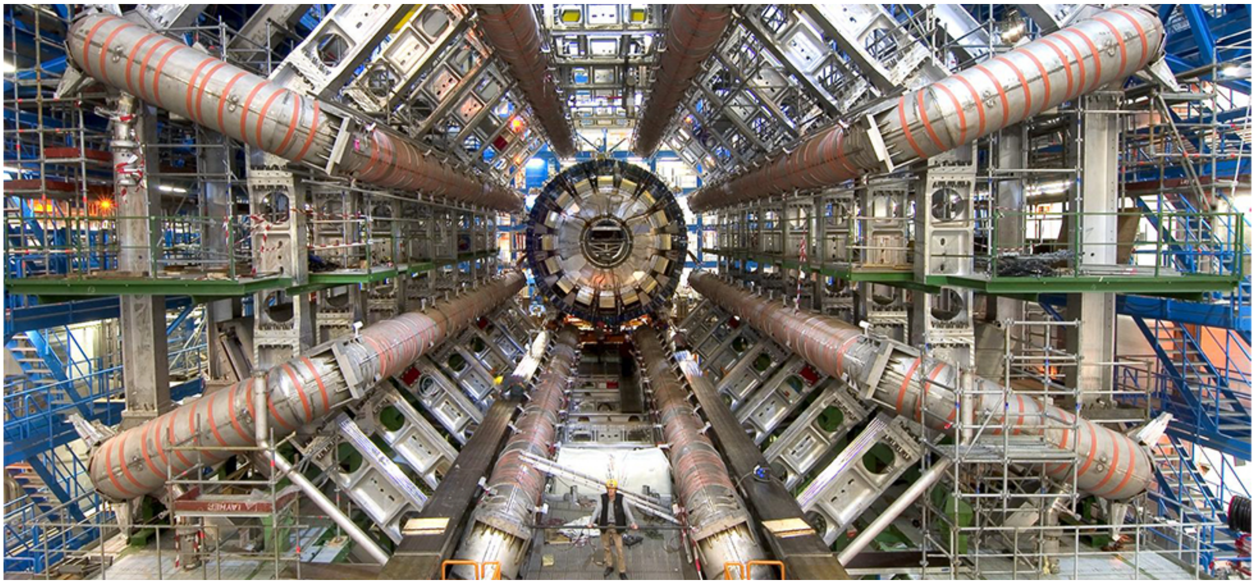


Figure 11.1 The Large Hadron Collider (LHC) is located over 150 meters (500 feet) underground on the border of Switzerland and France near Geneva, Switzerland. The LHC is the most powerful machine ever developed to test our understanding of elementary particle interactions. Shown here is the ATLAS detector, which helps identify new particles formed in collisions. (credit: modification of work by Maximilien Brice, CERN)

Chapter Outline

Introduction

At the very beginning of this text we discussed the wide range of scales that physics encompasses, from the very smallest particles to the largest scale possible—the universe itself. In this final chapter we examine some of the frontiers of research at these extreme scales. Particle physics deals with the most basic building blocks of matter and the forces that hold them together. Cosmology is the study of the stars, galaxies, and galactic structures that populate our universe, as well as their past history and future evolution.

These two areas of physics are not as disconnected as you might think. The study of elementary particles requires enormous energies to produce isolated particles, involving some of the largest machines humans have ever built. But such high energies were present in the earliest stages of the universe and the universe we see around us today was shaped in part by the nature and interactions of the elementary particles created then. Bear in mind that particle physics and cosmology are both areas of intense current research, subject to much speculation on the part of physicists (as well science-fiction writers). In this chapter we try to emphasize what is known on the basis of deductions from observational evidence, and identify ideas that are conjectured but still unproven.

11.1 | Introduction to Particle Physics

Learning Objectives

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

- Describe the four fundamental forces and what particles participate in them
- Identify and describe fermions and bosons
- Identify and describe the quark and lepton families
- Distinguish between particles and antiparticles, and describe their interactions

Elementary particle physics is the study of fundamental particles and their interactions in nature. Those who study elementary particle physics—the particle physicists—differ from other physicists in the scale of the systems that they study. A particle physicist is not content to study the microscopic world of cells, molecules, atoms, or even atomic nuclei. They are interested in physical processes that occur at scales even smaller than atomic nuclei. At the same time, they engage the most profound mysteries in nature: How did the universe begin? What explains the pattern of masses in the universe? Why is there more matter than antimatter in the universe? Why are energy and momentum conserved? How will the universe evolve?

Four Fundamental Forces

An important step to answering these questions is to understand particles and their interactions. Particle interactions are expressed in terms of four **fundamental forces**. In order of decreasing strength, these forces are the **strong nuclear force**, the electromagnetic force, the **weak nuclear force**, and the gravitational force.

1. **Strong nuclear force.** The strong nuclear force is a very strong attractive force that acts only over very short distances (about 10^{-15} m). The strong nuclear force is responsible for binding protons and neutrons together in atomic nuclei. Not all particles participate in the strong nuclear force; for instance, electrons and neutrinos are not affected by it. As the name suggests, this force is much stronger than the other forces.
2. **Electromagnetic force.** The electromagnetic force can act over very large distances (it has an infinite range) but is only 1/100 the strength of the strong nuclear force. Particles that interact through this force are said to have "charge." In the classical theory of static electricity (Coulomb's law), the electric force varies as the product of the charges of the interacting particles, and as the inverse square of the distances between them. In contrast to the strong force, the electromagnetic force can be attractive or repulsive (opposite charges attract and like charges repel). The magnetic force depends in a more complicated way on the charges and their motions. The unification of the electric and magnetic force into a single electromagnetic force (an achievement of James Clerk Maxwell) stands as one of the greatest intellectual achievements of the nineteenth century. This force is central to scientific models of atomic structure and molecular bonding.
3. **Weak nuclear force.** The weak nuclear force acts over very short distances $\left(10^{-15}\text{ m}\right)$ and, as its name suggest, is very weak. It is roughly 10^{-6} the strength of the strong nuclear force. This force is manifested most notably in decays of elementary particles and neutrino interactions. For example, the neutron can decay to a proton, electron, and electron neutrino through the weak force. The weak force is vitally important because it is essential for understanding stellar nucleosynthesis—the process that creates new atomic nuclei in the cores of stars.
4. **Gravitational force.** Like the electromagnetic force, the gravitational force can act over infinitely large distances; however, it is only 10^{-38} as strong as the strong nuclear force. In Newton's classical theory of gravity, the force of gravity varies as the product of the masses of the interacting particles and as the inverse square of the distance between them. This force is an attractive force that acts between all particles with mass. In modern theories of gravity, this force behavior is considered a special case for low-energy macroscopic interactions. Compared with the other forces of nature, gravity is by far the weakest.

The fundamental forces may not be truly "fundamental" but may actually be different aspects of the same force. Just as the electric and magnetic forces were unified into an electromagnetic force, physicists in the 1970s unified the electromagnetic force with the weak nuclear force into an **electroweak force**. Any scientific theory that attempts to unify the electroweak force and strong nuclear force is called a **grand unified theory**, and any theory that attempts to unify all four forces is called a **theory of everything**. We will return to the concept of unification later in this chapter.

Classifications of Elementary Particles

A large number of subatomic particles exist in nature. These particles can be classified in two ways: the property of spin and participation in the four fundamental forces. Recall that the spin of a particle is analogous to the rotation of a macroscopic object about its own axis. These types of classification are described separately below.

Classification by spin

Particles of matter can be divided into **fermions** and **bosons**. Fermions have half-integral spin $\left(\frac{1}{2}\hbar,\ \frac{3}{2}\hbar,\ \ldots\right)$ and bosons have integral spin $(0\hbar,\ 1\hbar,\ 2\hbar,\ \ldots)$. Familiar examples of fermions are electrons, protons, and neutrons. A familiar example of a boson is a photon. Fermions and bosons behave very differently in groups. For example, when electrons are confined to a small region of space, Pauli's exclusion principle states that no two electrons can occupy the same quantum-mechanical state. However, when photons are confined to a small region of space, there is no such limitation.

The behavior of fermions and bosons in groups can be understood in terms of the property of indistinguishability. Particles are said to be "indistinguishable" if they are identical to one another. For example, electrons are indistinguishable because every electron in the universe has exactly the same mass and spin as all other electrons—"when you've seen one electron, you've seen them all." If you switch two indistinguishable particles in the same small region of space, the square of the wave function that describes this system and can be measured $\left(|\psi|^2\right)$ is unchanged. If this were not the case, we could tell whether or not the particles had been switched and the particle would not be truly indistinguishable. Fermions and bosons differ by whether the sign of the wave function (ψ)— not directly observable—flips:

$$\psi \rightarrow -\psi \text{ (indistinguishable fermions)},$$
$$\psi \rightarrow +\psi \text{ (indistinguishable bosons)}.$$

Fermions are said to be "antisymmetric on exchange" and bosons are "symmetric on exchange." Pauli's exclusion principle is a consequence of **exchange symmetry** of fermions—a connection developed in a more advanced course in modern physics. The electronic structure of atoms is predicated on Pauli's exclusion principle and is therefore directly related to the indistinguishability of electrons.

Classification by force interactions

Fermions can be further divided into **quarks** and **leptons**. The primary difference between these two types of particles is that quarks interact via the strong force and leptons do not. Quarks and leptons (as well as bosons to be discussed later) are organized in **Figure 11.2**. The upper two rows (first three columns in purple) contain six quarks. These quarks are arranged into two particle families: up, charm, and top (u, c, t), and down, strange, and bottom (d, s, b). Members of the same particle family share the same properties but differ in mass (given in MeV/c^2). For example, the mass of the top quark is much greater than the charm quark, and the mass of the charm quark is much greater than the up quark. All quarks interact with one another through the strong nuclear force.

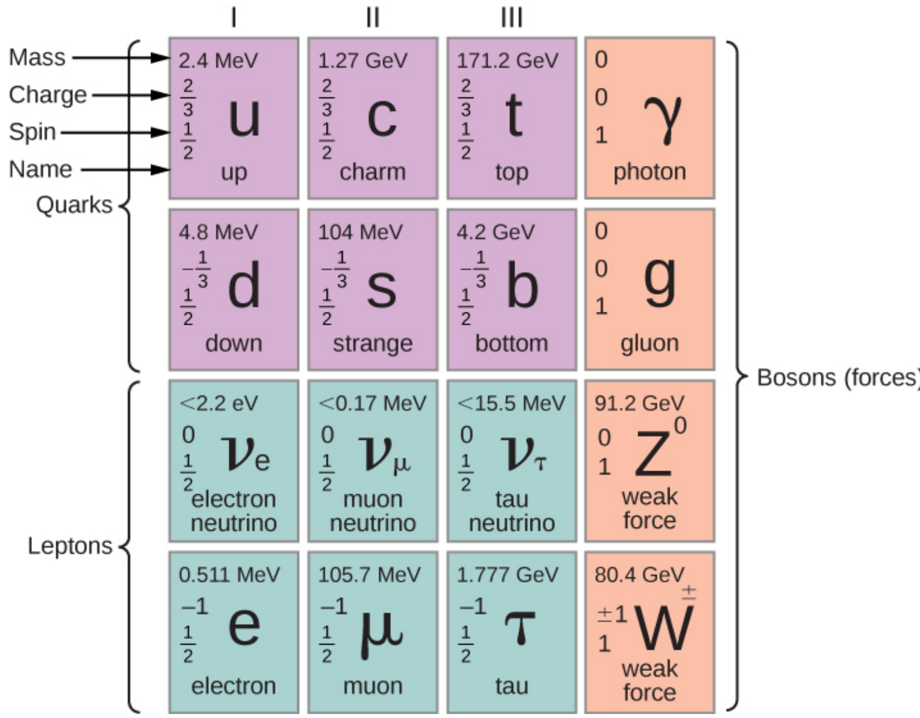


Figure 11.2 The families of subatomic particles, categorized by the types of forces with which they interact. (credit: modification of work by “MissMJ”/Wikimedia Commons)

Ordinary matter consists of two types of quarks: the up quark (elementary charge, $q = +2/3$) and the down quark $(q = -1/3)$. Heavier quarks are unstable and quickly decay to lighter ones via the weak force. Quarks bind together in groups of twos and threes called **hadrons** via the strong force. Hadrons that consist of two quarks are called **mesons**, and those that consist of three quarks are called **baryons**. Examples of mesons include the pion and kaon, and examples of baryons include the familiar proton and neutron. A proton is two up quarks and a down quark $(\mathrm{p} = uud,\ q = +1)$ and a neutron is one up quark and two down quarks ($\mathrm{n} = udd$, $q = 0$). Properties of sample mesons and baryons are given in Table 11.1. Quarks participate in all four fundamental forces: strong, weak, electromagnetic, and gravitational.

The lower two rows in the figure (in green) contain six leptons arranged into two particle families: electron, muon, and tau ($e,\ \mu,\ \tau$), and electron neutrino, muon neutrino, and tau neutrino ($\upsilon_e,\ \upsilon_\mu,\ \upsilon_\tau$). The muon is over 200 times heavier than an electron, but is otherwise similar to the electron. The tau is about 3500 times heavier than the electron, but is otherwise similar to the muon and electron. Once created, the muon and tau quickly decay to lighter particles via the weak force. Leptons do not participate in the strong force. Quarks and leptons will be discussed later in this chapter. Leptons participate in the weak, electromagnetic, and gravitational forces, but do not participate in the strong force.

Bosons (shown in red) are the force carriers of the fermions. In this model, leptons and quarks interact with each other by sending and receiving bosons. For example, Coulombic interaction occurs when two positively charged particles send and receive (exchange) photons. The photons are said to “carry” the force between charged particles. Likewise, attraction between two quarks in an atomic nucleus occurs when two quarks send and receive **gluons**. Additional examples include **W and Z bosons** (which carry weak nuclear force) and gravitons (which carry gravitational force). The Higgs boson is a special particle: When it interacts with other particles, it endows them not with force but with mass. In other words, the Higgs boson helps to explains *why* particles have mass. These assertions are part of a tentative but very productive scientific model (the Standard Model) discussed later.

Particles and Antiparticles

In the late 1920s, the special theory of relativity and quantum mechanics were combined into a relativistic quantum theory of the electron. A surprising result of this theory was the prediction of two energy states for each electron: One is associated with the electron, and the other is associated with another particle with the same mass of an electron but with a charge of e^+ . This particle is called the antielectron or **positron**. The positron was discovered experimentally in the 1930s.

Soon it was discovered that for every particle in nature, there is a corresponding **antiparticle**. An antiparticle has the same mass and lifetime as its associated particle, and the opposite sign of electric charge. These particles are produced in high-energy reactions. Examples of high-energy particles include the antimuon (μ^+), anti-up quark ($\bar{u}$), and anti-down quark ($\bar{d}$). (Note that antiparticles for quarks are designated with an over-bar.) Many mesons and baryons contain antiparticles. For example, the antiproton ($\bar{\mathrm{p}}$) is $\bar{u}\bar{u}\bar{d}$ and the positively charged pion (π^+) is $u\bar{d}$. Some neutral particles, such as the photon and the π^0 meson, are their own antiparticles. Sample particles, antiparticles, and their properties are listed in Table 11.1.

	Particle name	Symbol	Antiparticle	Mass (MeV/c^2)	Average lifetime (s)
			Leptons		
	Electron	e^-	e^+	0.511	Stable
	Electron neutrino	υ_e	$\overline{\upsilon_e}$	≈ 0	Stable
	Muon	μ^-	μ^+	105.7	2.20×10^{-6}
	Muon neutrino	υ_μ	$\overline{\upsilon_\mu}$	≈ 0	Stable
	Tau	τ^-	τ^+	1784	$< 4 \times 10^{-13}$
	Tau neutrino	υ_τ	$\overline{\upsilon_\tau}$	≈ 0	Stable
			Hadrons		
Baryons	Proton	p	$\bar{\mathrm{p}}$	938.3	Stable
	Neutron	n	$\bar{\mathrm{n}}$	939.6	920
	Lambda	Λ^0	$\overline{\Lambda^0}$	1115.6	2.6×10^{-10}
	Sigma	Σ^+	Σ^-	1189.4	0.80×10^{-10}
	Xi	Ξ^+	Ξ^-	1315	2.9×10^{-10}
	Omega	Ω^+	Ω^-	1672	0.82×10^{-10}
Mesons	Pion	π^+	π^-	139.6	2.60×10^{-8}
	π -Zero	π^0	π^0	135.0	0.83×10^{-16}
	Kaon	K^+	K^-	493.7	1.24×10^{-8}
	k-Short	K_S^0	$\overline{K_S^0}$	497.7	0.89×10^{-10}
	k-Long	K_L^0	$\overline{K_L^0}$	497.0	5.2×10^{-8}
	J/ψ	J/ψ	J/ψ	3100	7.1×10^{-21}
	Upsilon	Υ	Υ	9460	1.2×10^{-20}

Table 11.1 Particles and their Properties

The same forces that hold ordinary matter together also hold antimatter together. Under the right conditions, it is possible to create antiatoms such as antihydrogen, antioxygen, and even antiwater. In antiatoms, positrons orbit a negatively charged nucleus of antiprotons and antineutrons. Figure 11.3 compares atoms and antiatoms.

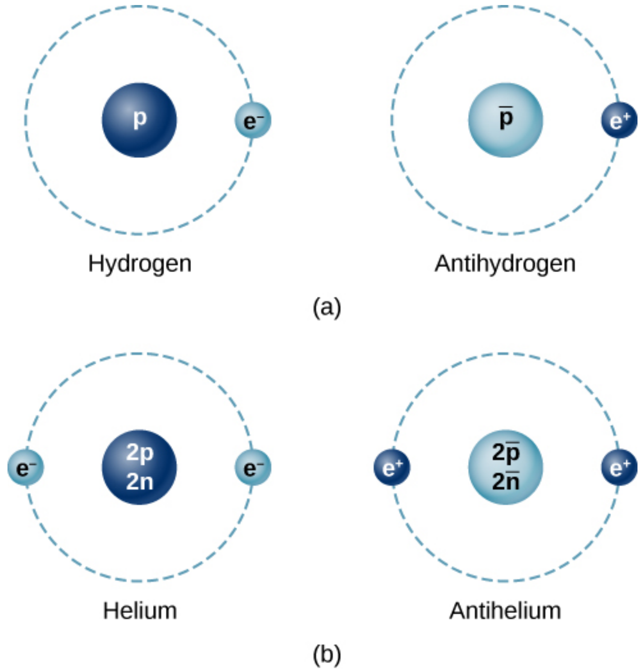


Figure 11.3 A comparison of the simplest atoms of matter and antimatter. (a) In the Bohr model, an antihydrogen atom consists of a positron that orbits an antiproton. (b) An antihelium atom consists of two positrons that orbit a nucleus of two antiprotons and two antineutrons.

Antimatter cannot exist for long in nature because particles and antiparticles annihilate each other to produce high-energy radiation. A common example is electron-positron annihilation. This process proceeds by the reaction

$$e^- + e^+ \rightarrow 2\gamma.$$

The electron and positron vanish completely and two photons are produced in their place. (It turns out that the production of a single photon would violate conservation of energy and momentum.) This reaction can also proceed in the reverse direction: Two photons can annihilate each other to produce an electron and positron pair. Or, a single photon can produce an electron-positron pair in the field of a nucleus, a process called pair production. Reactions of this kind are measured routinely in modern particle detectors. The existence of antiparticles in nature is not science fiction.

Watch this **video (https://openstaxcollege.org/l/21matter)** to learn more about matter and antimatter particles.

11.2 | Particle Conservation Laws

Learning Objectives

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

- Distinguish three conservation laws: baryon number, lepton number, and strangeness
- Use rules to determine the total baryon number, lepton number, and strangeness of particles before and after a reaction
- Use baryon number, lepton number, and strangeness conservation to determine if particle reactions or decays occur

Conservation laws are critical to an understanding of particle physics. Strong evidence exists that energy, momentum, and angular momentum are all conserved in all particle interactions. The annihilation of an electron and positron at rest, for example, cannot produce just one photon because this violates the conservation of linear momentum. As discussed in **Relativity**, the special theory of relativity modifies definitions of momentum, energy, and other familiar quantities. In particular, the relativistic momentum of a particle differs from its classical momentum by a factor $\gamma = 1/\sqrt{1-(v/c)^2}$ that varies from 1 to ∞, depending on the speed of the particle.

In previous chapters, we encountered other conservation laws as well. For example, charge is conserved in all electrostatic phenomena. Charge lost in one place is gained in another because charge is carried by particles. No known physical processes violate charge conservation. In the next section, we describe three less-familiar conservation laws: baryon number, lepton number, and strangeness. These are by no means the only conservation laws in particle physics.

Baryon Number Conservation

No conservation law considered thus far prevents a neutron from decaying via a reaction such as

$$\mathrm{n} \rightarrow \mathrm{e}^+ + \mathrm{e}^-.$$

This process conserves charge, energy, and momentum. However, it does not occur because it violates the law of baryon number conservation. This law requires that the total baryon number of a reaction is the same before and after the reaction occurs. To determine the total baryon number, every elementary particle is assigned a **baryon number** *B*. The baryon number has the value $B = +1$ for baryons, –1 for antibaryons, and 0 for all other particles. Returning to the above case (the decay of the neutron into an electron-positron pair), the neutron has a value $B = +1$, whereas the electron and the positron each has a value of 0. Thus, the decay does not occur because the total baryon number changes from 1 to 0. However, the proton-antiproton collision process

$$\mathrm{p} + \bar{\mathrm{p}} \rightarrow \mathrm{p} + \mathrm{p} + \bar{\mathrm{p}} + \bar{\mathrm{p}},$$

does satisfy the law of conservation of baryon number because the baryon number is zero before and after the interaction. The baryon number for several common particles is given in **Table 11.2**.

Particle name	Symbol	Lepton number (L_e)	Lepton number (L_μ)	Lepton number (L_τ)	Baryon number (*B*)	Strange-ness number
Electron	e^-	1	0	0	0	0
Electron neutrino	υ_e	1	0	0	0	0
Muon	μ^-	0	1	0	0	0
Muon neutrino	υ_μ	0	1	0	0	0
Tau	τ^-	0	0	1	0	0
Tau neutrino	υ_τ	0	0	1	0	0
Pion	π^+	0	0	0	0	0
Positive kaon	K^+	0	0	0	0	1
Negative kaon	K^-	0	0	0	0	–1
Proton	p	0	0	0	1	0
Neutron	n	0	0	0	1	0
Lambda zero	Λ^0	0	0	0	1	–1

Table 11.2 Conserved Properties of Particles

Particle name	Symbol	Lepton number (L_e)	Lepton number (L_μ)	Lepton number (L_τ)	Baryon number (*B*)	Strange-ness number
Positive sigma	Σ^+	0	0	0	1	–1
Negative sigma	Σ^-	0	0	0	1	–1
Xi zero	Ξ^0	0	0	0	1	–2
Negative xi	Ξ^-	0	0	0	1	–2
Omega	Ω^-	0	0	0	1	–3

Table 11.2 Conserved Properties of Particles

Example 11.1

Baryon Number Conservation

Based on the law of conservation of baryon number, which of the following reactions can occur?

$$\text{(a) } \pi^- + \text{p} \rightarrow \pi^0 + \text{n} + \pi^- + \pi^+$$
$$\text{(b) } \text{p} + \overline{\text{p}} \rightarrow \text{p} + \text{p} + \overline{\text{p}}$$

Strategy

Determine the total baryon number for the reactants and products, and require that this value does not change in the reaction. **Solution**

For reaction (a), the net baryon number of the two reactants is $0 + 1 = 1$ and the net baryon number of the four products is $0 + 1 + 0 + 0 = 1$. Since the net baryon numbers of the reactants and products are equal, this reaction is allowed on the basis of the baryon number conservation law.

For reaction (b), the net baryon number of the reactants is $1 + (-1) = 0$ and the net baryon number of the proposed products is $1 + 1 + (-1) = 1$. Since the net baryon numbers of the reactants and proposed products are not equal, this reaction cannot occur.

Significance

Baryon number is conserved in the first reaction, but not in the second. Baryon number conservation constrains what reactions can and cannot occur in nature.

11.1 Check Your Understanding What is the baryon number of a hydrogen nucleus?

Lepton Number Conservation

Lepton number conservation states that the sum of lepton numbers before and after the interaction must be the same. There are three different **lepton numbers**: the electron-lepton number L_e, the muon-lepton number L_μ, and the tau-lepton number L_τ. In any interaction, each of these quantities must be conserved *separately*. For electrons and electron neutrinos, $L_e = 1$; for their antiparticles, $L_e = -1$; all other particles have $L_e = 0$. Similarly, $L_\mu = 1$ for muons and muon neutrinos, $L_\mu = -1$ for their antiparticles, and $L_\mu = 0$ for all other particles. Finally, $L_\tau = 1, -1$, or 0, depending on whether we have a tau or tau neutrino, their antiparticles, or any other particle, respectively. Lepton number conservation guarantees that the number of electrons and positrons in the universe stays relatively constant. (*Note:* The total lepton number is, as far as we know, conserved in nature. However, observations have shown variations of family lepton number (for example, L_e) in a phenomenon called *neutrino oscillations.*)

To illustrate the lepton number conservation law, consider the following known two-step decay process:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \mathrm{e}^+ + \nu_c + \overline{\nu}_\mu.$$

In the first decay, all of the lepton numbers for π^+ are 0. For the products of this decay, $L_\mu = -1$ for μ^+ and $L_\mu = 1$ for ν_μ. Therefore, muon-lepton number is conserved. Neither electrons nor tau are involved in this decay, so $L_\mathrm{e} = 0$ and $L_\tau = 0$ for the initial particle and all decay products. Thus, electron-lepton and tau-lepton numbers are also conserved. In the second decay, μ^+ has a muon-lepton number $L_\mu = -1,$ whereas the net muon-lepton number of the decay products is $0 + 0 + (-1) = -1$. Thus, the muon-lepton number is conserved. Electron-lepton number is also conserved, as $L_\mathrm{e} = 0$ for μ^+, whereas the net electron-lepton number of the decay products is $(-1) + 1 + 0 = 0$. Finally, since no taus or tau-neutrons are involved in this decay, the tau-lepton number is also conserved.

Example 11.2

Lepton Number Conservation

Based on the law of conservation of lepton number, which of the following decays can occur?

$$\text{(a) } \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \overline{\nu}_e$$
$$\text{(b) } \pi^- \rightarrow \mu^- + \nu_\mu + \overline{\nu}_\mu$$

Strategy

Determine the total lepton number for the reactants and products, and require that this value does not change in the reaction.

Solution

For decay (a), the electron-lepton number of the neutron is 0, and the net electron-lepton number of the decay products is $0 + 1 + (-1) = 0$. Since the net electron-lepton numbers before and after the decay are the same, the decay is possible on the basis of the law of conservation of electron-lepton number. Also, since there are no muons or taus involved in this decay, the muon-lepton and tauon-lepton numbers are conserved.

For decay (b), the muon-lepton number of the π^- is 0, and the net muon-lepton number of the proposed decay products is $1 + 1 + (-1) = 1$. Thus, on the basis of the law of conservation of muon-lepton number, this decay cannot occur.

Significance

Lepton number is conserved in the first reaction, but not in the second. Lepton number conservation constrains what reactions can and cannot occur in nature.

11.2 Check Your Understanding What is the lepton number of an electron-positron pair?

Strangeness Conservation

In the late 1940s and early 1950s, cosmic-ray experiments revealed the existence of particles that had never been observed on Earth. These particles were produced in collisions of pions with protons or neutrons in the atmosphere. Their production and decay were unusual. They were produced in the strong nuclear interactions of pions and nucleons, and were therefore inferred to be hadrons; however, their decay was mediated by the much more slowly acting weak nuclear interaction. Their lifetimes were on the order of 10^{-10} to 10^{-8} s, whereas a typical lifetime for a particle that decays via the strong nuclear reaction is 10^{-23} s. These particles were also unusual because they were always produced in pairs in the pion-nucleon collisions. For these reasons, these newly discovered particles were described as *strange*. The production and subsequent decay of a pair of strange particles is illustrated in **Figure 11.4** and follows the reaction

$$\pi^- + \text{p} \rightarrow \Lambda^0 + \text{K}^0.$$

The lambda particle then decays through the weak nuclear interaction according to

$$\Lambda^0 \rightarrow \pi^- + \text{p},$$

and the kaon decays via the weak interaction

$$\text{K}^0 \rightarrow \pi^+ + \pi^-.$$

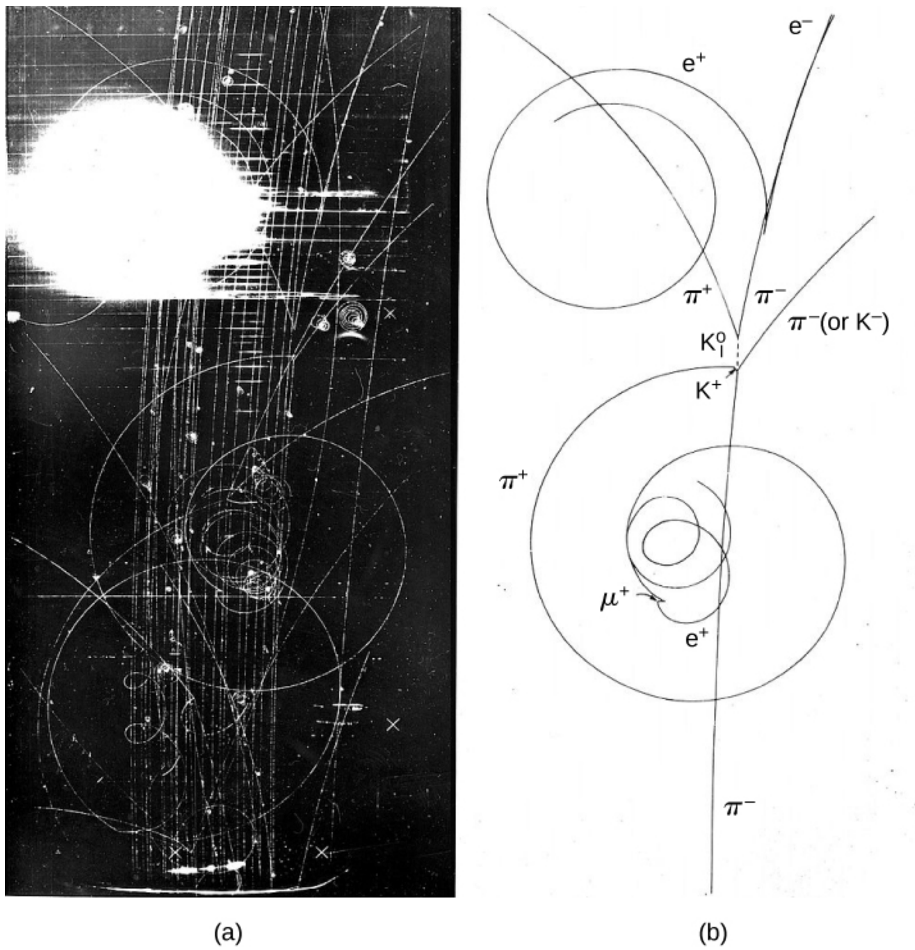


Figure 11.4 The interactions of hadrons. (a) Bubble chamber photograph; (b) sketch that represents the photograph.

To rationalize the behavior of these strange particles, particle physicists invented a particle property conserved in strong interactions but not in weak interactions. This property is called **strangeness** and, as the name suggests, is associated with the presence of a strange quark. The strangeness of a particle is equal to the number of strange quarks of the particle. Strangeness conservation requires the total strangeness of a reaction or decay (summing the strangeness of all the particles) is the same before and after the interaction. Strangeness conservation is not absolute: It is conserved in strong interactions and electromagnetic interactions but not in weak interactions. The strangeness number for several common particles is given in **Table 11.2**.

Example 11.3

Strangeness Conservation

(a) Based on the conservation of strangeness, can the following reaction occur?

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

(b) The following decay is mediated by the weak nuclear force:

$$\mathrm{K}^+ \rightarrow \pi^+ + \pi^0.$$

Does the decay conserve strangeness? If not, can the decay occur?

Strategy

Determine the strangeness of the reactants and products and require that this value does not change in the reaction.

Solution

a. The net strangeness of the reactants is $0 + 0 = 0,$ and the net strangeness of the products is $1 + (-1) + 0 = 0.$ Thus, the strong nuclear interaction between a pion and a proton is not forbidden by the law of conservation of strangeness. Notice that baryon number is also conserved in the reaction.

b. The net strangeness before and after this decay is 1 and 0, so the decay does not conserve strangeness. However, the decay may still be possible, because the law of conservation of strangeness does not apply to weak decays.

Significance

Strangeness is conserved in the first reaction, but not in the second. Strangeness conservation constrains what reactions can and cannot occur in nature.

11.3 Check Your Understanding What is the strangeness number of a muon?

11.3 | Quarks

Learning Objectives

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

- Compare and contrast the six known quarks
- Use quark composition of hadrons to determine the total charge of these particles
- Explain the primary evidence for the existence of quarks

In the 1960s, particle physicists began to realize that hadrons are not elementary particles but are made of particles called *quarks*. (The name 'quark' was coined by the physicist Murray Gell-Mann, from a phrase in the James Joyce novel *Finnegans Wake*.) Initially, it was believed there were only three types of quarks, called *up* (*u*), *down* (*d*), and *strange* (*s*). However, this number soon grew to six—interestingly, the same as the number of leptons—to include *charmed* (*c*), *bottom* (*b*), and *top* (*t*).

All quarks are spin-half fermions $(s = 1/2),$ have a fractional charge $(1/3 \text{ or } 2/3e)$, and have baryon number $B = 1/3.$ Each quark has an antiquark with the same mass but opposite charge and baryon number. The names and properties of the six quarks are listed in **Table 11.3**.

Quark	Charge (units of *e*)	Spin (*s*)	Baryon number	Strangeness number
Down (*d*)	$-1/3$	1/2	1/3	0
Up (*u*)	$+2/3$	1/2	1/3	0
Strange (*s*)	$-1/3$	1/2	1/3	-1
Charm (*c*)	$+2/3$	1/2	1/3	0
Bottom (*b*)	$-1/3$	1/2	1/3	0
Top (*t*)	$+2/3$	1/2	1/3	0

Table 11.3 Quarks

Quark Combinations

As mentioned earlier, quarks bind together in groups of two or three to form hadrons. Baryons are formed from three quarks. Sample baryons, including quark content and properties, are given in **Table 11.4**. Interestingly, the delta plus (Δ^+) baryon is formed from the same three quarks as the proton, but the total spin of the particle is 3/2 rather than 1/2. Similarly, the mass of Δ^+ with spin 3/2 is 1.3 times the mass of the proton, and the delta zero (Δ^0) baryon with a spin 3/2 is 1.3 times the neutron mass. Evidently, the energy associated with the spin (or angular momentum) of the particle contributes to its mass energy. It is also interesting that no baryons are believed to exist with top quarks, because top quarks decay too quickly to bind to the other quarks in their production.

Name	Symbol	Quarks	Charge (unit of *e*)	Spin (s)	Mass (GeV/c^2)
Proton	p	*u u d*	1	1/2	0.938
Neutron	n	*u d d*	0	1/2	0.940
Delta plus plus	Δ^{++}	*u u u*	2	3/2	1.232
Delta plus	Δ^{+}	*u u d*	1	3/2	1.232
Delta zero	Δ^{0}	*u d d*	0	3/2	1.232
Delta minus	Δ^{-}	*d d d*	-1	3/2	1.232
Lambda zero	Λ^0	*u d s*	0	1/2	1.116
Positive sigma	Σ^+	*u u s*	1	1/2	1.189
Neutral sigma	Σ^0	*u d s*	0	1/2	1.192
Negative xi	Ξ^-	*s d s*	-1	1/2	1.321
Neutral xi	Ξ^0	*s u s*	0	1/2	1.315
Omega minus	Ω^-	*s s s*	-1	3/2	1.672
Charmed lambda	Λ_{C+}	*u d c*	1	1/2	2.281
Charmed bottom	Λ_{b0}	*u d b*	0	1/2	5.619

Table 11.4 Baryon Quarks

Mesons are formed by two quarks—a quark-antiquark pair. Sample mesons, including quark content and properties, are given in **Table 11.5**. Consider the formation of the pion ($\pi^+ = u\bar{d}$). Based on its quark content, the charge of the pion is

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

Both quarks are spin-half ($s = ½$), so the resultant spin is either 0 or 1. The spin of the π^+ meson is 0. The same quark-antiquark combination gives the rho (ρ) meson with spin 1. This meson has a mass approximately 5.5 times that of the π^+ meson.

Example 11.4

Quark Structure

Show that the quark composition given in **Table 11.5** for Ξ^0 is consistent with the known charge, spin, and strangeness of this baryon.

Strategy

Ξ^0 is composed of two strange quarks and an up quark (*s u s*). We can add together the properties of quarks to predict the resulting properties of the Ξ^0 baryon.

Solution

The charge of the *s* quark is $-e/3$ and the charge of the *u* quark is 2*e*/3. Thus, the combination (*s u s*) has no net charge, in agreement with the known charge of Ξ^0. Since three spin $-1/2$ quarks can combine to produce a particle with spin of either 1/2 or 3/2, the quark composition is consistent with the known spin ($s = 1/2$) of Ξ^0. Finally, the net strangeness of the (*s u s*) combination is $(-1) + 0 + (-1) = -2,$ which also agrees with experiment.

Significance

The charge, spin, and strangeness of the Ξ^0 particle can be determined from the properties of its constituent quarks. The great diversity of baryons and mesons can be traced to the properties of just six quarks: up, down, charge, strange, top, and bottom.

11.4 Check Your Understanding What is the baryon number of a pion?

Name	Symbol	Quarks	Charge (*e*)	Spin	Mass (GeV/c^2)
Positive pion	π^+	$u\bar{d}$	1	0	0.140
Positive rho	ρ^+	$u\bar{d}$	1	1	0.768
Negative pion	π^-	$\bar{u}d$	-1	0	0.140
Negative rho	ρ^-	$\bar{u}d$	-1	1	0.768
Neutral Pion	π^0	$\bar{u}u$ or $\bar{d}d$	0	0	0.135
Neutral eta	η^0	$\bar{u}u$, $\bar{d}d$ or $\bar{s}s$	0	0	0.547
Positive kaon	K^+	$u\bar{s}$	1	0	0.494
Neutral kaon	K^0	$d\bar{s}$	0	0	0.498
Negative kaon	K^-	$\bar{u}s$	-1	0	0.494
J/Psi	J/ψ	$\bar{c}c$	0	1	3.10

Table 11.5 Meson Quarks

Name	Symbol	Quarks	Charge (*e*)	Spin	Mass (GeV/c^2)
Charmed eta	$\eta 0$	$c\bar{c}$	0	0	2.98
Neutral D	D^0	$\bar{u}c$	0	0	1.86
Neutral D	D^{*0}	$\bar{u}c$	0	1	2.01
Positive D	D^+	$\bar{d}c$	1	0	1.87
Neutral B	B^0	$\bar{d}b$	0	0	5.26
Upsilon	Υ	$b\bar{b}$	0	1	9.46

Table 11.5 Meson Quarks

Color

Quarks are fermions that obey Pauli's exclusion principle, so it might be surprising to learn that three quarks can bind together within a nucleus. For example, how can two up quarks exist in the same small region of space within a proton? The solution is to invent a third new property to distinguish them. This property is called **color**, and it plays the same role in the strong nuclear interaction as charge does in electromagnetic interactions. For this reason, quark color is sometimes called "strong charge."

Quarks come in three colors: red, green, and blue. (These are just labels—quarks are not actually colored.) Each type of quark (u, d, c, s, b, t) can possess any other colors. For example, three strange quarks exist: a red strange quark, a green strange quark, and a blue strange quark. Antiquarks have anticolor. Quarks that bind together to form hadrons (baryons and mesons) must be color neutral, colorless, or "white." Thus, a baryon must contain a red, blue, and green quark. Likewise, a meson contains either a red-antired, blue-antiblue, or green-antigreen quark pair. Thus, two quarks can be found in the same spin state in a hadron, without violating Pauli's exclusion principle, because their colors are different.

Quark Confinement

The first strong evidence for the existence of quarks came from a series of experiments performed at the Stanford Linear Accelerator Center (SLAC) and at CERN around 1970. This experiment was designed to probe the structure of the proton, much like Rutherford studied structure inside the atom with his α-particle scattering experiments. Electrons were collided with protons with energy in excess of 20 GeV. At this energy, $E \approx pc$, so the de Broglie wavelength of an electron is

$$\lambda = \frac{h}{p} = \frac{hc}{E} \approx 6 \times 10^{-17} \text{ m}. \quad (11.1)$$

The wavelength of the electron is much smaller than the diameter of the proton (about 10^{-15} m). Thus, like an automobile traveling through a rocky mountain range, electrons can be used to probe the structure of the nucleus.

The SLAC experiments found that some electrons were deflected at very large angles, indicating small scattering centers within the proton. The scattering distribution was consistent with electrons being scattered from sites with spin 1/2, the spin of quarks. The experiments at CERN used neutrinos instead of electrons. This experiment also found evidence for the tiny scattering centers. In both experiments, the results suggested that the charges of the scattering particles were either $+2/3e$ or $-1/3e$, in agreement with the quark model.

Watch this **video (https://openstaxcollege.org/l/21quarks)** to learn more about quarks.

The quark model has been extremely successful in organizing the complex world of subatomic particles. Interestingly, however, no experiment has ever produced an isolated quark. All quarks have fractional charge and should therefore be easily distinguishable from the known elementary particles, whose charges are all an integer multiple of *e*. Why are isolated quarks not observed? In current models of particle interactions, the answer is expressed in terms of quark confinement. Quark confinement refers to the confinement of quarks in groups of two or three in a small region of space. The quarks are completely free to move about in this space, and send and receive gluons (the carriers of the strong force). However, if these quarks stray too far from one another, the strong force pulls them back it. This action is likened to a bola, a weapon used for hunting (**Figure 11.5**). The stones are tied to a central point by a string, so none of the rocks can move too far from the others. The bola corresponds to a baryon, the stones correspond to quarks, and the string corresponds to the gluons that hold the system together.

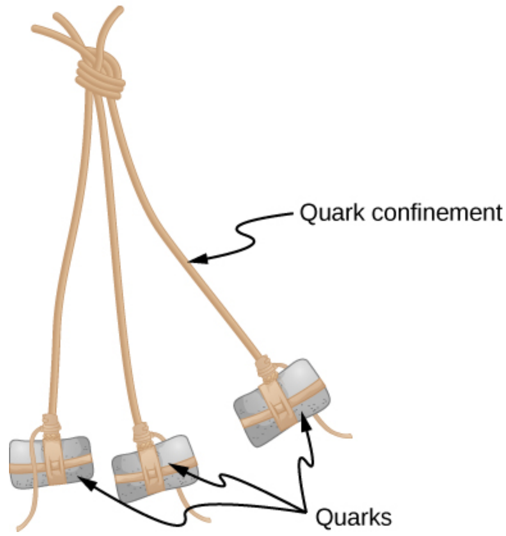


Figure 11.5 A baryon is analogous to a bola, a weapon used for hunting. The rocks in this image correspond to the baryon quarks. The quarks are free to move about but must remain close to the other quarks.

11.4 | Particle Accelerators and Detectors

Learning Objectives

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

- Compare and contrast different types of particle accelerators
- Describe the purpose, components, and function of a typical colliding beam machine
- Explain the role of each type of subdetector of a typical multipurpose particle detector
- Use the curvature of a charge track to determine the momentum of a particle

The goal of experimental particle physics is to accurately measure elementary particles. The primary method used to achieve this end is to produce these particles in high-energy collisions and then measure the products of using highly sensitive particle detectors. These experiments are used to test and revise scientific models of particle interactions. The purpose of this section is to describe particle accelerators and detectors. Modern machines are based on earlier ones, so it is helpful to present a brief history of accelerators and detectors.

Early Particle Accelerators

A **particle accelerator** is a machine designed to accelerate charged particles. This acceleration is usually achieved with strong electric fields, magnetic fields, or both. A simple example of a particle accelerator is the Van de Graaff accelerator (see **Electric Potential (http://cnx.org/content/m58427/latest/)**). This type of accelerator collects charges on a hollow metal sphere using a moving belt. When the electrostatic potential difference of the sphere is sufficiently large, the field is used to accelerate particles through an evacuated tube. Energies produced by a Van de Graaff accelerator are not large enough to create new particles, but the machine was important for early exploration of the atomic nucleus.

Larger energies can be produced by a linear accelerator (called a “linac”). Charged particles produced at the beginning of the linac are accelerated by a continuous line of charged hollow tubes. The voltage between a given pair of tubes is set to draw the charged particle in, and once the particle arrives, the voltage between the next pair of tubes is set to push the charged particle out. In other words, voltages are applied in such a way that the tubes deliver a series of carefully synchronized electric kicks (**Figure 11.6**). Modern linacs employ radio frequency (RF) cavities that set up oscillating electromagnetic fields, which propel the particle forward like a surfer on an ocean wave. Linacs can accelerate electrons to over 100 MeV. (Electrons with kinetic energies greater than 2 MeV are moving very close to the speed of light.) In modern particle research, linear accelerators are often used in the first stage of acceleration.

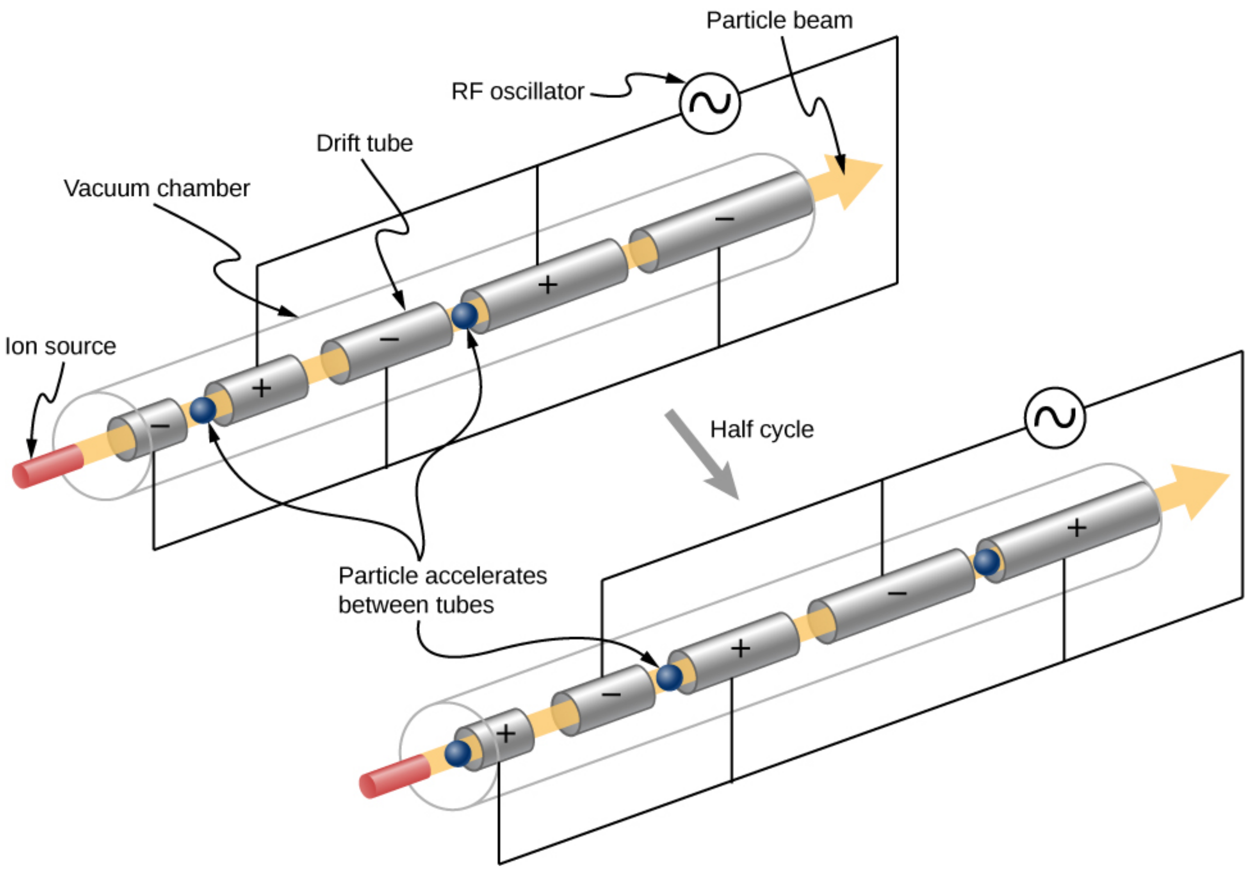


Figure 11.6 In a linear accelerator, charged tubes accelerate particles in a series of electromagnetic kicks. Each tube is longer than the preceding tube because the particle is moving faster as it accelerates.

Example 11.5

Accelerating Tubes

A linear accelerator designed to produce a beam of 800-MeV protons has 2000 accelerating tubes separated by gaps. What average voltage must be applied between tubes to achieve the desired energy? (*Hint*: $U = qV$.)

Strategy

The energy given to the proton in each gap between tubes is $U = qV$, where q is the proton's charge and V is the potential difference (voltage) across the gap. Since $q = q_e = 1.6 \times 10^{-19}\,\text{C}$ and $1\text{ eV} = (1\text{ V})\left(1.6 \times 10^{-19}\text{ C}\right)$, the proton gains 1 eV in energy for each volt across the gap that it passes through. The ac voltage applied to the tubes is timed so that it adds to the energy in each gap. The effective voltage is the sum of the gap voltages and equals 800 MV to give each proton an energy of 800 MeV.

Solution

There are 2000 gaps and the sum of the voltages across them is 800 MV. Therefore, the average voltage applied is 0.4 MV or 400 kV.

Significance

A voltage of this magnitude is not difficult to achieve in a vacuum. Much larger gap voltages would be required for higher energy, such as those at the 50-GeV SLAC facility. Synchrotrons are aided by the circular path of the accelerated particles, which can orbit many times, effectively multiplying the number of accelerations by the number of orbits. This makes it possible to reach energies greater than 1 TeV.

11.5 Check Your Understanding How much energy does an electron receive in accelerating through a 1-V potential difference?

The next-generation accelerator after the linac is the cyclotron (**Figure 11.7**). A cyclotron uses alternating electric fields and fixed magnets to accelerate particles in a circular spiral path. A particle at the center of the cyclotron is first accelerated by an electric field in a gap between two D-shaped magnets (Dees). As the particle crosses over the D-shaped magnet, the particle is bent into a circular path by a Lorentz force. (The Lorentz force was discussed in **Magnetic Forces and Fields (http://cnx.org/content/m58737/latest/)** .) Assuming no energy losses, the momentum of the particle is related to its radius of curvature by

$$p = 0.3Br \tag{11.2}$$

where p is the momentum in GeV/c, B is in teslas, and r is the radius of the trajectory ("orbit") in meters. This expression is valid to classical and relativistic velocities. The circular trajectory returns the particle to the electric field gap, the electric field is reversed, and the process continues. As the particle is accelerated, the radius of curvature gets larger and larger—spirally outward—until the electrons leave the device.

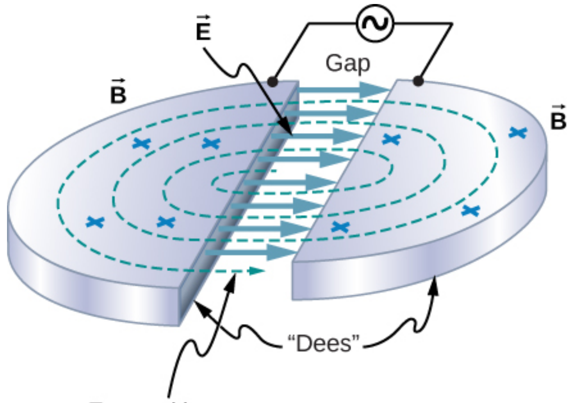


Figure 11.7 Cyclotrons use a magnetic field to cause particles to move in circular orbits. As the particles pass between the plates of the "Dees," the voltage across the gap is reversed so the particles are accelerated twice in each orbit.

Watch this **video (https://openstaxcollege.org/l/21cyclotron)** to learn more about cyclotrons.

A **synchrotron** is a circular accelerator that uses alternating voltage and increasing magnetic field strength to accelerate particles to higher energies. Charged particles are accelerated by RF cavities, and steered and focused by magnets. RF cavities are *synchronized* to deliver "kicks" to the particles as they pass by, hence the name. Steering high-energy particles requires strong magnetic fields, so superconducting magnets are often used to reduce heat losses. As the charged particles move in a circle, they radiate energy: According to classical theory, any charged particle that accelerates (and circular motion is an accelerated motion) also radiates. In a synchrotron, such radiation is called **synchrotron radiation**. This radiation is useful for many other purposes, such as medical and materials research.

Example 11.6

The Energy of an Electron in a Cyclotron

An electron is accelerated using a cyclotron. If the magnetic field is 1.5 T and the radius of the "Dees" is 1.2 m, what is the kinetic energy of the outgoing particle?

Strategy

If the radius of orbit of the electron exceeds the radius of the "Dees," the electron exits the device. So, the radius of the "Dees" places an upper limit on the radius and, therefore, the momentum and energy of the accelerated particle. The exit momentum of the particle is determined using the radius of orbit and strength of the magnetic field. The exit energy of the particle can be determined the particle momentum (**Relativity**).

Solution

Assuming no energy losses, the momentum of the particle in the cyclotron is

$$p = 0.3Br = 0.3(1.5\ \text{T})(1.2\ \text{m}) = 0.543\ \text{GeV}/c.$$

The momentum energy $pc^2 = 0.543\ \text{GeV} = 543\ \text{MeV}$ is much larger than the rest mass energy of the electron, $mc^2 = 0.511\ \text{MeV},$ so relativistic expression for the energy of the electron must be used (see **Relativity**). The total energy of the electron is

$$E_{\text{total}} = \sqrt{(pc)^2 + (mc^2)^2} = \sqrt{(543)^2 + (0.511)^2} \approx 543\ \text{MeV and}$$
$$K = E_{total} - mc^2 = 543\ \text{GeV} - 0.511\ \text{GeV} \approx 543\ \text{MeV}.$$

Significance

The total energy of the electron is much larger than its rest mass energy. In other words, the total energy of the electron is almost all in the form of kinetic energy. Cyclotrons can be used to conduct nuclear physics experiments or in particle therapy to treat cancer.

11.6 Check Your Understanding A charged particle of a certain momentum travels in an arc through a uniform magnetic field. What happens if the magnetic field is doubled?

Colliding Beam Machines

New particles can be created by colliding particles at high energies. According to Einstein's mass-energy relation, the energies of the colliding particles are converted into mass energy of the created particle. The most efficient way to do this is with particle-colliding beam machines. A colliding beam machine creates two counter-rotating beams in a circular accelerator, stores the beams at constant energy, and then at the desired moment, focuses the beams on one another at the center of a sensitive detector.

The prototypical colliding beam machine is the Cornell Electron Storage Ring, located in Ithaca, New York (**Figure 11.8**). Electrons (e^-) and positrons (e^+) are created at the beginning of the linear accelerator and are accelerated up to 150 MeV. The particles are then injected into the inner synchrotron ring, where they are accelerated by RF cavities to 4.5 to 6 GeV. When the beams are up to speed, they are transferred and "stored" in an outer storage ring at the same energy. The two counter-rotating beams travel through the same evacuated pipe, but are kept apart until collisions are desired. The electrons and positrons circle the machine in bunches 390,000 times every second.

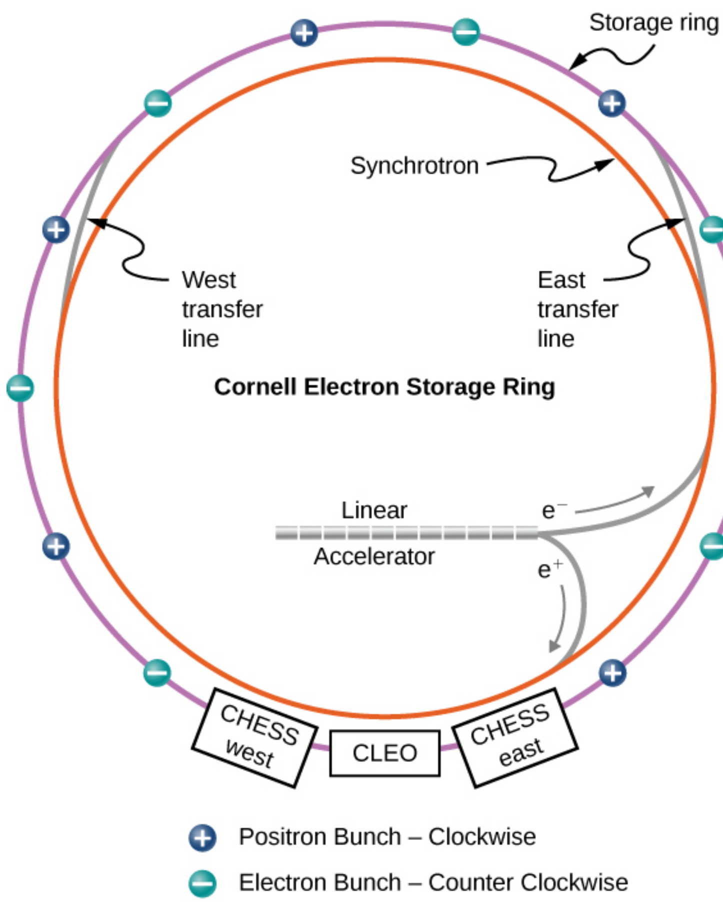


Figure 11.8 The Cornell Electron Storage Ring uses a linear accelerator and a synchrotron to accelerate electrons and positrons to 4.5–6 GeV. The particles are held in the outer storage ring at that energy until they are made to collide in a particle detector. (credit: modification of work by Laboratory of Nuclear Studies, Cornell Electron Storage Ring)

When an electron and positron collide, they annihilate each other to produce a photon, which exists for too short a time to be detected. The photon produces either a lepton pair (e.g., an electron and position, muon or antimuon, or tau and antitau) or a quark pair. If quarks are produced, mesons form, such as $c\bar{c}$ and $b\bar{b}$. These mesons are created nearly at rest since the initial total momentum of the electron-positron system is zero. Note, mesons cannot be created at just any colliding energy but only at "resonant" energies that correspond to the unique masses of the mesons (**Table 11.5**). The mesons created in this way are highly unstable and decay quickly into lighter particles, such as electrons, protons, and photons. The collision "fragments" provide valuable information about particle interactions.

As the field of particle physics advances, colliding beam machines are becoming more powerful. The Large Hadron Collider (LHC), currently the largest accelerator in the world, collides protons at beam energies exceeding 6 TeV. The center-of-mass energy (*W*) refers to the total energy available to create new particles in a colliding machine, or the total energy of incoming particles in the center-of-mass frame. (The concept of a center-of-mass frame of reference is discussed in **Linear Momentum and Collisions (http://cnx.org/content/m58317/latest/)** .) Therefore, the LHC is able to produce one or more particles with a total mass exceeding 12 TeV. The center-of-mass energy is given by:

$$W^2 = 2[E_1 E_2 + (p_1 c)(p_2 c)] + (m_1 c^2)^2 + (m_2 c^2)^2, \tag{11.3}$$

where E_1 and E_2 are the total energies of the incoming particles (1 and 2), p_1 and p_2 are the magnitudes of their momenta, and m_1 and m_2 are their rest masses.

Example 11.7

Creating a New Particle

The mass of the upsilon (Υ) meson ($b\bar{b}$) is created in a symmetric electron-positron collider. What beam energy is required?

Strategy

The Particle Data Group (https://openstaxcollege.org/l/21particledata) has stated that the rest mass energy of this meson is approximately 10.58 GeV. The above expression for the center-of-mass energy can be simplified because a symmetric collider implies $\vec{p}_1 = -\vec{p}_2$. Also, the rest masses of the colliding electrons and positrons are identical $\left(m_e c^2 = 0.511 \text{ MeV}\right)$ and much smaller than the mass of the energy particle created. Thus, the center-of-mass energy (W) can be expressed completely in terms of the beam energy, $E_{\text{beam}} = E_1 = E_2$.

Solution

Based on the above assumptions, we have

$$W^2 \approx 2[E_1 E_2 + E_1 E_2] = 4E_1 E_2 = 4E_1^2.$$

The beam energy is therefore

$$E_{\text{beam}} \approx E_1 = \frac{W}{2}.$$

The rest mass energy of the particle created in the collision is equal to the center-of-mass energy, so

$$E_{\text{beam}} \approx \frac{10.58 \text{ GeV}}{2} = 5.29 \text{ GeV}.$$

Significance

Given the energy scale of this problem, the rest mass energy of the upsilon (Υ) meson is due almost entirely due to the initial kinetic energies of the electron and positrons. This meson is highly unstable and quickly decays to lighter and more stable particles. The existence of the upsilon (Υ) particle appears as a dramatic increase of such events at 5.29 GeV.

11.7 Check Your Understanding Why is a symmetric collider "symmetric?"

Higher beam energies require larger accelerators, so modern colliding beam machines are very large. The LHC, for example, is 17 miles in circumference (Figure 5.27). (In the 1940s, Enrico Fermi envisioned an accelerator that encircled all of Earth!) An important scientific challenge of the twenty-first century is to reduce the size of particle accelerators.

Particle Detectors

The purpose of a **particle detector** is to accurately measure the outcome of collisions created by a particle accelerator. The detectors are multipurpose. In other words, the detector is divided into many subdetectors, each designed to measure a different aspect of the collision event. For example, one detector might be designed to measure photons and another might be designed to measure muons. To illustrate how subdetectors contribute to an understanding of an entire collision event, we describe the subdetectors of the Compact Muon Solenoid (CMS), which was used to discover the Higgs Boson at the LHC (Figure 11.9).

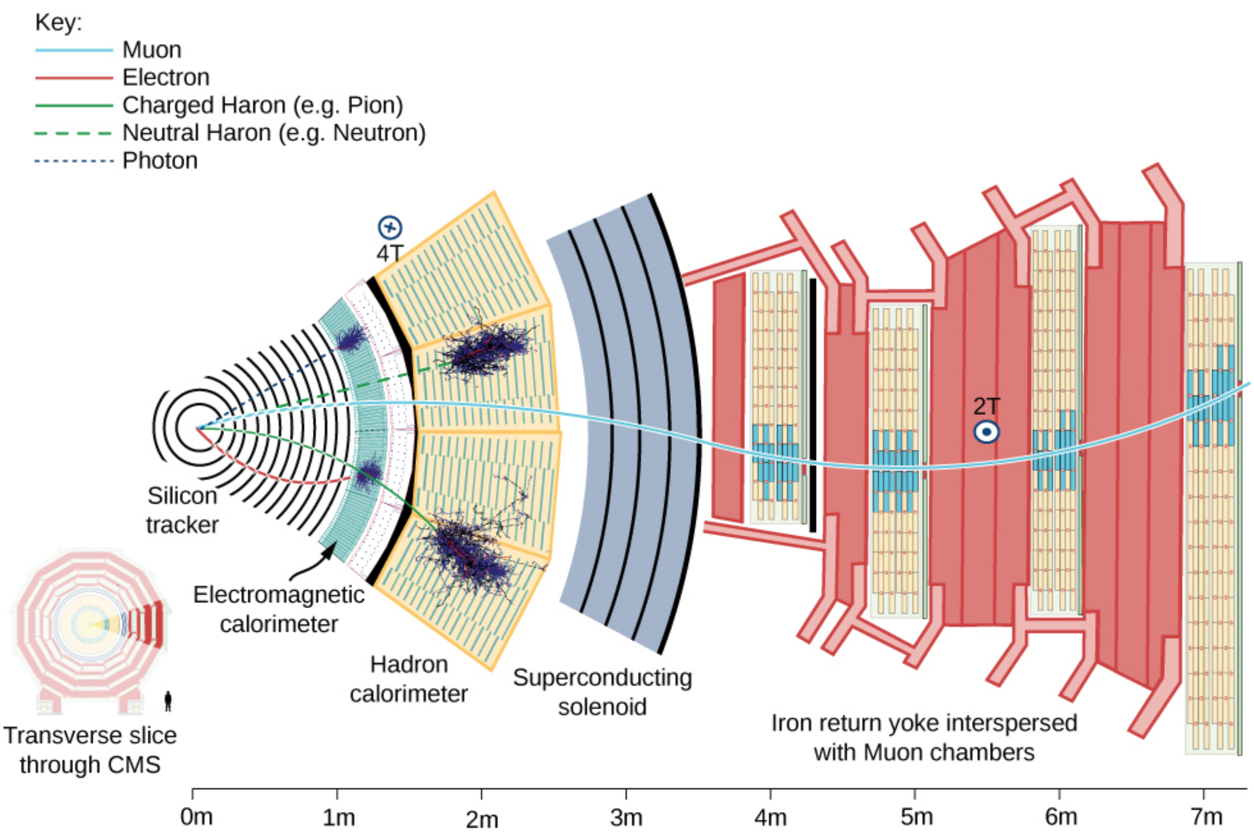


Figure 11.9 Compact Muon Solenoid detector. The detector consists of several layers, each responsible for measuring different types of particles. (credit: modification of work by David Barney/CERN)

The beam pipe of the detector is out of (and into) the page at the left. Particles produced by *pp* collisions (the "collision fragments") stream out of the detector in all directions. These particles encounter multiple layers of subdetectors. A subdetector is a particle detector within a larger system of detectors designed to measure certain types of particles. There are several main types of subdetectors. Tracking devices determine the path and therefore momentum of a particle; calorimeters measure a particle's energy; and particle-identification detectors determine a particle's identity (mass).

The first set of subdetectors that particles encounter is the silicon tracking system. This system is designed to measure the momentum of charged particles (such as electrons and protons). The detector is bathed in a uniform magnetic field, so the charged particles are bent in a circular path by a Lorentz force (as for the cyclotron). If the momentum of the particle is large, the radius of the trajectory is large, and the path is almost straight. But if the momentum is small, the radius of the trajectory is small, and the path is tightly curved. As the particles pass through the detector, they interact with silicon microstrip detectors at multiple points. These detectors produce small electrical signals as the charged particles pass near the detector elements. The signals are then amplified and recorded. A series of electrical "hits" is used to determine the trajectory of the particle in the tracking system. A computer-generated "best fit" to this trajectory gives the track radius and therefore the particle momentum. At the LHC, a large number of tracks are recorded for the same collision event. Fits to the tracks are shown by the blue and green lines in **Figure 11.10**.

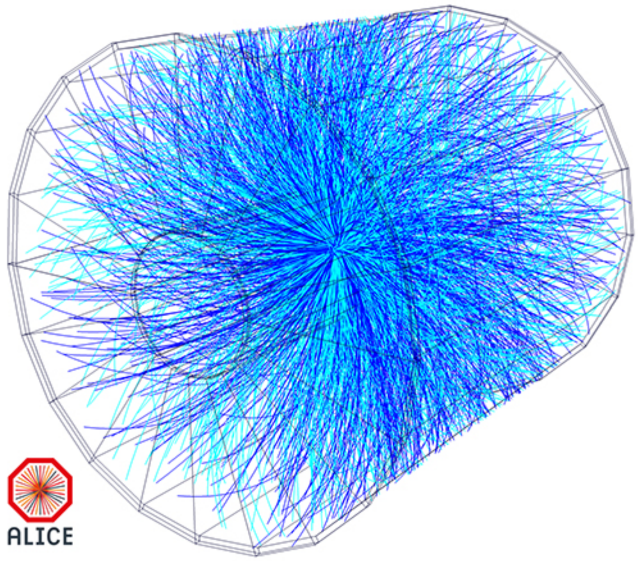


Figure 11.10 A three-dimensional view of particle fragments in the LHC as seen by the ATLAS detector. (credit: LHC/CERN)

Beyond the tracking layers is the electromagnetic calorimeter. This detector is made of clear, lead-based crystals. When electrons interact with the crystals, they radiate high-energy photons. The photons interact with the crystal to produce electron-positron pairs. Then, these particles radiate more photons. The process repeats, producing a particle shower (the crystal "glows"). A crude model of this process is as follows.

An electron with energy E_0 strikes the crystal and loses half of its energy in the form of a photon. The photon produces an electron-positron pair, and each particle proceeds away with half the energy of the photon. Meanwhile, the original electron radiates again. So, we are left with four particles: two electrons, one positron, and one photon, each with an energy $E_0/4$. The number of particles in the shower increases geometrically. After *n* radiation events, there are $N = 2^n$ particles. Hence, the total energy per particle after *n* radiation events is

$$E(t) = \frac{E_0}{2^n},$$

where E_0 is the incident energy and $E(t)$ is the amount of energy per particle after *n* events. An incoming photon triggers a similar chain of events (**Figure 11.11**). If the energy per particle drops below a particular threshold value, other types of radiative processes become important and the particle shower ceases. Eventually, the total energy of the incoming particle is absorbed and converted into an electrical signal.

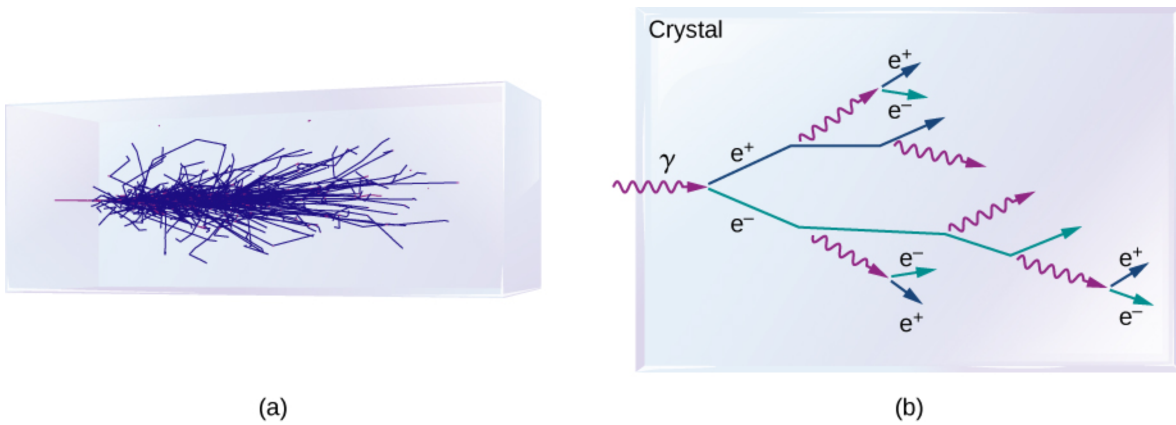


Figure 11.11 (a) A particle shower produced in a crystal calorimeter. (b) A diagram showing a typical sequence of reactions in a particle shower.

Beyond the crystal calorimeter is the hadron calorimeter. As the name suggests, this subdetector measures hadrons such as protons and pions. The hadron calorimeter consists of layers of brass and steel separated by plastic scintillators. Its purpose is to absorb the particle energy and convert it into an electronic signal. Beyond this detector is a large magnetic coil used to produce a uniform field for tracking.

The last subdetector is the muon detector, which consists of slabs of iron that only muons (and neutrinos) can penetrate. Between the iron slabs are multiple types of muon-tracking elements that accurately measure the momentum of the muon. The muon detectors are important because the Higgs boson (discussed soon) can be detected through its decays to four muons—hence the name of the detector.

Once data is collected from each of the particle subdetectors, the entire collision event can be assessed. The energy of the *i*th particle is written

$$E_i = \sqrt{(p_i c)^2 + (m_i c^2)^2},$$

where p_i is the absolute magnitude of the momentum of the *i*th particle, and m_i is its rest mass.

The total energy of all particles is therefore

$$E_{\text{total}} = \sum_i E_i.$$

If all particles are detected, the total energy should be equal to the center-of-mass energy of the colliding beam machine (W). In practice, not all particles are identified, either because these particles are too difficult to detect (neutrinos) or because these particles "slip through." In many cases, whole chains of decays can be "reconstructed," like putting back together a watch that has been smashed to pieces. Information about these decay chains are critical to the evaluation of models of particle interactions.

11.5 | The Standard Model

Learning Objectives

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

- Describe the Standard Model in terms of the four fundamental forces and exchange particles
- Draw a Feynman diagram for a simple particle interaction
- Use Heisenberg's uncertainty principle to determine the range of forces described by the Standard Model
- Explain the rationale behind grand unification theories

The chief intellectual activity of any scientist is the development and revision of scientific models. A particle physicist seeks to develop models of particle interactions. This work builds directly on work done on gravity and electromagnetism in the seventeenth, eighteenth, and nineteenth centuries. The ultimate goal of physics is a unified "theory of everything" that describes all particle interactions in terms of a single elegant equation and a picture. The equation itself might be complex, but many scientists suspect the *idea* behind the equation will make us exclaim: "How could we have missed it? It was so obvious!"

In this section, we introduce the Standard Model, which is the best current model of particle interactions. We describe the Standard Model in detail in terms of electromagnetic, weak nuclear, and strong forces. At the end of this section, we review unification theories in particle physics.

Introduction to the Standard Model

The **Standard Model** of particle interactions contains two ideas: *electroweak theory* and **quantum chromodynamics (QCD)** (the force acting between color charges). Electroweak theory unifies the theory of **quantum electrodynamics (QED)**, the modern equivalent of classical electromagnetism, and the theory of weak nuclear interactions. The Standard Model combines the theory of relativity and quantum mechanics.

In the Standard Model, particle interactions occur through the exchange of bosons, the "force carriers." For example, the electrostatic force is communicated between two positively charged particles by sending and receiving massless photons.

This can occur at a theoretical infinite range. The result of these interactions is Coulomb repulsion (or attraction). Similarly, quarks bind together through the exchange of massless gluons. Leptons scatter off other leptons (or decay into lighter particles) through the exchange of massive W and Z bosons. A summary of forces as described by the Standard Model is given in Table 11.6. The gravitational force, mediated by the exchange of massless gravitations, is added in this table for completeness but is not part of the Standard Model.

Force	Relative strength	Exchange particle (bosons)	Particles acted upon	Range
Strong	1	Gluon	Quarks	10^{-15} m
Electromagnetic	1/137	photon	Charged particles	∞
Weak	10^{-10}	W^+, W^-, Z bosons	Quarks, leptons, neutrinos	10^{-18} m
Gravitational	10^{-38}	graviton	All particles	∞

Table 11.6 Four Forces and the Standard Model

The Standard Model can be expressed in terms of equations and diagrams. The equations are complex and are usually covered in a more advanced course in modern physics. However, the essence of the Standard Model can be captured using **Feynman diagrams**. A Feynman diagram, invented by American physicist Richard Feynman (1918–1988), is a space-time diagram that describes how particles move and interact. Different symbols are used for different particles. Particle interactions in one dimension are shown as a time-position graph (not a position-time graph). As an example, consider the scattering of an electron and electron-neutrino (Figure 11.12). The electron moves toward positive values of *x* (to the right) and collides with an electron neutrino moving to the left. The electron exchanges a Z boson (charge zero). The electron scatters to the left and the neutrino scatters to the right. This exchange is not instantaneous. The Z boson travels from one particle to the other over a short period of time. The interaction of the electron and neutrino is said to occur via the weak nuclear force. This force cannot be explained by classical electromagnetism because the charge of the neutrino is zero. The weak nuclear force is discussed again later in this section.

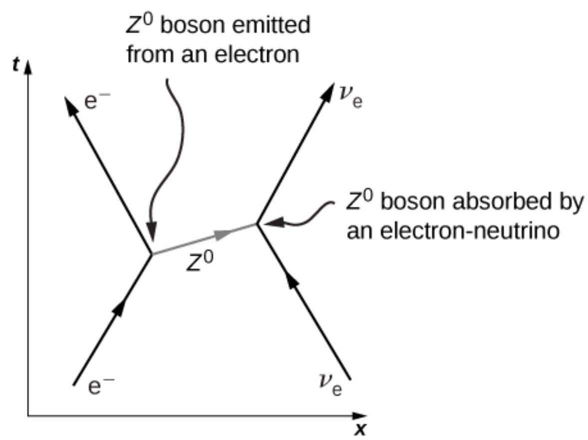


Figure 11.12 In this Feynman diagram, the exchange of a virtual Z^0 carries the weak nuclear force between an electron and a neutrino.

Electromagnetic Force

According to QED, the electromagnetic force is transmitted between charged particles through the exchange of photons. The theory is based on three basic processes: An electron travels from one place to the next, emits or absorbs a photon, and travels from one place to another again. When two electrons interact, one electron emits the photon and the other receives it (Figure 11.13). Photons transfer energy and momentum from one electron to the other. The net result in this case is a repulsive force. The photons exchanged are virtual. A **virtual particle** is a particle that exists for too short a time to be observable. Virtual photons may violate the law of conservation of energy. To see this, consider that if the photon transit time Δt is extremely small, then Heisenberg's uncertainty principle states that the uncertainly in the photon's energy, ΔE, may be very large.

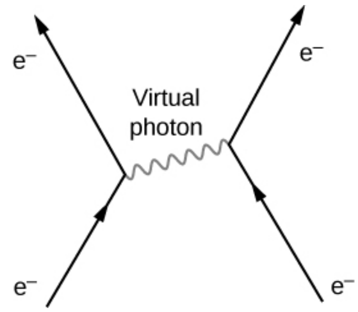


Figure 11.13 Feynman diagram of two electrons interacting through the exchange of a photon.

To estimate the range of the electromagnetic interaction, assume that the uncertainty on the energy is comparable to the energy of the photon itself, written

$$\Delta E \approx E. \tag{11.4}$$

The Heisenberg uncertainly principle states that

$$\Delta E \approx \frac{h}{\Delta t}. \tag{11.5}$$

Combining these equations, we have

$$\Delta t \approx \frac{h}{E}. \tag{11.6}$$

The energy of a photon is given by $E = hf$, so

$$\Delta t \approx \frac{h}{hf} \approx \frac{1}{f} = \frac{\lambda}{c}. \tag{11.7}$$

The distance *d* that the photon can move in this time is therefore

$$d = c\,\Delta t \approx c\left(\frac{\lambda}{c}\right) = \lambda. \tag{11.8}$$

The energy of the virtual photon can be arbitrarily small, so its wavelength can be arbitrarily large—in principle, even infinitely large. The electromagnetic force is therefore a long-range force.

Weak Nuclear Force

The weak nuclear force is responsible for radioactive decay. The range of the weak nuclear force is very short (only about 10^{-18} m) and like the other forces in the Standard Model, the weak force can be described in terms of particle exchange. (There is no simple function like the Coulomb force to describe these interactions.) The particle exchanged is one of three bosons: W^+, W^-, and Z^0. The Standard Model predicts the existence of these spin-1 particles and also predicts their specific masses. In combination with previous experiments, the mass of the charged W bosons was predicted to be $81\,\mathrm{GeV}/c^2$ and that of the Z^0 was predicted to be $90\,\mathrm{GeV}/c^2$. A CERN experiment discovered particles in the 1980s with precisely these masses—an impressive victory for the model.

The weak nuclear force is most frequently associated with scattering and decays of unstable particles to light particles. For example, neutrons decay to protons through the weak nuclear force. This reaction is written

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \nu_\mathrm{e},$$

where n is the neutron, p is a proton, e^- is an electron, and ν_e is a nearly massless electron neutrino. This process, called beta decay, is important in many physical processes. A Feynman diagram of beta decay is given in **Figure 11.14**(a). The neutron emits a W^- and becomes a proton, then the W^- produces an electron and an antineutrino. This process is similar to the scattering event

$$e^- + p \rightarrow n + \nu_e,$$

In this process, the proton emits a W^+ and is converted into a neutron (b). The W^+ then combines with the electron, forming a neutrino. Other electroweak interactions are considered in the exercises.

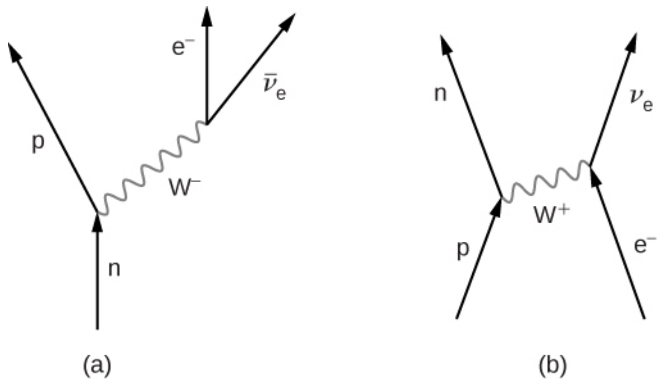


Figure 11.14 Feynman diagram of particles interacting through the exchange of a W boson: (a) beta decay; (b) conversion of a proton into a neutron.

The range of the weak nuclear force can be estimated with an argument similar to the one before. Assuming the uncertainty on the energy is comparable to the energy of the exchange particle by $\left(E \approx mc^2\right),$ we have

$$\Delta t \approx \frac{h}{mc^2}. \tag{11.9}$$

The maximum distance *d* that the exchange particle can travel (assuming it moves at a speed close to *c*) is therefore

$$d \approx c\Delta t = \frac{h}{mc}. \tag{11.10}$$

For one of the charged vector bosons with $mc^2 \approx 80\,\text{GeV} = 1.28 \times 10^{-8}\ \text{J},$ we obtain $mc = 4.27 \times 10^{-17}\ \text{J} \cdot \text{s/m}.$ Hence, the range of the force mediated by this boson is

$$d \approx \frac{1.05 \times 10^{-34}\ \text{J} \cdot \text{s}}{4.27 \times 10^{-17}\ \text{J} \cdot \text{s/m}} \approx 2 \times 10^{-18}\ \text{m}. \tag{11.11}$$

Strong Nuclear Force

Strong nuclear interactions describe interactions between quarks. Details of these interactions are described by QCD. According to this theory, quarks bind together by sending and receiving gluons. Just as quarks carry electric charge [either $(+2/3)e$ or $(-1/3)e$] that determines the strength of electromagnetic interactions between the quarks, quarks also carry "color charge" (either red, blue, or green) that determines the strength of strong nuclear interactions. As discussed before, quarks bind together in groups in color neutral (or "white") combinations, such as red-blue-green and red-antired.

Interestingly, the gluons themselves carry color charge. Eight known gluons exist: six that carry a color and anticolor, and two that are color neutral (**Figure 11.15**(a)). To illustrate the interaction between quarks through the exchange of charged gluons, consider the Feynman diagram in part (b). As time increases, a red down quark moves right and a green strange quark moves left. (These appear at the lower edge of the graph.) The up quark exchanges a red-antigreen gluon with the strange quark. (Anticolors are shown as secondary colors. For example, antired is represented by cyan because cyan mixes with red to form white light.) According to QCD, all interactions in this process—identified with the vertices—must be color neutral. Therefore, the down quark transforms from red to green, and the strange quark transforms from green to red.

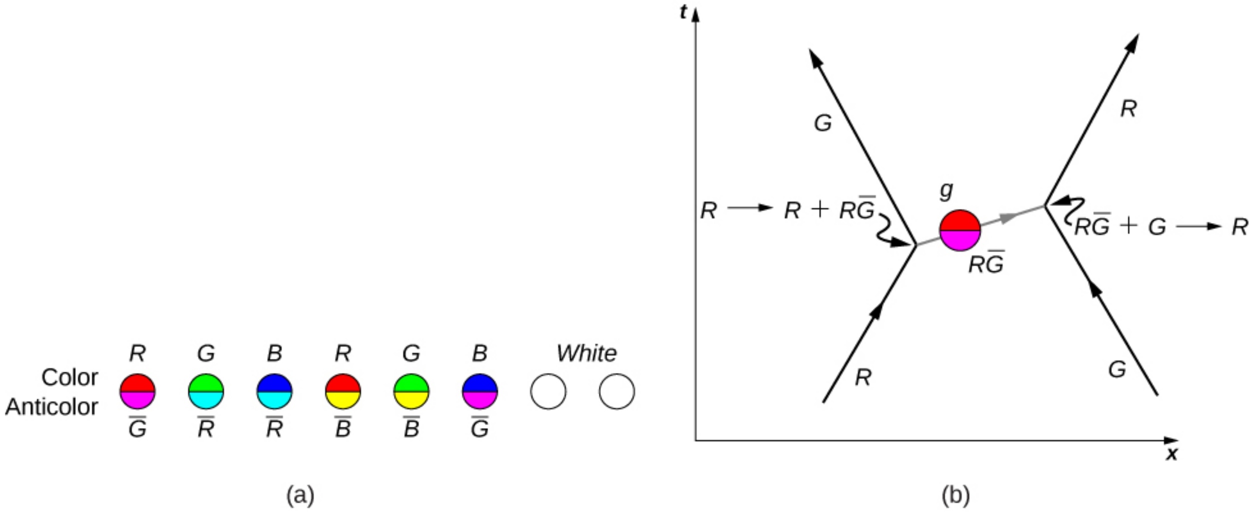


Figure 11.15 (a) Eight types of gluons carry the strong nuclear force. The white gluons are mixtures of color-anticolor pairs. (b) An interaction between two quarks through the exchange of a gluon.

As suggested by this example, the interaction between quarks in an atomic nucleus can be very complicated. **Figure 11.16** shows the interaction between a proton and neutron. Notice that the proton converts into a neutron and the neutron converts into a proton during the interaction. The presence of quark-antiquark pairs in the exchange suggest that bonding between nucleons can be modeled as an exchange of pions.

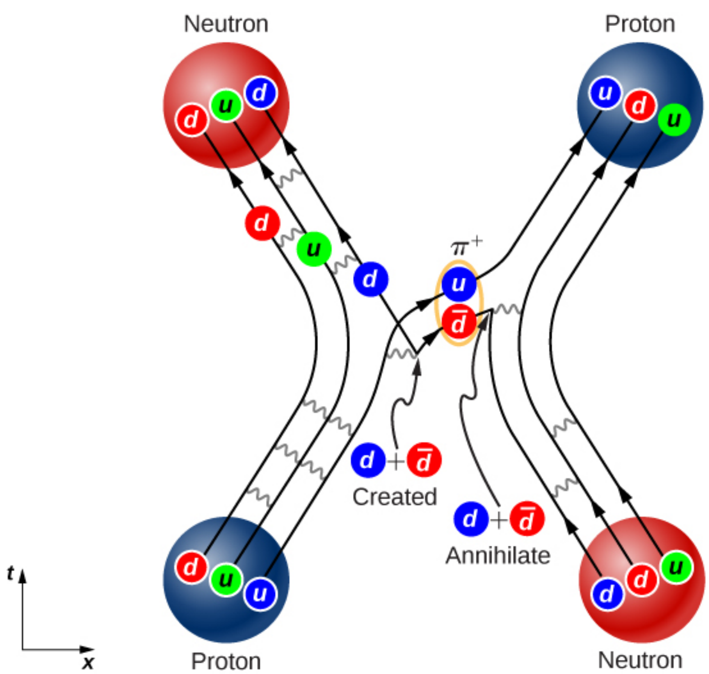


Figure 11.16 A Feynman diagram that describes a strong nuclear interaction between a proton and a neutron.

In practice, QCD predictions are difficult to produce. This difficulty arises from the inherent strength of the force and the inability to neglect terms in the equations. Thus, QCD calculations are often performed with the aid of supercomputers. The existence of gluons is supported by electron-nucleon scattering experiments. The estimated quark momenta implied by these scattering events are much smaller than we would expect without gluons because the gluons carry away some of the momentum of each collision.

Unification Theories

Physicists have long known that the strength of an interaction between particles depends on the distance of the interaction.

For example, two positively charged particles experience a larger repulsive force at a short distance then at a long distance. In scattering experiments, the strength of an interaction depends on the energy of the interacting particle, since larger energy implies both closer and stronger interactions.

Particle physicists now suspect that the strength of all particle interactions (the four forces) merge at high energies, and the details of particle interactions at these energies can be described in terms of a single force (**Figure 11.17**). A unified theory describes what these interactions are like and explains why this description breaks down at low-energy scales. A grand unified theory is a theory that attempts to describe strong and electroweak interaction in terms of just one force. A theory of everything (TOE) takes the unification concept one step further. A TOE combines all four fundamental forces (including gravity) into one theory.

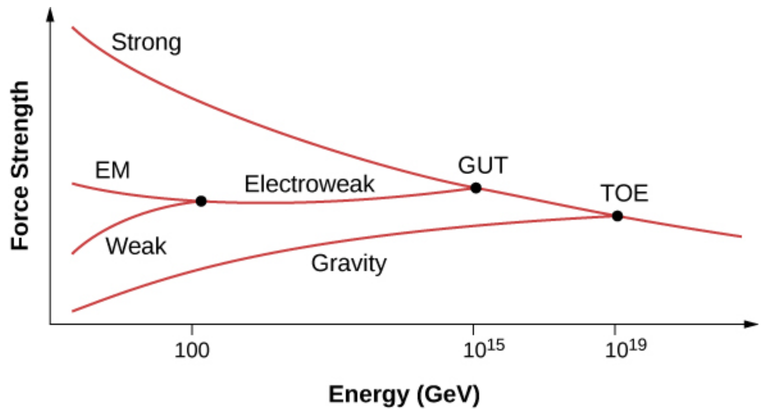


Figure 11.17 Grand unification of forces at high energies.

11.6 | The Big Bang

Learning Objectives

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

- Explain the expansion of the universe in terms of a Hubble graph and cosmological redshift
- Describe the analogy between cosmological expansion and an expanding balloon
- Use Hubble's law to make predictions about the measured speed of distant galaxies

We have been discussing elementary particles, which are some of the smallest things we can study. Now we are going to examine what we know about the universe, which is the biggest thing we can study. The link between these two topics is high energy: The study of particle interactions requires very high energies, and the highest energies we know about existed during the early evolution of the universe. Some physicists think that the unified force theories we described in the preceding section may actually have governed the behavior of the universe in its earliest moments.

Hubble's Law

In 1929, Edwin Hubble published one of the most important discoveries in modern astronomy. Hubble discovered that (1) galaxies appear to move away from Earth and (2) the velocity of recession (v) is proportional to the distance (d) of the galaxy from Earth. Both v and d can be determined using stellar light spectra. A best fit to the sample illustrative data is given in **Figure 11.18**. (Hubble's original plot had a considerable scatter but a general trend was still evident.)

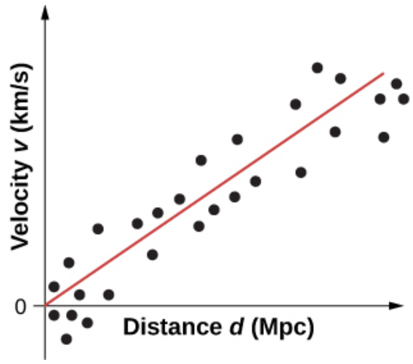


Figure 11.18 This graph of red shift versus distance for galaxies shows a linear relationship, with larger red shifts at greater distances, implying an expanding universe. The slope gives an approximate value for the expansion rate. (credit: John Cub)

The trend in the data suggests the simple proportional relationship:

$$v = H_0 d, \tag{11.12}$$

where $H_0 = 70\,\text{km}/\text{s}/\text{Mpc}$ is known as **Hubble's constant**. (*Note:* 1 Mpc is one megaparsec or one million parsecs, where one parsec is 3.26 light-years.) This relationship, called **Hubble's law**, states that distant stars and galaxies recede away from us at a speed of 70 km/s for every one megaparsec of distance from us. Hubble's constant corresponds to the slope of the line in **Figure 11.18**. Hubble's constant is a bit of a misnomer, because it varies with time. The value given here is only its value *today*.

Watch this **video (https://openstaxcollege.org/l/21hubble)** to learn more about the history of Hubble's constant.

Hubble's law describes an average behavior of all but the closest galaxies. For example, a galaxy 100 Mpc away (as determined by its size and brightness) typically moves away from us at a speed of

$$v = \left(\left(70\frac{\text{km}}{\text{s}}\right)/\text{Mpc}\right)(100\,\text{Mpc}) = 7000\,\text{km/s}.$$

This speed may vary due to interactions with neighboring galaxies. Conversely, if a galaxy is found to be moving away from us at speed of 100,000 km/s based on its red shift, it is at a distance

$$d = v/H_0 = (10{,}000\,\text{km/s})/\left(\left(70\frac{\text{km}}{\text{s}}\right)/\text{Mpc}\right) = 143\,\text{Mpc}.$$

This last calculation is approximate because it assumes the expansion rate was the same 5 billion years ago as it is now.

Big Bang Model

Scientists who study the origin, evolution, and ultimate fate of the universe (**cosmology**) believe that the universe began in an explosion, called the **Big Bang**, approximately 13.7 billion years ago. This explosion was not an explosion of particles through space, like fireworks, but a rapid expansion of space itself. The distances and velocities of the outward-going stars and galaxies permit us to estimate when all matter in the universe was once together—at the beginning of time.

Scientists often explain the Big Bang expansion using an inflated-balloon model (**Figure 11.19**). Dots marked on the surface of the balloon represent galaxies, and the balloon skin represents four-dimensional space-time (**Relativity**). As the balloon is inflated, every dot "sees" the other dots moving away. This model yields two insights. First, the expansion is observed by all observers in the universe, no matter where they are located. The "center of expansion" does not exist, so Earth does not reside at the "privileged" center of the expansion (see **Exercise 11.24**).

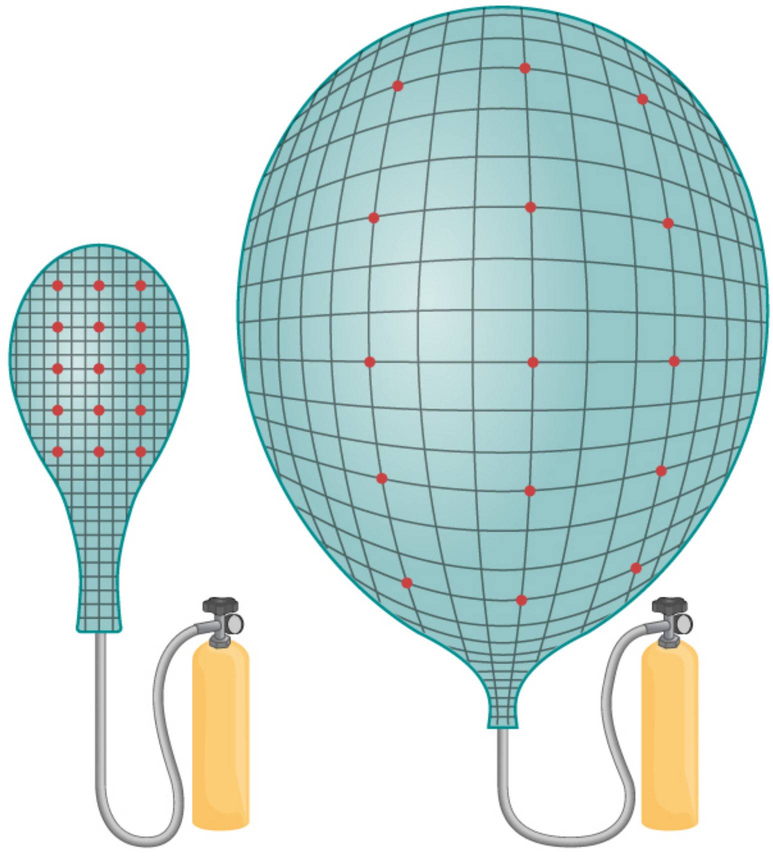


Figure 11.19 An analogy to the expanding universe: The dots move away from each other as the balloon expands; compare (a) to (b) after expansion.

Second, as mentioned already, the Big Bang expansion is due to the expansion of space, not the increased separation of galaxies in ordinary (static) three-dimensional space. This cosmological expansion affects all things: dust, stars, planets, and even light. Thus, the wavelength of light (λ) emitted by distant galaxies is "stretched" out. This makes the light appear "redder" (lower energy) to the observer—a phenomenon called cosmological **redshift**. Cosmological redshift is measurable only for galaxies farther away than 50 million light-years.

Example 11.8

Calculating Speeds and Galactic Distances

A galaxy is observed to have a redshift:

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = 4.5.$$

This value indicates a galaxy moving close to the speed of light. Using the relativistic redshift formula (given in **Relativity**), determine (a) How fast is the galaxy receding with respect to Earth? (b) How far away is the galaxy?

Strategy

We need to use the relativistic Doppler formula to determine speed from redshift and then use Hubble's law to find the distance from the speed.

Solution

a. According to the relativistic redshift formula:

$$z = \sqrt{\frac{1+\beta}{1-\beta}} - 1,$$

where $\beta = v/c$. Substituting the value for z and solving for β, we get $\beta = 0.93$. This value implies that the speed of the galaxy is 2.8×10^8 m/s.

b. Using Hubble's law, we can find the distance to the galaxy if we know its recession velocity:

$$d = \frac{v}{H_0} = \frac{2.8 \times 10^8 \text{ m/s}}{73.8 \times 10^3 \text{ m/s per Mpc}} = 3.8 \times 10^3 \text{ Mpc}.$$

Significance

Distant galaxies appear to move very rapidly away from Earth. The redshift of starlight from these galaxies can be used to determine the precise speed of recession, over 90% of the speed of light in this case. This motion is not due to the motion of galaxy through space but by the expansion of space itself.

11.8 Check Your Understanding The light of a galaxy that moves away from us is "redshifted." What occurs to the light of a galaxy that moves toward us?

View this **video (https://openstaxcollege.org/l/21expansion)** to learn more about the cosmological expansion.

Structure and Dynamics of the Universe

At large scales, the universe is believed to be both isotropic and homogeneous. The universe is believed to isotropic because it appears to be the same in all directions, and homogeneous because it appears to be the same in all places. A universe that is isotropic and homogeneous is said to be smooth. The assumption of a smooth universe is supported by the Automated Plate Measurement Galaxy Survey conducted in the 1980s and 1900s (**Figure 11.20**). However, even before these data were collected, the assumption of a smooth universe was used by theorists to simplify models of the expansion of the universe. This assumption of a smooth universe is sometimes called the cosmological principle.

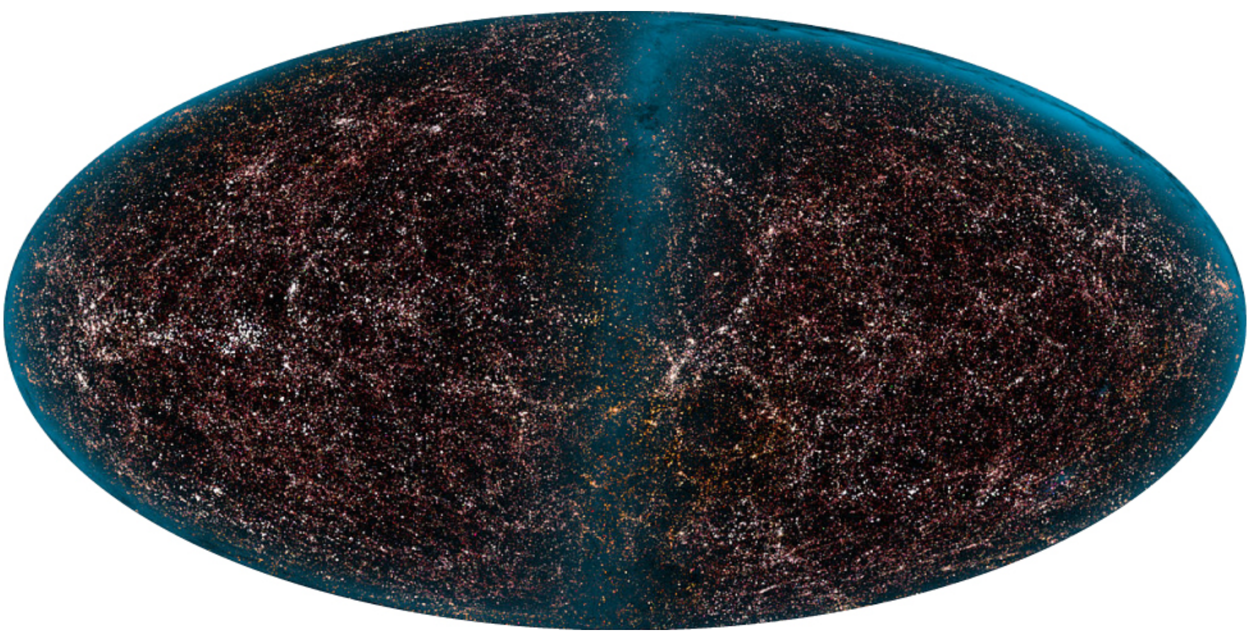


Figure 11.20 The Automated Plate Measurement (APM) Galaxy Survey. Over 2 million galaxies are depicted in a region 100 degrees across centered toward the Milky Way's south pole. (credit: 2MASS/T. H. Jarrett, J. Carpenter, & R. Hurt)

The fate of this expanding and smooth universe is an open question. According to the general theory of relativity, an important way to characterize the state of the universe is through the space-time metric:

$$ds^2 = c^2 dt^2 - a(t)^2 d\Sigma^2, \tag{11.13}$$

where *c* is the speed of light, *a* is a scale factor (a function of time), and $d\Sigma$ is the length element of the space. In spherical coordinates (r, θ, ϕ), this length element can be written

$$d\Sigma^2 = \frac{dr^2}{1 - kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right), \tag{11.14}$$

where *k* is a constant with units of inverse area that describes the curvature of space. This constant distinguishes between open, closed, and flat universes:

- $k = 0$ (flat universe)
- $k > 0$ (closed universe, such as a sphere)
- $k < 0$ (open universe, such as a hyperbola)

In terms of the scale factor *a*, this metric also distinguishes between static, expanding, and shrinking universes:

- $a = 1$ (static universe)
- $da/dt > 0$ (expanding universe)
- $da/dt < 0$ (shrinking universe)

The scale factor *a* and the curvature *k* are determined from Einstein's general theory of relativity. If we treat the universe as a gas of galaxies of density ρ and pressure *p*, and assume $k = 0$ (a flat universe), than the scale factor *a* is given by

$$\frac{d^2 a}{dt^2} = -\frac{4\pi G}{3}(\rho + 3p)a, \tag{11.15}$$

where *G* is the universal gravitational constant. (For ordinary matter, we expect the quantity $\rho + 3p$ to be greater than zero.) If the scale factor is positive ($a > 0$), the value of the scale factor "decelerates" ($d^2 a/dt^2 < 0$), and the expansion of the universe slows down over time. If the numerator is less than zero (somehow, the pressure of the universe is negative), the value of the scale factor "accelerates," and the expansion of the universe speeds up over time. According to recent cosmological data, the universe appears to be expanding. Many scientists explain the current state of the universe in terms of a very rapid expansion in the early universe. This expansion is called inflation.

11.7 | Evolution of the Early Universe

Learning Objectives

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

- Describe the evolution of the early universe in terms of the four fundamental forces
- Use the concept of gravitational lensing to explain astronomical phenomena
- Provide evidence of the Big Bang in terms of cosmic background radiation
- Distinguish between dark matter and dark energy

In the previous section, we discussed the structure and dynamics of universe. In particular, the universe appears to be expanding and even accelerating. But what was the universe like at the beginning of time? In this section, we discuss what evidence scientists have been able to gather about the early universe and its evolution to present time.

The Early Universe

Before the short period of cosmic inflation, cosmologists believe that all matter in the universe was squeezed into a space much smaller than an atom. Cosmologists further believe that the universe was extremely dense and hot, and interactions between particles were governed by a single force. In other words, the four fundamental forces (strong nuclear, electromagnetic, weak nuclear, and gravitational) merge into one at these energies (**Figure 11.21**). How and why this “unity” breaks down at lower energies is an important unsolved problem in physics.

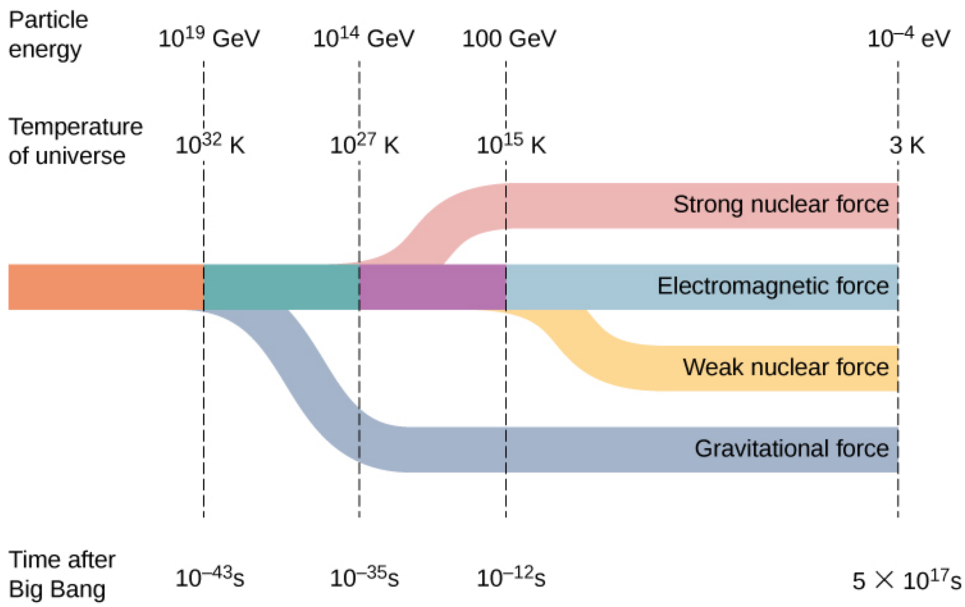


Figure 11.21 The separation of the four fundamental forces in the early universe.

Scientific models of the early universe are highly speculative. **Figure 11.22** shows a sketch of one possible timeline of events.

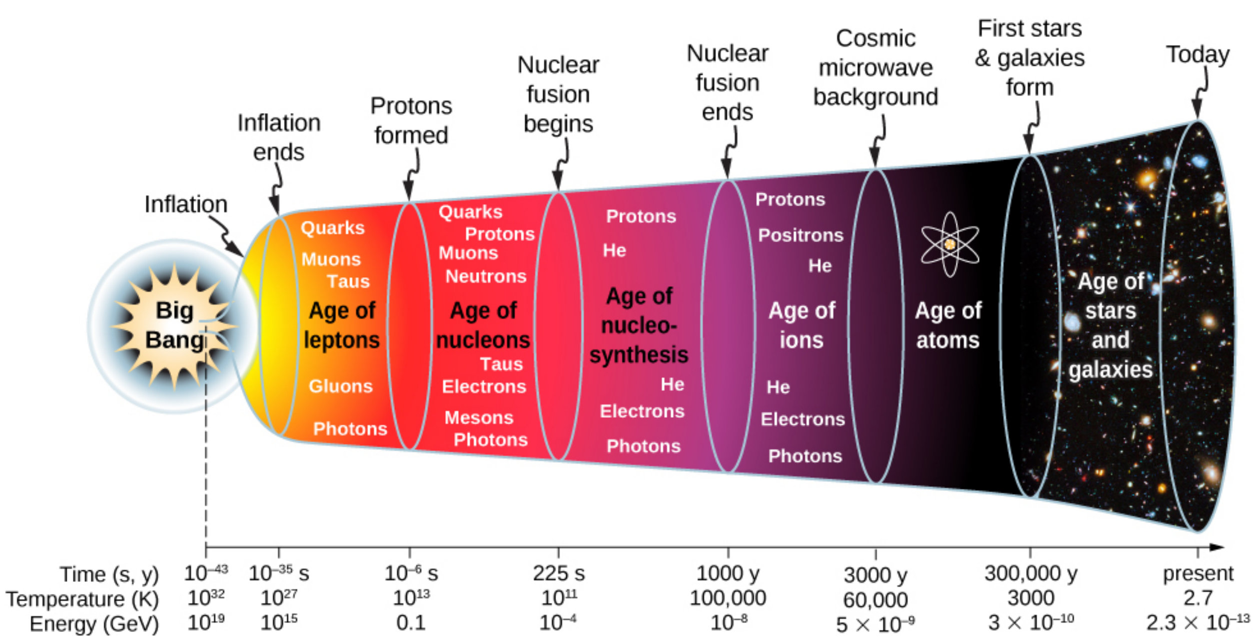


Figure 11.22 An approximate timeline for the evolution of the universe from the Big Bang to the present.

1. *Big Bang* $\left(t < 10^{-43}\,\text{s}\right)$: The current laws of physics break down. At the end of the initial Big Bang event, the temperature of the universe is approximately $T = 10^{32}\,\text{K}$.

2. *Inflationary phase* $\left(t = 10^{-43}\text{ to }10^{-35}\text{ s}\right)$: The universe expands exponentially, and gravity separates from the other forces. The universe cools to approximately $T = 10^{27}\text{ K}$.
3. *Age of leptons* $\left(t = 10^{-35}\text{ to }10^{-6}\text{ s}\right)$: As the universe continues to expand, the strong nuclear force separates from the electromagnetic and weak nuclear forces (or electroweak force). Soon after, the weak nuclear force separates from the electromagnetic force. The universe is a hot soup of quarks, leptons, photons, and other particles.
4. *Age of nucleons* $\left(t = 10^{-6}\text{ to }225\text{ s}\right)$: The universe consists of leptons and hadrons (such as protons, neutrons, and mesons) in thermal equilibrium. Pair production and pair annihilation occurs with equal ease, so photons remain in thermal equilibrium:

$$\begin{aligned}\gamma + \gamma &\leftrightarrow \mathrm{e}^- + \mathrm{e}^+\\ \gamma + \gamma &\leftrightarrow \mathrm{p} + \bar{\mathrm{p}}\\ \gamma + \gamma &\leftrightarrow \mathrm{n} + \bar{\mathrm{n}}.\end{aligned}$$

The number of protons is approximately equal to the number of neutrons through interactions with neutrinos:

$$\begin{aligned}\nu_e + \mathrm{n} &\leftrightarrow \mathrm{e}^- + \mathrm{p}\\ \bar{\nu}_e + \mathrm{p} &\leftrightarrow \mathrm{e}^+ + \mathrm{n}.\end{aligned}$$

The temperature of the universe settles to approximately 10^{11} K —much too cool for the continued production of nucleon-antinucleon pairs. The numbers of protons and neutrons begin to dominate over their anti-particles, so proton-antiproton $(\mathrm{p}\bar{\mathrm{p}})$ and neutron-antineutron ($\mathrm{n}\bar{\mathrm{n}}$) annihilations decline. Deuterons (proton-neutron pairs) begin to form.
5. *Age of nucleosynthesis* ($t = 225\text{ s}$ to 1000 years): As the universe continues to expand, deuterons react with protons and neutrons to form larger nuclei; these larger nuclei react with protons and neutrons to form still larger nuclei. At the end of this period, about 1/4 of the mass of the universe is helium. (This explains the current amount of helium in the universe.) Photons lack the energy to continue electron-positron production, so electrons and positrons annihilate each other to photons only.
6. *Age of ions* ($t = 1000$ to 3000 years): The universe is hot enough to ionize any atoms formed. The universe consists of electrons, positrons, protons, light nuclei, and photons.
7. *Age of atoms* ($t = 3000$ to 300,000 years): The universe cools below 10^5 K and atoms form. Photons do not interact strongly with neutral atoms, so they "decouple" (separate) from atoms. These photons constitute the **cosmic microwave background radiation** to be discussed later.
8. *Age of stars and galaxies* ($t = 300{,}000$ years to present): The atoms and particles are pulled together by gravity and form large lumps. The atoms and particles in stars undergo nuclear fusion reaction.

Watch this **video (https://openstaxcollege.org/l/21bigbang)** to learn more about Big Bang cosmology.

To describe the conditions of the early universe quantitatively, recall the relationship between the average thermal energy of particle (E) in a system of interacting particles and equilibrium temperature (T) of that system:

$$E = k_B T, \tag{11.16}$$

where k_B is Boltzmann's constant. In the hot conditions of the early universe, particle energies were unimaginably large.

Example 11.9

What Was the Average Thermal Energy of a Particle just after the Big Bang?

Strategy

The average thermal energy of a particle in a system of interacting particles depends on the equilibrium temperature of that system Equation 11.1. We are given this approximate temperature in the above timeline.

Solution

Cosmologists think the temperature of the universe just after the Big Bang was approximately $T = 10^{32}\,\text{K}$. Therefore, the average thermal energy of a particle would have been

$$k_B T \approx (10^{-4}\ \text{eV/K})(10^{32}\,\text{K}) = 10^{28}\ \text{eV} = 10^{19}\ \text{GeV}.$$

Significance

This energy is many orders of magnitude larger than particle energies produced by human-made particle accelerators. Currently, these accelerators operate at energies less than 10^4 GeV.

11.9 Check Your Understanding Compare the abundance of helium by mass 10,000 years after the Big Bang and now.

Nucleons form at energies approximately equal to the rest mass of a proton, or 1000 MeV. The temperature corresponding to this energy is therefore

$$T = \frac{1000\ \text{MeV}}{8.62 \times 10^{11}\ \text{MeV} \cdot \text{K}^{-1}} = 1.2 \times 10^{13}\ \text{K}.$$

Temperatures of this value or higher existed within the first second of the early universe. A similar analysis can be done for atoms. Atoms form at an energy equal to the ionization energy of ground-state hydrogen (13 eV). The effective temperature for atom formation is therefore

$$T = \frac{13\ \text{eV}}{8.62 \times 10^{5}\ \text{eV} \cdot \text{K}^{-1}} = 1.6 \times 10^{5}\ \text{K}.$$

This occurs well after the four fundamental forces have separated, including forces necessary to bind the protons and neutrons in the nucleus (strong nuclear force), and bind electrons to the nucleus (electromagnetic force).

Nucleosynthesis of Light Elements

The relative abundances of the light elements hydrogen, helium, lithium, and beryllium in the universe provide key evidence for the Big Bang. The data suggest that much of the helium in the universe is primordial. For instance, it turns out that that 25% of the matter in the universe is helium, which is too high an abundance and cannot be explained based on the production of helium in stars.

How much of the elements in the universe were created in the Big Bang? If you run the clock backward, the universe becomes more and more compressed, and hotter and hotter. Eventually, temperatures are reached that permit **nucleosynthesis**, the period of formation of nuclei, similar to what occurs at the core of the Sun. Big Bang nucleosynthesis is believed to have occurred within a few hundred seconds of the Big Bang.

How did Big Bang nucleosynthesis occur? At first, protons and neutrons combined to form deuterons, ^2H. The deuteron captured a neutron to form triton, ^3H —the nucleus of the radioactive hydrogen called tritium. Deuterons also captured protons to make helium ^3He. When ^3H captures a proton or ^3He captures a neutron, helium ^4He results. At this stage in the Big Bang, the ratio of protons to neutrons was about 7:1. Thus, the process of conversion to ^4He used up almost all neutrons. The process lasted about 3 minutes and almost 25% of all the matter turned into ^4He, along with small percentages of ^2H, ^3H, and ^3He. Tiny amounts of ^7Li and ^7Be were also formed. The expansion during this time cooled the universe enough that the nuclear reactions stopped. The abundances of the light nuclei ^2H, ^4He, and ^7Li created after the Big Bang are very dependent on the matter density.

The predicted abundances of the elements in the universe provide a stringent test of the Big Bang and the Big Bang nucleosynthesis. Recent experimental estimates of the matter density from the Wilkinson Microwave Anisotropy Probe (WMAP) agree with model predictions. This agreement provides convincing evidence of the Big Bang model.

Cosmic Microwave Background Radiation

According to cosmological models, the Big Bang event should have left behind thermal radiation called the cosmic microwave background radiation (CMBR). The intensity of this radiation should follow the blackbody radiation curve (**Photons and Matter Waves**). Wien's law states that the wavelength of the radiation at peak intensity is

$$\lambda_{\text{max}} = \frac{2.898 \times 10^{-3}\ \text{m-K}}{T}, \tag{11.17}$$

where T is temperature in kelvins. Scientists expected the expansion of the universe to "stretch the light," and the temperature to be very low, so cosmic background radiation should be long-wavelength and low energy.

In the 1960s, Arno Penzias and Robert Wilson of Bell Laboratories noticed that no matter what they did, they could not get rid of a faint background noise in their satellite communication system. The noise was due to radiation with wavelengths in the centimeter range (the microwave region). Later, this noise was associated with the cosmic background radiation. An intensity map of the cosmic background radiation appears in **Figure 11.23**. The thermal spectrum is modeled well by a blackbody curve that corresponds to a temperature $T = 2.7\text{K}$ (**Figure 11.24**).

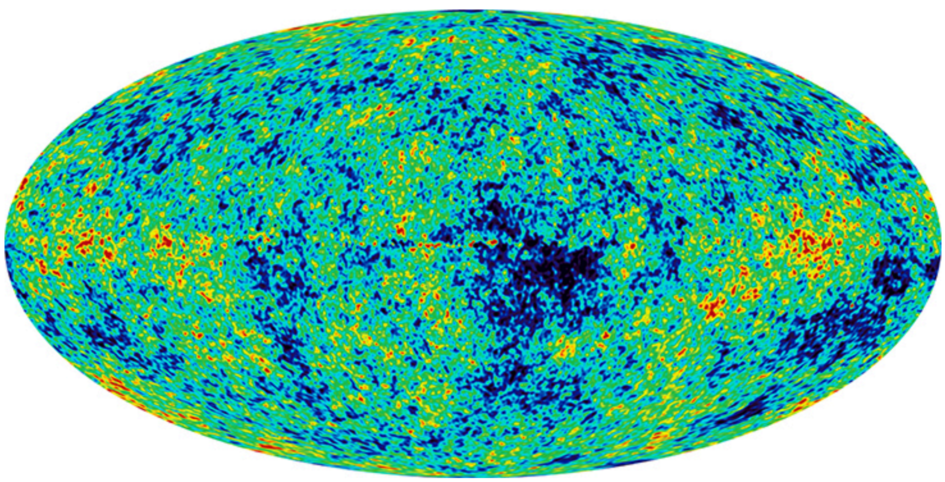


Figure 11.23 This map of the sky uses color to show fluctuations, or wrinkles, in the cosmic microwave background observed with the WMAP spacecraft. The Milky Way has been removed for clarity. Red represents higher temperature and higher density, whereas blue indicates lower temperature and density. This map does not contradict the earlier claim of smoothness because the largest fluctuations are only one part in one million. (credit: NASA/WMAP Science Team)

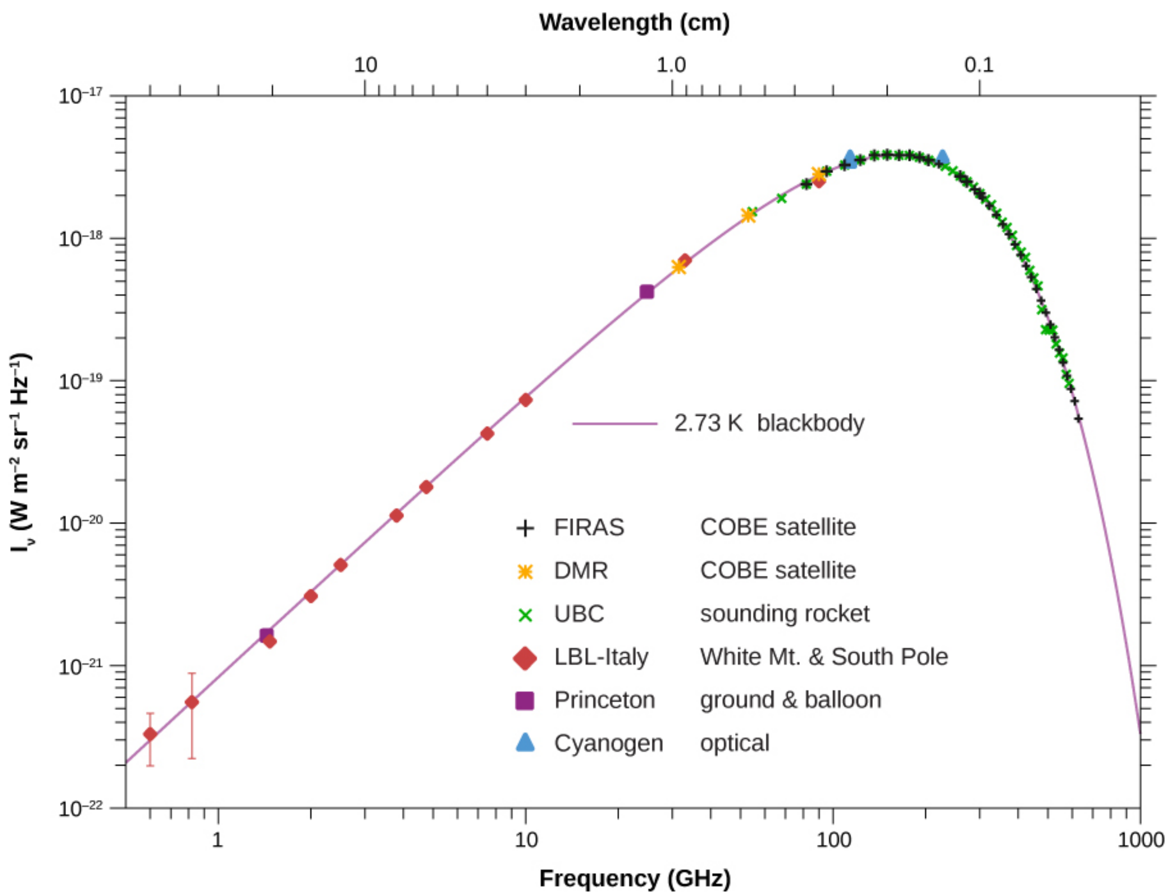


Figure 11.24 Intensity distribution of cosmic microwave background radiation. The model predictions (the line) agree extremely well with the experimental results (the dots). Frequency and brightness values are shown on a log axis. (credit: modification of work by George Smoot/NASA COBE Project)

The formation of atoms in the early universe makes these atoms less likely to interact with light. Therefore, photons that belong to the cosmic background radiation must have separated from matter at a temperature T associated with 1 eV (the approximate ionization energy of an atom) . The temperature of the universe at this point was

$$\mathrm{k_B T} \sim 1\ \mathrm{eV} \Rightarrow T = \frac{1\ \mathrm{eV}}{8.617 \times 10^{5}\ \mathrm{eV/K}} \sim 10^4\ \mathrm{K}.$$

According to cosmological models, the time when photons last scattered off charged particles was approximately 380,000 years after the Big Bang. Before that time, matter in the universe was in the plasma form and the photons were "thermalized."

Antimatter and Matter

We know from direct observation that antimatter is rare. Earth and the solar system are nearly pure matter, and most of the universe also seems dominated by matter. This is proven by the lack of annihilation radiation coming to us from space, particularly the relative absence of 0.511-MeV γ rays created by the mutual annihilation of electrons and positrons. (Antimatter in nature is created in particle collisions and in β^+ decays, but only in small amounts that quickly annihilate, leaving almost pure matter surviving.)

Despite the observed dominance of matter over antimatter in the universe, the Standard Model of particle interactions and experimental measurement suggests only small differences in the ways that matter and antimatter interact. For example, neutral kaon decays produce only slightly more matter than antimatter. Yet, if through such decay, slightly more matter than antimatter was produced in the early universe, the rest could annihilate pair by pair, leaving mostly ordinary matter to form the stars and galaxies. In this way, the vast number of stars we observe may be only a tiny remnant of the original matter created in the Big Bang.

Dark Matter and Dark Energy

In the last two decades, new and more powerful techniques have revealed that the universe is filled with **dark matter**. This type of matter is interesting and important because, currently, scientists do not know what it is! However, we can infer its existence by the deflection of distant starlight. For example, if light from a distant galaxy is bent by the gravitational field of a clump of dark matter between us and the galaxy, it is possible that two images of the same galaxy can be produced (Figure 11.25). The bending of light by the gravitational field of matter is called gravitational lensing. In some cases, the starlight travels to an observer by multiple paths around the galaxy, producing a ring (Figure 11.26).

Based on current research, scientist know only that dark matter is cold, slow moving, and interacts weakly with ordinary matter. Dark matter candidates include neutralinos (partners of Z bosons, photons, and Higgs bosons in "supersymmetry theory") and particles that circulate in tiny rings set up by extra spatial dimensions.

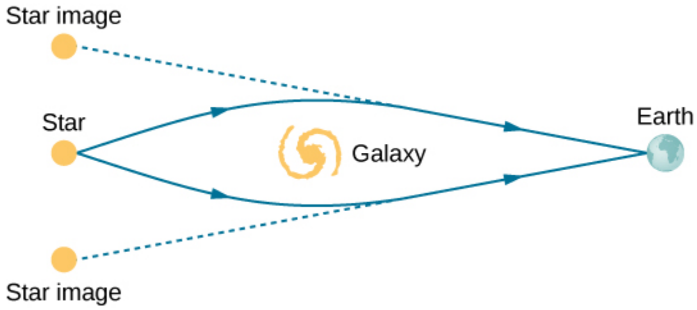


Figure 11.25 Light from a distant star is bent around a galaxy. Under the right conditions, two duplicate images of the same star can be seen.

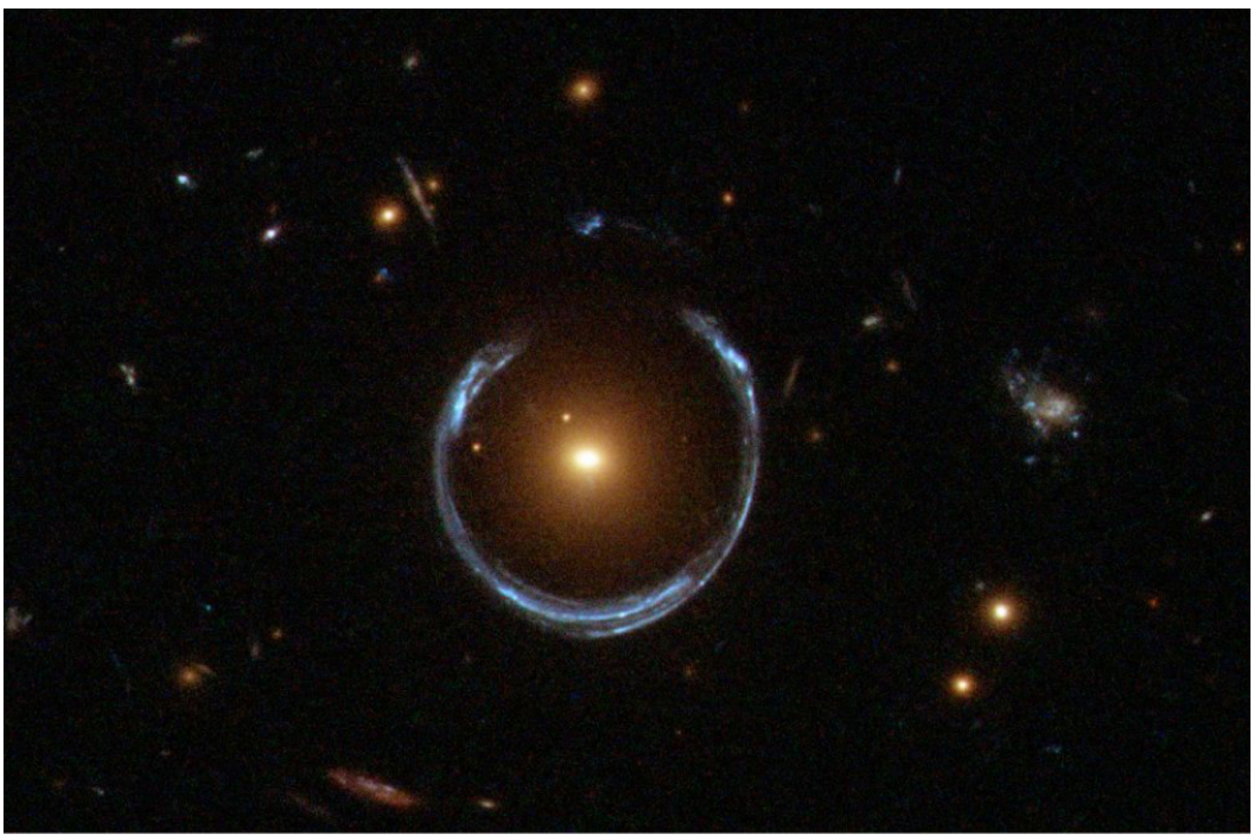


Figure 11.26 Light from a distant star is bent around a galaxy. Under the right conditions, we can see a ring of light instead of a single star. (credit: modification of work by ESA/Hubble & NASA)

Increasingly precise astronomical measurements of the expanding universe also reveal the presence of a new form of energy called **dark energy**. This energy is thought to explain larger-than-expected values for the observed galactic redshifts for distant galaxies. These redshifts suggest that the universe is not only expanding, but expanding at an increasing rate. Virtually nothing is known about the nature and properties of dark energy. Together, dark energy and dark matter represent two of the most interesting and unsolved puzzles of modern physics. Scientists attribute 68.3% of the energy of the universe to dark energy, 26.8% to dark matter, and just 4.9% to the mass-energy of ordinary particles (**Figure 11.27**). Given the current great mystery over the nature of dark matter and dark energy, Isaac Newton's humble words are as true now as they were centuries ago:

"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

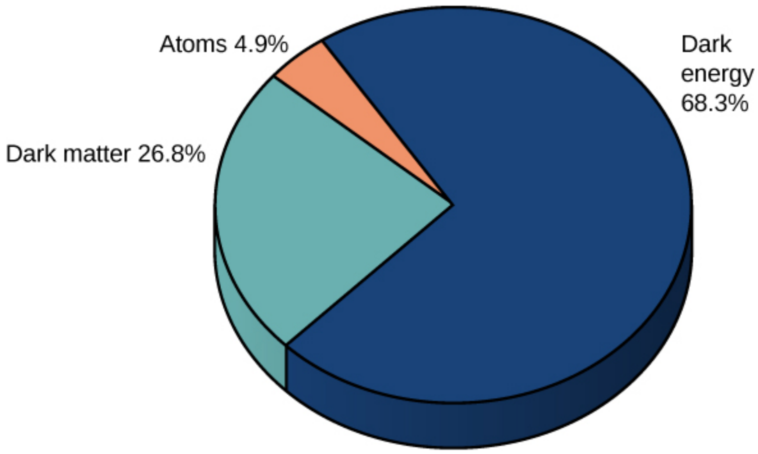


Figure 11.27 Estimated distribution of matter and energy in the universe. (credit: NASA/WMAP Science Team)

CHAPTER 11 REVIEW

KEY TERMS

antiparticle subatomic particle with the same mass and lifetime as its associated particle, but opposite electric charge

baryon number baryon number has the value $B = +1$ for baryons, -1 for antibaryons, and 0 for all other particles and is conserved in particle interactions

baryons group of three quarks

Big Bang rapid expansion of space that marked the beginning of the universe

boson particle with integral spin that are symmetric on exchange

color property of particles and that plays the same role in strong nuclear interactions as electric charge does in electromagnetic interactions

cosmic microwave background radiation (CMBR) thermal radiation produced by the Big Bang event

cosmology study of the origin, evolution, and ultimate fate of the universe

dark energy form of energy believed to be responsible for the observed acceleration of the universe

dark matter matter in the universe that does not interact with other particles but that can be inferred by deflection of distance star light

electroweak force unification of electromagnetic force and weak-nuclear force interactions

exchange symmetry property of a system of indistinguishable particles that requires the exchange of any two particles to be unobservable

fermion particle with half-integral spin that is antisymmetric on exchange

Feynman diagram space-time diagram that describes how particles move and interact

fundamental force one of four forces that act between bodies of matter: the strong nuclear, electromagnetic, weak nuclear, and gravitational forces

gluon particle that that carry the strong nuclear force between quarks within an atomic nucleus

grand unified theory theory of particle interactions that unifies the strong nuclear, electromagnetic, and weak nuclear forces

hadron a meson or baryon

Hubble's constant constant that relates speed and distance in Hubble's law

Hubble's law relationship between the speed and distance of stars and galaxies

lepton a fermion that participates in the electroweak force

lepton number electron-lepton number L_e, the muon-lepton number L_μ, and the tau-lepton number L_τ are conserved separately in every particle interaction

mesons a group of two quarks

nucleosynthesis creation of heavy elements, occurring during the Big Bang

particle accelerator machine designed to accelerate charged particles; this acceleration is usually achieved with strong electric fields, magnetic fields, or both

particle detector detector designed to accurately measure the outcome of collisions created by a particle accelerator; particle detectors are hermetic and multipurpose

positron antielectron

quantum chromodynamics (QCD) theory that describes strong interactions between quarks

quantum electrodynamics (QED) theory that describes the interaction of electrons with photons

quark a fermion that participates in the electroweak and strong nuclear force

redshift lengthening of the wavelength of light (or reddening) due to cosmological expansion

Standard Model model of particle interactions that contains the electroweak theory and quantum chromodynamics (QCD)

strangeness particle property associated with the presence of a strange quark

strong nuclear force relatively strong attractive force that acts over short distances (about 10^{-15} m) responsible for binding protons and neutrons together in atomic nuclei

synchrotron circular accelerator that uses alternating voltage and increasing magnetic field strengths to accelerate particles to higher and higher energies

synchrotron radiation high-energy radiation produced in a synchrotron accelerator by the circular motion of a charged beam

theory of everything a theory of particle interactions that unifies all four fundamental forces

virtual particle particle that exists for too short of time to be observable

W and Z boson particle with a relatively large mass that carries the weak nuclear force between leptons and quarks

weak nuclear force relative weak force (about 10^{-6} the strength of the strong nuclear force) responsible for decays of elementary particles and neutrino interactions

KEY EQUATIONS

Momentum of a charged particle in a cyclotron	$p = 0.3Br$
Center-of-mass energy of a colliding beam machine	$W^2 = 2[E_1 E_2 + (p_1 c)(p_2 c)] + (m_1 c^2)^2 + (m_2 c^2)^2$
Approximate time for exchange of a virtual particle between two other particles	$\Delta t = \frac{h}{E}$
Hubble's law	$v = H_0 d$
Cosmological space-time metric	$ds^2 = c^2 dt^2 - a(t)^2 d\Sigma^2$

SUMMARY

11.1 Introduction to Particle Physics

- The four fundamental forces of nature are, in order of strength: strong nuclear, electromagnetic, weak nuclear, and gravitational. Quarks interact via the strong force, but leptons do not. Both quark and leptons interact via the electromagnetic, weak, and gravitational forces.
- Elementary particles are classified into fermions and boson. Fermions have half-integral spin and obey the exclusion principle. Bosons have integral spin and do not obey this principle. Bosons are the force carriers of particle interactions.
- Quarks and leptons belong to particle families composed of three members each. Members of a family share many properties (charge, spin, participation in forces) but not mass.
- All particles have antiparticles. Particles share the same properties as their antimatter particles, but carry opposite charge.

11.2 Particle Conservation Laws

- Elementary particle interactions are governed by particle conservation laws, which can be used to determine what particle reactions and decays are possible (or forbidden).
- The baryon number conservation law and the three lepton number conversation law are valid for all physical

processes. However, conservation of strangeness is valid only for strong nuclear interactions and electromagnetic interactions.

11.3 Quarks

- Six known quarks exist: up (u), down (d), charm (c), strange (s), top (t), and bottom (b). These particles are fermions with half-integral spin and fractional charge.
- Baryons consist of three quarks, and mesons consist of a quark-antiquark pair. Due to the strong force, quarks cannot exist in isolation.
- Evidence for quarks is found in scattering experiments.

11.4 Particle Accelerators and Detectors

- Many types of particle accelerators have been developed to study particles and their interactions. These include linear accelerators, cyclotrons, synchrotrons, and colliding beams.
- Colliding beam machines are used to create massive particles that decay quickly to lighter particles.
- Multipurpose detectors are used to design all aspects of high-energy collisions. These include detectors to measure the momentum and energies of charge particles and photons.
- Charged particles are measured by bending these particles in a circle by a magnetic field.
- Particles are measured using calorimeters that absorb the particles.

11.5 The Standard Model

- The Standard Model describes interactions between particles through the strong nuclear, electromagnetic, and weak nuclear forces.
- Particle interactions are represented by Feynman diagrams. A Feynman diagram represents interactions between particles on a space-time graph.
- Electromagnetic forces act over a long range, but strong and weak forces act over a short range. These forces are transmitted between particles by sending and receiving bosons.
- Grand unified theories seek an understanding of the universe in terms of just one force.

11.6 The Big Bang

- The universe is expanding like a balloon—every point is receding from every other point.
- Distant galaxies move away from us at a velocity proportional to its distance. This rate is measured to be approximately 70 km/s/Mpc. Thus, the farther galaxies are from us, the greater their speeds. These “recessional velocities” can be measure using the Doppler shift of light.
- According to current cosmological models, the universe began with the Big Bang approximately 13.7 billion years ago.

11.7 Evolution of the Early Universe

- The early universe was hot and dense.
- The universe is isotropic and expanding.
- Cosmic background radiation is evidence for the Big Bang.
- The vast portion of the mass and energy of the universe is not well understood.

CONCEPTUAL QUESTIONS

11.1 Introduction to Particle Physics

1. What are the four fundamental forces? Briefly describe them.

2. Distinguish fermions and bosons using the concepts of indistiguishability and exchange symmetry.

3. List the quark and lepton families

4. Distinguish between elementary particles and antiparticles. Describe their interactions.

11.2 Particle Conservation Laws

5. What are six particle conservation laws? Briefly describe them.

6. In general, how do we determine if a particle reaction or decay occurs?

7. Why might the detection of particle interaction that violates an established particle conservation law be considered a *good* thing for a scientist?

11.3 Quarks

8. What are the six known quarks? Summarize their properties.

9. What is the general quark composition of a baryon? Of a meson?

10. What evidence exists for the existence of quarks?

11. Why do baryons with the same quark composition sometimes differ in their rest mass energies?

11.4 Particle Accelerators and Detectors

12. Briefly compare the Van de Graaff accelerator, linear accelerator, cyclotron, and synchrotron accelerator.

13. Describe the basic components and function of a typical colliding beam machine.

14. What are the subdetectors of the Compact Muon Solenoid experiment? Briefly describe them.

15. What is the advantage of a colliding-beam accelerator over one that fires particles into a fixed target?

16. An electron appears in the muon detectors of the CMS. How is this possible?

11.5 The Standard Model

17. What is the Standard Model? Express your answer in terms of the four fundamental forces and exchange particles.

18. Draw a Feynman diagram to represents annihilation of an electron and positron into a photon.

19. What is the motivation behind grand unification theories?

20. If a theory is developed that unifies all four forces, will it still be correct to say that the orbit of the Moon is determined by the gravitational force? Explain why.

21. If the Higgs boson is discovered and found to have mass, will it be considered the ultimate carrier of the weak force? Explain your response.

22. One of the common decay modes of the Λ^0 is $\Lambda^0 \rightarrow \pi^- + \text{p}$. Even though only hadrons are involved in this decay, it occurs through the weak nuclear force. How do we know that this decay does not occur through the strong nuclear force?

11.6 The Big Bang

23. What is meant by cosmological expansion? Express your answer in terms of a Hubble graph and the red shift of distant starlight.

24. Describe the balloon analogy for cosmological expansion. Explain why it only *appears* that we are at the center of expansion of the universe.

25. Distances to local galaxies are determined by measuring the brightness of stars, called Cepheid variables, that can be observed individually and that have absolute brightnesses at a standard distance that are well known. Explain how the measured brightness would vary with distance, as compared with the absolute brightness.

11.7 Evolution of the Early Universe

26. What is meant by a “cosmological model of the early universe?” Briefly describe this model in terms of the four fundamental forces.

27. Describe two pieces of evidence that support the Big Bang model.

28. In what sense are we, as Newton once said, “a boy playing on the sea-shore”? Express your answer in terms of the concepts of dark matter and dark energy.

29. If some unknown cause of redshift—such as light becoming “tired” from traveling long distances through empty space—is discovered, what effect would that have on cosmology?

30. In the past, many scientists believed the universe to be infinite. However, if the universe is infinite, then any line of sight should eventually fall on a star’s surface and the night sky should be very bright. How is this paradox resolved in modern cosmology?

PROBLEMS

11.1 Introduction to Particle Physics

31. How much energy is released when an electron and a positron at rest annihilate each other? (For particle masses, see **Table 11.1**.)

32. If 1.0×10^{30} MeV of energy is released in the annihilation of a sphere of matter and antimatter, and the spheres are equal mass, what are the masses of the spheres?

33. When both an electron and a positron are at rest, they can annihilate each other according to the reaction

$$e^- + e^+ \rightarrow \gamma + \gamma.$$

In this case, what are the energy, momentum, and frequency of each photon?

34. What is the *total kinetic energy* carried away by the particles of the following decays?

(a) $\pi^0 \rightarrow \gamma + \gamma$
(b) $K^0 \rightarrow \pi^+ + \pi^-$
(c) $\Sigma^+ \rightarrow n + \pi^+$
(d) $\Sigma^0 \rightarrow \Lambda^0 + \gamma$.

11.2 Particle Conservation Laws

35. Which of the following decays cannot occur because the law of conservation of lepton number is violated?

(a) $n \rightarrow p + e^-$
(b) $\mu^+ \rightarrow e^+ + \upsilon_e$
(c) $\pi^+ \rightarrow e^+ + \upsilon_e + \bar{\upsilon}_\mu$
(d) $p \rightarrow n + e^+ + \upsilon_e$
(e) $\pi^- \rightarrow e^- + \bar{\upsilon}_e$
(f) $\mu^- \rightarrow e^- + \bar{\upsilon}_e + \upsilon_\mu$
(g) $\Lambda^0 \rightarrow \pi^- + p$
(h) $K^+ \rightarrow \mu^+ + \upsilon_\mu$

36. Which of the following reactions cannot because the law of conservation of strangeness is violated?

(a) $p + n \rightarrow p + p + \pi^-$
(b) $p + n \rightarrow p + p + K^-$
(c) $K^- + p \rightarrow K^- + \sum^+$
(d) $\pi^- + p \rightarrow K^+ + \sum^-$
(e) $K^- + p \rightarrow \Xi^0 + K^+ + \pi^-$
(f) $K^- + p \rightarrow \Xi^0 + \pi^- + \pi^-$
(g) $\pi^+ + p \rightarrow \Sigma^+ + K^+$
(h) $\pi^- + n \rightarrow K^- + \Lambda^0$

37. Identify one possible decay for each of the following antiparticles:

(a) $\bar{n}$, (b) $\overline{\Lambda^0}$, (c) Ω^+, (d) K^-, and (e) $\bar{\Sigma}$.

38. Each of the following strong nuclear reactions is forbidden. Identify a conservation law that is violated for each one.

(a) $p + \bar{p} \rightarrow p + n + \bar{p}$
(b) $p + n \rightarrow p + \bar{p} + n + \pi^+$
(c) $\pi^- + p \rightarrow \Sigma^+ + K^-$
(d) $K^- + p \rightarrow \Lambda^0 + n$

11.3 Quarks

39. Based on quark composition of a proton, show that its charge is $+1$.

40. Based on the quark composition of a neutron, show that is charge is 0.

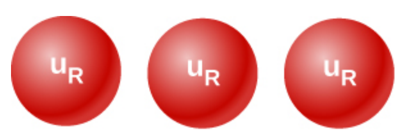
41. Argue that the quark composition given in **Table 11.5** for the positive kaon is consistent with the known charge, spin, and strangeness of this baryon.

42. Mesons are formed from the following combinations of quarks (subscripts indicate color and $AR =$ antired):

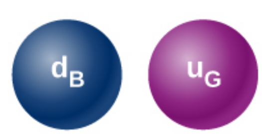
$(d_R, \bar{d}_{AR})$, $(s_G, \bar{u}_{AG})$, and $(s_R, \bar{s}_{AR})$.

(a) Determine the charge and strangeness of each combination. (*b*) Identify one or more mesons formed by each quark-antiquark combination.

43. Why can't either set of quarks shown below form a hadron?



(a)



(b)

44. Experimental results indicate an isolate particle with charge $+2/3$ —an isolated quark. What quark could this be? Why would this discovery be important?

45. Express the β decays $n \to p + e^- + \bar{\nu}$ and $p \to n + e^+ + \nu$ in terms of β decays of quarks. Check to see that the conservation laws for charge, lepton number, and baryon number are satisfied by the quark β decays.

11.4 Particle Accelerators and Detectors

46. A charged particle in a 2.0-T magnetic field is bent in a circle of radius 75 cm. What is the momentum of the particle?

47. A proton track passes through a magnetic field with radius of 50 cm. The magnetic field strength is 1.5 T. What is the total energy of the proton?

48. Derive the equation $p = 0.3Br$ using the concepts of centripetal acceleration (**Motion in Two and Three Dimensions (http://cnx.org/content/m58288/latest/)**) and relativistic momentum (**Relativity**)

49. Assume that beam energy of an electron-positron collider is approximately 4.73 GeV. What is the total mass (W) of a particle produced in the annihilation of an electron and positron in this collider? What meson might be produced?

50. At full energy, protons in the 2.00-km-diameter Fermilab synchrotron travel at nearly the speed of light, since their energy is about 1000 times their rest mass energy. (a) How long does it take for a proton to complete one trip around? (b) How many times per second will it pass through the target area?

51. Suppose a W^- created in a particle detector lives for 5.00×10^{-25} s . What distance does it move in this time if it is traveling at 0.900*c*? (Note that the time is longer than the given W^- lifetime, which can be due to the statistical nature of decay or time dilation.)

52. What length track does a π^+ traveling at 0.100*c* leave in a bubble chamber if it is created there and lives for 2.60×10^{-8} s ? (Those moving faster or living longer may escape the detector before decaying.)

53. The 3.20-km-long SLAC produces a beam of 50.0-GeV electrons. If there are 15,000 accelerating tubes, what average voltage must be across the gaps between them to achieve this energy?

11.5 The Standard Model

54. Using the Heisenberg uncertainly principle, determine the range of the weak force if this force is produced by the exchange of a Z boson.

55. Use the Heisenberg uncertainly principle to estimate the range of a weak nuclear decay involving a graviton.

56. (a) The following decay is mediated by the electroweak force:

$$\mathrm{p} \to \mathrm{n} + \mathrm{e}^+ + \upsilon_\mathrm{e}.$$

Draw the Feynman diagram for the decay.

(b) The following scattering is mediated by the electroweak force:

$$\upsilon_e + \mathrm{e}^- \to \upsilon_e + \mathrm{e}^-.$$

Draw the Feynman diagram for the scattering.

57. Assuming conservation of momentum, what is the energy of each γ ray produced in the decay of a neutral pion at rest, in the reaction $\pi^0 \to \gamma + \gamma$?

58. What is the wavelength of a 50-GeV electron, which is produced at SLAC? This provides an idea of the limit to the detail it can probe.

59. The primary decay mode for the negative pion is $\pi^- \to \mu^- + \bar{\nu}_\mu$. (a) What is the energy release in MeV in this decay? (b) Using conservation of momentum, how much energy does each of the decay products receive, given the π^- is at rest when it decays? You may assume the muon antineutrino is massless and has momentum $p = E/c$, just like a photon.

60. Suppose you are designing a proton decay experiment and you can detect 50 percent of the proton decays in a tank of water. (a) How many kilograms of water would you need to see one decay per month, assuming a lifetime of 10^{31} y? (b) How many cubic meters of water is this? (c) If the actual lifetime is 10^{33} y , how long would you have to wait on an average to see a single proton decay?

11.6 The Big Bang

61. If the speed of a distant galaxy is 0.99*c*, what is the distance of the galaxy from an Earth-bound observer?

62. The distance of a galaxy from our solar system is 10 Mpc. (a) What is the recessional velocity of the galaxy? (b) By what fraction is the starlight from this galaxy redshifted (that is, what is its *z* value)?

63. If a galaxy is 153 Mpc away from us, how fast do we expect it to be moving and in what direction?

64. On average, how far away are galaxies that are moving away from us at 2.0% of the speed of light?

65. Our solar system orbits the center of the Milky Way Galaxy. Assuming a circular orbit 30,000 ly in radius and an orbital speed of 250 km/s, how many years does it take for one revolution? Note that this is approximate, assuming constant speed and circular orbit, but it is representative of the time for our system and local stars to make one revolution around the galaxy.

66. (a) What is the approximate velocity relative to us of a galaxy near the edge of the known universe, some 10 Gly away? (b) What fraction of the speed of light is this? Note that we have observed galaxies moving away from us at greater than 0.9*c*.

67. (a) Calculate the approximate age of the universe from the average value of the Hubble constant, $H_0 = 20\,\text{km/s} \cdot \text{Mly}$. To do this, calculate the time it would take to travel 0.307 Mpc at a constant expansion rate of 20 km/s. (b) If somehow acceleration occurs, would the actual age of the universe be greater or less than that found here? Explain.

68. The Andromeda Galaxy is the closest large galaxy and is visible to the naked eye. Estimate its brightness relative to the Sun, assuming it has luminosity 10^{12} times that of the Sun and lies 0.613 Mpc away.

69. Show that the velocity of a star orbiting its galaxy in a circular orbit is inversely proportional to the square root of its orbital radius, assuming the mass of the stars inside its orbit acts like a single mass at the center of the galaxy. You may use an equation from a previous chapter to support your conclusion, but you must justify its use and define all terms used.

ADDITIONAL PROBLEMS

70. Experimental results suggest that a muon decays to an electron and photon. How is this possible?

71. Each of the following reactions is missing a single particle. Identify the missing particle for each reaction.

(a) $\text{p} + \bar{\text{p}} \rightarrow \text{n} + \ ?$

(b) $\text{p} + \text{p} \rightarrow \text{p} + \Lambda^0 + \ ?$

(c) $\pi^? + \text{p} \rightarrow \Sigma^- + \ ?$

(d) $\text{K}^- + \text{n} \rightarrow \Lambda^0 + \ ?$

(e) $\tau^+ \rightarrow \text{e}^+ + \upsilon_\text{e} + \ ?$

(f) $\bar{\upsilon}_\text{e} + \text{p} \rightarrow \text{n} + \ ?$

72. Because of energy loss due to synchrotron radiation in the LHC at CERN, only 5.00 MeV is added to the energy of each proton during each revolution around the main ring. How many revolutions are needed to produce 7.00-TeV (7000 GeV) protons, if they are injected with an initial energy of 8.00 GeV?

73. A proton and an antiproton collide head-on, with each having a kinetic energy of 7.00 TeV (such as in the LHC at CERN). How much collision energy is available, taking into account the annihilation of the two masses? (Note that this is not significantly greater than the extremely relativistic kinetic energy.)

74. When an electron and positron collide at the SLAC facility, they each have 50.0-GeV kinetic energies. What is the total collision energy available, taking into account the annihilation energy? Note that the annihilation energy is insignificant, because the electrons are highly relativistic.

75. The core of a star collapses during a supernova, forming a neutron star. Angular momentum of the core is conserved, so the neutron star spins rapidly. If the initial core radius is 5.0×10^5 km and it collapses to 10.0 km, find the neutron star's angular velocity in revolutions per second, given the core's angular velocity was originally 1 revolution per 30.0 days.

76. Using the solution from the previous problem, find the increase in rotational kinetic energy, given the core's mass is 1.3 times that of our Sun. Where does this increase in kinetic energy come from?

77. (a) What Hubble constant corresponds to an approximate age of the universe of 10^{10} y? To get an approximate value, assume the expansion rate is constant and calculate the speed at which two galaxies must move apart to be separated by 1 Mly (present average galactic separation) in a time of 10^{10} y. (b) Similarly, what Hubble constant corresponds to a universe approximately 2×10^{10} years old?

CHALLENGE PROBLEMS

78. Electrons and positrons are collided in a circular accelerator. Derive the expression for the center-of-mass energy of the particle.

79. The intensity of cosmic ray radiation decreases rapidly with increasing energy, but there are occasionally extremely energetic cosmic rays that create a shower of radiation from all the particles they create by striking a nucleus in the atmosphere. Suppose a cosmic ray particle having an energy of 10^{10} GeV converts its energy into particles with masses averaging $200\text{MeV}/c^2$.

(a) How many particles are created? (b) If the particles rain down on a 1.00-km^2 area, how many particles are there per square meter?

80. (a) Calculate the relativistic quantity $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ for 1.00-TeV protons produced at Fermilab. (b) If such a proton created a π^+ having the same speed, how long would its life be in the laboratory? (c) How far could it travel in this time?

81. Plans for an accelerator that produces a secondary beam of K mesons to scatter from nuclei, for the purpose of studying the strong force, call for them to have a kinetic energy of 500 MeV. (a) What would the relativistic quantity $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ be for these particles? (b) How long would their average lifetime be in the laboratory? (c) How far could they travel in this time?

82. In supernovae, neutrinos are produced in huge amounts. They were detected from the 1987A supernova in the Magellanic Cloud, which is about 120,000 light-years away from Earth (relatively close to our Milky Way Galaxy). If neutrinos have a mass, they cannot travel at the speed of light, but if their mass is small, their velocity would be almost that of light. (a) Suppose a neutrino with a $7\text{-eV}/c^2$ mass has a kinetic energy of 700 keV. Find the relativistic quantity $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$ for it. (b) If the neutrino leaves the 1987A supernova at the same time as a photon and both travel to Earth, how much sooner does the photon arrive? This is not a large time difference, given that it is impossible to know which neutrino left with which photon and the poor efficiency of the neutrino detectors. Thus, the fact that neutrinos were observed within hours of the brightening of the supernova only places an upper limit on the neutrino's mass. (*Hint:* You may need to use a series expansion to find *v* for the neutrino, since its γ is so large.)

83. Assuming a circular orbit for the Sun about the center of the Milky Way Galaxy, calculate its orbital speed using the following information: The mass of the galaxy is equivalent to a single mass 1.5×10^{11} times that of the Sun (or 3×10^{41} kg), located 30,000 ly away.

84. (a) What is the approximate force of gravity on a 70-kg person due to the Andromeda Galaxy, assuming its total mass is 10^{13} that of our Sun and acts like a single mass 0.613 Mpc away? (b) What is the ratio of this force to the person's weight? Note that Andromeda is the closest large galaxy.

85. (a) A particle and its antiparticle are at rest relative to an observer and annihilate (completely destroying both masses), creating two γ rays of equal energy. What is the characteristic γ-ray energy you would look for if searching for evidence of proton-antiproton annihilation? (The fact that such radiation is rarely observed is evidence that there is very little antimatter in the universe.) (b) How does this compare with the 0.511-MeV energy associated with electron-positron annihilation?

86. The peak intensity of the CMBR occurs at a wavelength of 1.1 mm. (a) What is the energy in eV of a 1.1-mm photon? (b) There are approximately 10^9 photons for each massive particle in deep space. Calculate the energy of 10^9 such photons. (c) If the average massive particle in space has a mass half that of a proton, what energy would be created by converting its mass to energy? (d) Does this imply that space is "matter dominated"? Explain briefly.

87. (a) Use the Heisenberg uncertainty principle to calculate the uncertainty in energy for a corresponding time interval of 10^{-43} s. (b) Compare this energy with the 10^{19} GeV unification-of-forces energy and discuss why they are similar.