CHAPTER 52

PARTICLE PHYSICS AND COSMOLOGY

Particle physics deals with the very small. It asks questions about the structure of matter at its most fundamental or elementary level. From the debris of high-energy collisions, particle physicists have been able to create an enormous variety of new particles, study their properties, classify them into groups, and thus understand their internal structure. Cosmology deals with the very large—the origin and evolution of the universe. By studying the radiation that reaches us from throughout the universe, we can draw conclusions about how it was formed and what its future may be. It may seem surprising that we have grouped these two subjects together in one chapter. It turns out that they are closely related: what particle physicists learn about the properties of elementary particles tells us about the structure of the universe just after its birth, and conclusions by cosmologists can set limits on the varieties of particles that can exist and the interactions between them.

52-1 PARTICLE INTERACTIONS

There are tens of thousands of chemical compounds of varying degrees of complexity. Understanding this huge number of systems would be a hopeless task if it were not for the underlying simplicity of the 116 fundamental units (elements) of which these compounds are made and the relatively small number of types of bonds through which they can interact. To understand chemistry, we need not study the properties of tens of thousands of compounds, but only those of about 100 elements, along with a few basic types of bonds between them.

In fact, the task is even simpler. The 116 known elements can be classified into groups with similar properties: inert gases, halogens, alkali metals, transition metals, rare earths, and so forth. If we understand the properties of one member of a group, we can infer the properties of the other members of that group.

The subatomic world can be understood in a similar way. We know that the 116 different kinds of atoms are not fundamental units, but rather they are in turn composed of three different particles: protons, neutrons, and electrons. When we look still further, by smashing particles together at high energy and studying the debris of the collisions (see Fig. 52-1), we find what appears at first glance to be a complexity approaching that of chemistry: hundreds of different particles are produced. Yet when we look carefully we find that we can classify those particles into a few groups whose members have similar properties. Eventually we find that this classification leads to clues about the underlying substructure that is based again on a small number of truly fundamental particles and a small number of possible interactions among them.

The Four Basic Forces

All of the known forces in the universe can be grouped into four basic types. In order of increasing strength, these are: gravitation, the weak force, electromagnetism, and the strong force. These forces have important roles not only in the interactions between particles, but also in the decay of one particle into other particles.

1. *The gravitational force.* Gravity is of course exceedingly important in our daily lives, but on the scale

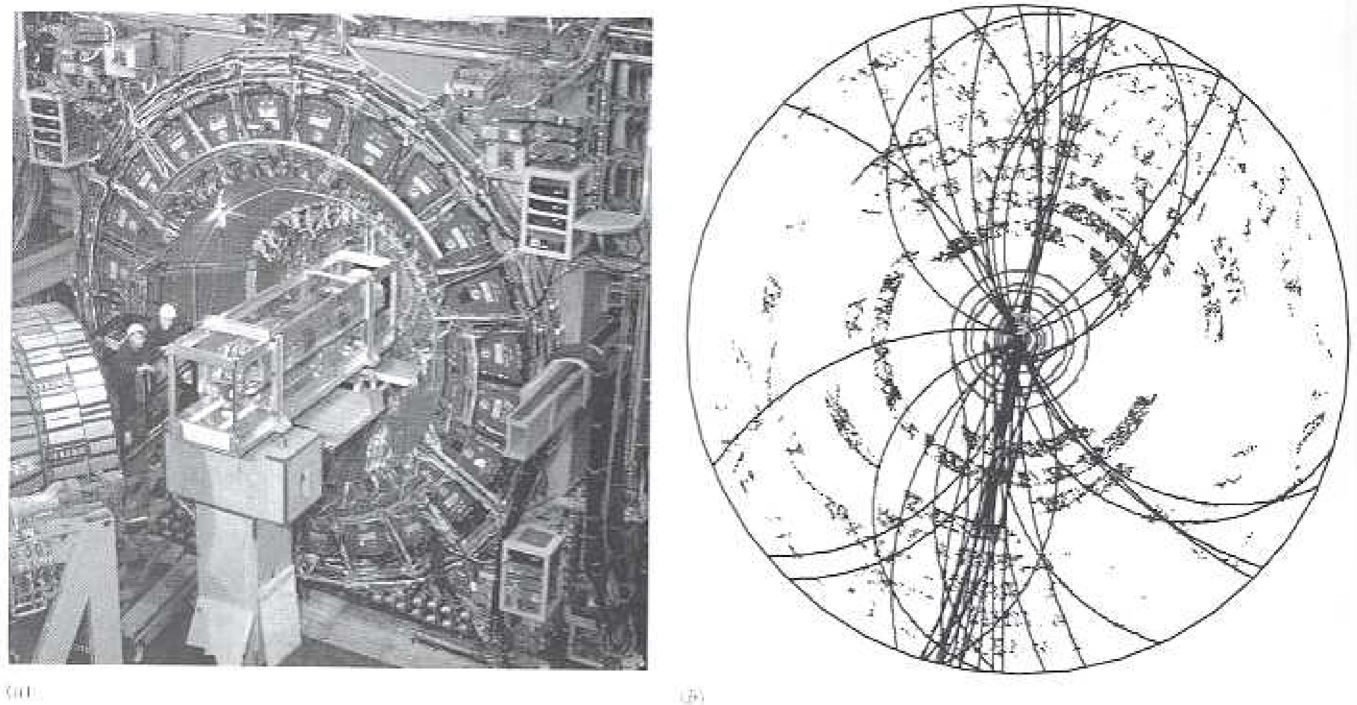

FIGURE 52-1. (*a*) The CDF detector system at Fermilab. Collisions between protons and antiprotons occur inside the detector and produce a multitude of particles: which are recorded and tracked by the detector. (*b*) An example of the trajectories of particles leaving the collision region as reconstructed by the detector. The curved paths are due to the presence of a magnetic field, which allows the momentum of the particles to be determined. For more information, see http://www-cdf.fnal.gov.

of fundamental interactions between particles in the subatomic realm, it is of no importance at all. To give a relative figure: the gravitational force between two protons just touching at their surfaces is about 10^{-38} of the strong force between them. The principal difference between gravitation and the other forces is that, on the practical scale, gravity is cumulative and infinite in range. For example, your weight is the cumulative effect of the gravitational force exerted by each atom of the Earth on each atom of your body.

2. *The weak force.* The weak force is responsible for nuclear beta decay (see Section 50-5) and other similar decay processes involving fundamental particles. It does not play a major role in the binding of nuclei. The weak force between two neighboring protons is about 10^{-7} of the strong force between them, and the range of the weak force is smaller than 1 fm. That is, at separations greater than about 1 fm, the weak force between particles is negligible. Nevertheless, the weak force is important in understanding the behavior of fundamental particles, and it is critical in understanding the evolution of the universe.

3. *The electromagnetic force.* Electromagnetism is important in the structure and the interactions of the fundamental particles. For example, some particles interact or decay primarily through this mechanism. Electromagnetic forces are of infinite range, but shielding generally diminishes their effect for ordinary objects. The properties of atoms and molecules are determined by electromagnetic forces, and many common macroscopic forces (such as friction, air resistance, drag, and tension) are ultimately due to the electromagnetic force. The electromagnetic force between neighboring protons is about 10^{-2} of the strong force, but within the nucleus the electromagnetic forces can act cumulatively because there is no shielding. As a result, the electromagnetic force can compete with the strong force in determining the stability and the structure of nuclei.

4. *The strong force.* The strong force, which is responsible for the binding of nuclei, is the dominant one in the reactions and decays of most of the fundamental particles. However, as we shall see, some particles (such as the electron) do not feel this force at all. It has a relatively short range, on the order of 1 fm.

The relative strength of a force determines the time scale over which it acts. If we bring two particles close enough together for any of these forces to act, then a longer time is required for the weak force to cause a decay or reaction than for the strong force. As we shall see, the mean lifetime of a decay process is often a signal of the type of interaction responsible for the process, with strong forces being at the shortest end of the time scale (often down to 10^{-23} s). Table 52-1 summarizes the four forces and some of their properties. The characteristic time for each force gives a typical range of time intervals observed for systems

TABLE 52-1 The Four Basic Forces

Type	*Range*	*Relative Strength*	*Characteristic Time*
Strong	1 fm	1	10^{-23} s
Electromagnetic	∞	10^{-2}	10^{-14}–10^{-20} s
Weak	$\ll$ 1 fm	10^{-7}	10^{-8}–10^{-13} s
Gravitational	∞	10^{-38}	Years

in which each force acts. Usually this is the typical lifetime of a particle that decays through that force.

Unification of Forces

One of the landmark achievements in the history of physics was the 19th century theory of electromagnetism, based on the theory of Maxwell and experiments by Faraday and Oersted showing that magnetic effects could produce electric fields and electrical effects could produce magnetic fields. The previously separate sciences of electricity and magnetism became linked under the common designation of electromagnetism. This linking was later shown to be a fundamental part of the special theory of relativity, according to which electric fields and magnetic fields can be transformed into one another due entirely to the relative motion of the observer.

In the 20th century, the attempt was made to carry this linking further to include other forces. First it was shown that electromagnetism and the weak force can be understood as two different aspects of the same force, called the *electroweak* force. If we study particle interactions at a high enough energy, these two forces behave similarly. It is convenient for us to regard them as separate forces for many of the effects we shall discuss, just as we often find it convenient to speak separately of electric and magnetic forces when we discuss electromagnetic phenomena. The theory of the electroweak force, which was proposed independently in 1967 by Stephen Weinberg and Abdus Salam (and for which they, along with Sheldon Glashow, another originator of the theory, received the 1979 Nobel Prize in physics), suggested that, just as the photon is the carrier of the electromagnetic force, there should be heavy particles that carry the weak force, and these new particles should, on an energy scale of 100 GeV (about 100 times the rest energy of the proton), behave similarly to a high-energy photon. In 1983, a research team at the European Center for Nuclear Physics (CERN), led by Carlo Rubbia and using experimental techniques developed by Simon van der Meer, discovered the predicted particles, now known as W^-, W^+, and Z^0, for which Rubbia and van der Meer were awarded the 1984 Nobel Prize in physics. The discovery of these particles provided the evidence for the unification of the electromagnetic and weak interactions into the electroweak interaction.

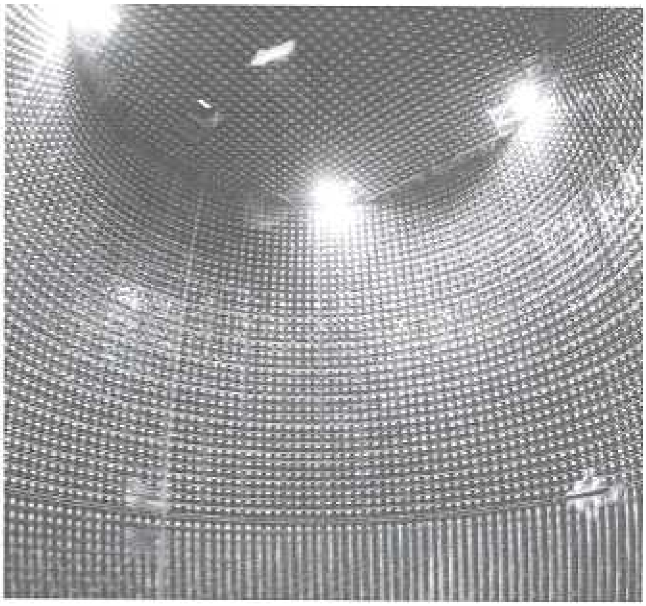

FIGURE 52-2. The Super-Kamiokande detector, located in Japan. The detector contains 32,000 tons of water. Decays of protons in the water molecules produce flashes of light, which are viewed by 11,200 photomultiplier tubes that can be seen lining the walls of the chamber. At right is a raft used by the researchers to service the tubes. The detector is also used to observe neutrinos emitted by the sun. See http://www-sk.icrr.u-tokyo.ac.jp.

Next the attempt was made to combine the strong and electroweak forces at a new higher level of unification. Theories that do so are called grand unified theories (GUTs), and at the present time there are many candidates for GUTs but none has as yet emerged as the correct one. Because the energy at which the forces merge is immense, perhaps 10^{15} GeV (10^{11} times the energy of the largest particle accelerator yet built or even contemplated), we cannot do experiments to test the GUTs directly. We must therefore rely on tests at obtainable energies, where the effects are exceedingly small. One prediction of these theories is that the proton should not be a stable particle but should decay on a time scale greater than 10^{31} years. (Compare this number with the age of the universe, about 10^{10} years.) Searches for proton decay have been made by looking for a characteristic light signal that would accompany the decay of one of the protons in a large volume of water (Fig. 52-2). So far such experiments have not observed proton decay, but they have placed a lower limit of 10^{33} years on the decay lifetime. These results exclude certain of the GUTs, and experiments continue to try to verify the theories.

The final step in the unification would be to include gravity in the scheme to create a *theory of everything* (TOE). There is not yet a quantum theory of gravity, so it is difficult to anticipate the form that these theories might take, but they nevertheless provide challenges for theoretical speculation.

SAMPLE PROBLEM 52-1. Suppose the half-life of the proton were 10^{31} y, as predicted by certain GUTs. (*a*) On the average, how long must we observe a liter of water before we would see one of its protons decay? (*b*) What volume of water would be required to have a proton decay rate of one per day?

Solution (*a*) A liter of water (approximately 1000 g) contains a number of molecules given by

$$\frac{(1000\ \mathrm{g})(6.02\times10^{23}\ \mathrm{molecules/mole})}{18\ \mathrm{g/mole}} = 3.3\times10^{25}\ \mathrm{molecules}.$$

Each molecule contains 10 protons (2 from the hydrogens and 8 from the oxygen), so that the number of protons in a liter of water is $N = 3.3\times10^{26}$. The decay rate R is given by Eq. 50-5 as

$$R = \lambda N = \frac{\ln 2}{t_{1/2}}N = \frac{0.693}{10^{31}\ \mathrm{y}}3.3\times10^{26}$$

$$= 2.3\times10^{-5}\ \mathrm{y}^{-1} = \frac{1}{43{,}000\ \mathrm{y}}.$$

That is, on the average we must wait for 43,000 years before a proton decay occurs in a liter of water.

(*b*) If $R = 1\ \mathrm{d}^{-1}$, we obtain

$$N = \frac{R}{\lambda} = \frac{1\ \mathrm{d}^{-1}}{0.693/(10^{31}\ \mathrm{y})} = 5.3\times10^{33}\ \mathrm{protons}$$

or 5.3×10^{32} molecules of water. This works out to be 1.6×10^{7} L, equivalent to a cube of water measuring 25 m on a side!

52-2 FAMILIES OF PARTICLES

We can learn a lot about things by classifying them. This is a technique used commonly by many scientists; for example, by grouping plants or animals into categories based on certain obvious features of their structure, biologists can form a basis for studying their behavior. From the scientific standpoint it may be more enlightening to compare one spider with another spider than with a fly or a moth. Part of the training of a scientist is concerned with learning how to make and to use these classifications.

The earliest classification scheme for particles was based on their masses. The lightest particles, including the electron ($m_ec^2 = 0.511$ MeV), were called *leptons* (from the Greek word for "small"). The heaviest particles, including the proton ($m_pc^2 = 938$ MeV), were called *baryons* (from the Greek word for "heavy"). In between were particles, including the pion ($m_\pi c^2 = 140$ MeV), called *mesons* (from the Greek word for "middle"). Today these classifications based on mass are no longer valid; for example, one lepton and many mesons are more massive than the proton. However, we retain these three names as descriptive of particles with similar properties, even though the classification based only on mass is no longer valid. Table 52-2 summarizes these three families of particles and some of their properties.

Leptons

The leptons are fundamental particles that interact only through the weak and electromagnetic interactions; even though the strong force can exceed the weak or electromagnetic force in strength by many orders of magnitude, the leptons do not feel this force at all. The leptons are true fundamental particles: they have no internal structure and are not composed of other, still smaller particles. We can consider the leptons to be point particles with no finite dimensions. All known leptons have a spin of $\frac{1}{2}$.

Table 52-3 shows the six leptons, which appear as three pairs of particles. Each pair includes a charged particle (e^-, μ^-, τ^-) and an uncharged neutrino (ν_e, ν_μ, ν_τ). We discussed the electron neutrino previously in connection with beta decay (Section 50-5). Both the charged leptons and the neutrinos have antiparticles.

Electron neutrinos and antineutrinos are produced in the beta decay (Section 50-5) of radioactive elements. They are also produced in great quantity in solar fusion processes; large underground detectors, such as that shown in Fig. 52-2, have been constructed to observe solar neutrinos and measure their properties. Because neutrinos interact only very weakly with matter, the solar neutrinos come to us directly from the core of the Sun, where the fusion reactions take place. (The photons from the Sun, on the other hand, come to us from its surface and therefore carry no direct information about fusion processes in the core.) Experiments have been underway for the past 40 years to count these solar neutrinos; the results of these experiments indicate that only about one-third to one-half of the expected number are reaching the Earth. Neutrinos are also produced in intense bursts from supernovas; the first such observation of supernova neutrinos was made in 1987 (Fig. 52-3).

Some theories of the properties of the neutrinos require that the neutrinos are massless, like the photon. Other theories allow a small but definitely nonzero mass. Measuring a small neutrino mass, especially for the electron neutrino, is

TABLE 52-2 Three Families of Particles

Family	*Structure*	*Interactions*	*Spin*	*Examples*
Leptons	Fundamental	Weak, electromagnetic	Half integral	e,ν
Mesons	Composite	Weak, electromagnetic, strong	Integral	π,K
Baryons	Composite	Weak, electromagnetic, strong	Half integral	p,n

TABLE 52-3 The Lepton Family

Particle	*Antiparticle*	*Particle Charge (e)*	*Spin ($h/2\pi$)*	*Rest Energy (MeV)*	*Mean Life (s)*	*Typical Decay Products*
e^-	e^+	-1	$\frac{1}{2}$	0.511	∞	—
ν_e	$\bar{\nu}_e$	0	$\frac{1}{2}$	<0.000015	∞	—
μ^-	μ^+	-1	$\frac{1}{2}$	105.7	2.2×10^{-6}	$e^- + \bar{\nu}_e + \nu_\mu$
ν_μ	$\bar{\nu}_\mu$	0	$\frac{1}{2}$	<0.19	∞	—
τ^-	τ^+	-1	$\frac{1}{2}$	1777	2.9×10^{-13}	$\mu^- + \bar{\nu}_\mu + \nu_\tau$
ν_τ	$\bar{\nu}_\tau$	0	$\frac{1}{2}$	<18	∞	—

a challenging experimental problem. So far the best experimental upper limit on the rest energy of the electron neutrino, about 15 eV, comes from the beta decay of ^{3}H. By comparing the arrival time of the neutrino burst from Supernova 1987A (Fig. 52-3) with the arrival time of the light signal from the supernova, a similar upper limit of about 20 eV was estimated.

If neutrinos do have mass, then they are permitted to transform from one type to another, such as electron neutrinos to muon neutrinos. This transformation, called *neutrino oscillation*, has not yet been seen directly, but it has been suspected as an explanation of the reduction in the number of electron neutrinos reaching us from the Sun. In 1999, the detector shown in Fig. 52-2 produced the first evidence for neutrino oscillations—the number of muon neutrinos (produced in the atmosphere by collisions of energetic cosmic rays with air molecules) coming down from above differed from the number coming up from below (that is, traveling through the Earth). This discrepancy could not be explained simply by absorption during passage through the Earth, because the neutrinos have a mean free path in matter that is measured in light-years, so they have almost no chance of being absorbed in passing through the Earth. Currently there are many experiments underway to measure neutrino masses, partly to achieve a better understanding of the properties of the neutrinos, but also because of the implications of a nonzero neutrino mass for cosmology, as we discuss later in this chapter.

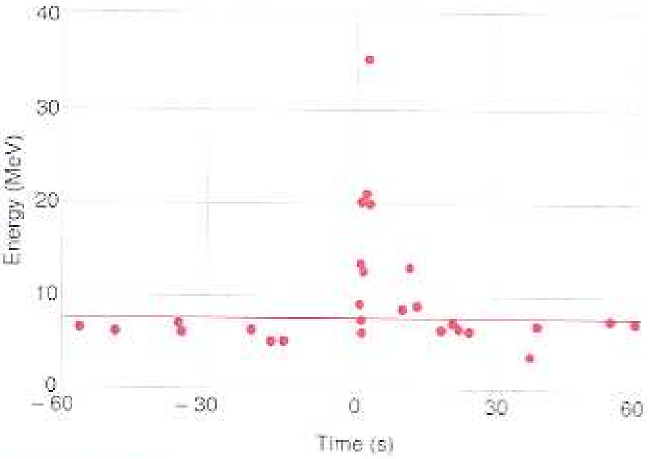

FIGURE 52-3. Evidence for a burst of neutrinos from the supernova SN 1987A.

The electron is a stable particle, but the muon and tau decay to other leptons, according to

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad (\text{mean life} = 2.2 \times 10^{-6}\ \text{s}),$$
$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \qquad (\text{mean life} = 2.9 \times 10^{-13}\ \text{s}).$$

These decays are caused by the weak interaction, as we can conclude from the presence of neutrinos (which *always* indicates a weak interaction process) among the decay products and as we infer from comparing the decay lifetimes to the characteristic times listed in Table 52-1. The form of these decays can be understood based on a conservation law for leptons discussed in Section 52-3.

Mesons

Mesons are strongly interacting particles having integral spin. A partial list of some mesons is given in Table 52-4. Generally, mesons are produced in reactions by the strong interaction; they decay, usually to other mesons or leptons, through the strong, electromagnetic, or weak interactions. For example, pions can be produced in reactions of nucleons, such as

$$p + n \to p + p + \pi^- \quad \text{or} \quad p + n \to p + n + \pi^0,$$

and the pions can decay according to

$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad (\text{mean life} = 2.6 \times 10^{-8}\ \text{s}),$$
$$\pi^0 \to \gamma + \gamma \qquad (\text{mean life} = 8.4 \times 10^{-17}\ \text{s}),$$

where the first decay occurs due to the weak interaction (indicated by the neutrinos and suggested by the mean life) and the second due to the electromagnetic interaction (indicated by the photons and suggested by the mean life).*

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*Although neutrinos always indicate a weak-interaction decay, not all weak-interaction decays produce neutrinos. The same is true for photons in electromagnetic decays.

TABLE 52-4 Some Selected Mesons

Particle	*Antiparticle*	*Charge*[a] *(e)*	*Spin* *(h/2π)*	*Strangeness*[a]	*Rest Energy* *(MeV)*	*Mean Life* *(s)*	*Typical Decay Products*
π^+	π^-	+1	0	0	140	2.6×10^{-8}	$\mu^+ + \nu_\mu$
π^0	π^0	0	0	0	135	8.4×10^{-17}	$\gamma + \gamma$
K^+	K^-	+1	0	+1	494	1.2×10^{-8}	$\mu^+ + \nu_\mu$
K^0	$\bar{K}^0$	0	0	+1	498	0.9×10^{-10}	$\pi^+ + \pi^-$
η	η	0	0	0	547	5.5×10^{-19}	$\gamma + \gamma$
ρ^+	ρ^-	+1	1	0	770	4.4×10^{-24}	$\pi^+ + \pi^0$
η'	η'	0	0	0	958	2.2×10^{-21}	$\eta + \pi^+ + \pi^-$
D^+	D^-	+1	0	0	1869	1.1×10^{-12}	$K^- + \pi^+ + \pi^+$
ψ	ψ	0	1	0	3097	7.6×10^{-21}	$e^+ + e^-$
B^+	B^-	+1	0	0	5279	1.6×10^{-12}	$D^- + \pi^+ + \pi^+$
Υ	Υ	0	1	0	9460	1.3×10^{-20}	$e^+ + e^-$

[a] The charge and strangeness are those of the particle. Values for the antiparticle have the opposite sign. The spin, rest energy, and mean life are the same for a particle and its antiparticle.

Baryons

Baryons are strongly interacting particles having half-integral spins ($\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$). A partial listing of some baryons is given in Table 52-5. The familiar members of the baryon family are the proton and neutron. Baryons have distinct antiparticles—for example, the antiproton ($\bar{p}$) and antineutron ($\bar{n}$).

We can produce heavier baryons in reactions between nucleons, such as

$$p + p \rightarrow p + \Lambda^0 + K^+,$$

which produces the Λ^0 baryon and the K^+ meson. The Λ^0 decays according to

$$\Lambda^0 \rightarrow p + \pi^- \qquad (\text{mean life} = 2.6 \times 10^{-10}\ \text{s}).$$

Although there are no neutrinos produced in the decay, the mean life indicates that the decay is governed by the weak interaction. We shall learn the reason for this "slow" decay in Section 52-3.

Field Particles and Exchange Forces

There is one additional small family of particles that cannot be classified among the leptons, mesons, or baryons. These are the *field particles*, those responsible for carrying the forces with which the particles interact.

Newton's law of gravitation and Coulomb's law of electrostatics were originally based on the concept of "action at a distance." Later, in the nineteenth century, this concept

TABLE 52-5 Some Selected Baryons

Particle	*Antiparticle*	*Charge*[a] *(e)*	*Spin* *(h/2π)*	*Strangeness*[a]	*Rest Energy* *(MeV)*	*Mean Life* *(s)*	*Typical Decay Products*
p	$\bar{p}$	+1	$\frac{1}{2}$	0	938	∞	
n	$\bar{n}$	0	$\frac{1}{2}$	0	940	887	$p + e^- + \bar{\nu}_e$
Λ^0	$\bar{\Lambda}^0$	0	$\frac{1}{2}$	−1	1116	2.6×10^{-10}	$p + \pi^-$
Σ^+	$\bar{\Sigma}^-$	+1	$\frac{1}{2}$	−1	1189	0.8×10^{-10}	$p + \pi^0$
Σ^0	$\bar{\Sigma}^0$	0	$\frac{1}{2}$	−1	1193	7.4×10^{-20}	$\Lambda^0 + \gamma$
Σ^-	$\bar{\Sigma}^+$	−1	$\frac{1}{2}$	−1	1197	1.5×10^{-10}	$n + \pi^-$
Ξ^0	$\bar{\Xi}^0$	0	$\frac{1}{2}$	−2	1315	2.9×10^{-10}	$\Lambda^0 + \pi^0$
Ξ^-	$\bar{\Xi}^+$	−1	$\frac{1}{2}$	−2	1321	1.6×10^{-10}	$\Lambda^0 + \pi^-$
Δ^*	$\bar{\Delta}^*$	+2, +1, 0, −1	$\frac{3}{2}$	0	1232	5.9×10^{-24}	$p + \pi$
Σ^*	$\bar{\Sigma}^*$	+1, 0, −1	$\frac{3}{2}$	−1	1385	1.8×10^{-23}	$\Lambda^0 + \pi$
Ξ^*	$\bar{\Xi}^*$	−1, 0	$\frac{3}{2}$	−2	1530	7.3×10^{-23}	$\Xi + \pi$
Ω^-	$\bar{\Omega}^-$	−1	$\frac{3}{2}$	−3	1672	8.2×10^{-11}	$\Lambda^0 + K^-$
Λ_c^+	$\bar{\Lambda}_c^-$	+1	$\frac{1}{2}$	0	2285	2.1×10^{-13}	$p + K^- + \pi^+$
Λ_b^0	$\bar{\Lambda}_b^0$	0	$\frac{1}{2}$	0	5624	1.2×10^{-12}	$p + D^0 + \pi^-$

[a] The charge and strangeness are those of the particle. Values for the antiparticle have the opposite sign. The spin, rest energy, and mean life are the same for a particle and its antiparticle.

TABLE 52-6 The Field Particles

Particle	*Symbol*	*Interaction*	*Charge (e)*	*Spin ($h/2\pi$)*	*Rest Energy (GeV)*
Graviton		Gravitation	0	2	0
Weak boson	W^+, W^-	Weak	± 1	1	80.4
Weak boson	Z^0	Weak	0	1	91.2
Photon	γ	Electromagnetic	0	1	0
Gluon	g	Strong (color)	0	1	0

was replaced by the notion of a field. Two particles interact through the fields that they establish: one particle sets up a field, and the other interacts with that field rather than directly with the first particle. Quantum field theory takes this notion one step further by supposing that the fields are carried by quanta. In this view, instead of the first particle setting up the field, we say that it emits quanta of the field. The second particle then absorbs these quanta. For example, the electromagnetic interaction between two particles can be viewed in terms of the emission and absorption of photons, which are quanta of the electromagnetic field. Each type of field has its characteristic field particles. A list of the particles associated with the four basic forces can be found in Table 52-6.

A force accomplished through the exchange of particles is called an *exchange force*. For example, the force between two nucleons in a nucleus takes place through the exchange of pions. In this case the pions, along with other mesons, can act as field particles associated with the strong force between nucleons.

How is it possible for a particle, such as a proton, to emit another particle with nonzero mass and still remain a proton? This process seems to violate conservation of energy. The solution to this dilemma lies in the energy–time form of the uncertainty relationships. The uncertainty principle is a fundamental limitation on our ability to measure a system. That is, if we observe a system for a time interval Δt, there is a corresponding uncertainty ΔE in its energy, according to Eq. 46-9, given at minimum by

$$\Delta E = \frac{h}{2\pi\,\Delta t}. \tag{52-1}$$

We cannot know the energy of a system more precisely than this ΔE unless we measure for a time longer than Δt. If we observe only for a very short time, the uncertainty in the rest energy of a proton can be at least as large as the rest energy of a pion, as the following sample problem demonstrates.

SAMPLE PROBLEM 52-2. (*a*) What is the longest interval of time for which we can observe a proton for the uncertainty in its rest energy to be equal to the pion rest energy? (*b*) What is the greatest distance the pion can travel in that time?

Solution (*a*) For the proton's rest energy to be uncertain by an amount $\Delta E = m_\pi c^2$, the observation time interval can, according to Eq. 52-1, be at most

$$\begin{aligned}\Delta t &= \frac{h}{2\pi\,\Delta E} = \frac{h}{2\pi m_\pi c^2}\\ &= \frac{4.14\times10^{-15}\ \mathrm{eV\cdot s}}{(2\pi)(140\ \mathrm{MeV})} = 4.7\times10^{-24}\ \mathrm{s}.\end{aligned}$$

In a time interval shorter than 4.7×10^{-24} s, a proton can emit and absorb a pion without our observing a violation of conservation of energy.

(*b*) If the pion travels at nearly the speed of light, the maximum distance d it can travel in this time interval is

$$\begin{aligned}d &= c\,\Delta t = (3.00\times10^{8}\ \mathrm{m/s})(4.7\times10^{-24}\ \mathrm{s})\\ &= 1.4\times10^{-15}\ \mathrm{m} = 1.4\ \mathrm{fm}.\end{aligned}$$

This distance defines the *range* of the nuclear force. Two nucleons closer than about 1.4 fm can interact through the exchange of pions. If the nucleons are separated by a greater distance, pion exchange cannot operate, and there is no nuclear force.

52-3 CONSERVATION LAWS

We would have a difficult time analyzing physical processes without the laws of conservation of energy and linear and angular momentum. These conservation laws help us understand why certain outcomes occur (such as in the case of the collisions that we considered in Chapter 6). They also help us understand why certain processes (those that violate the conservation laws) are never observed. In one sense they are empirical laws, deduced from observing physical processes and carefully tested in the laboratory. In another sense they reveal to us fundamental aspects of the laws of nature.

An example of a conservation law is the conservation of electric charge. By observing the outcomes of many processes, we are led to propose this law: the net amount of electric charge must not change in any process. Equivalently, we may say that the net charge before a particular reaction or decay must equal the net charge after the reaction or decay. No violation of this law has ever been observed, even though it has been carefully tested (see Section 25-6).

Conservation of Lepton Number

In reactions and decays of fundamental particles, we often find a certain set of outcomes but fail to observe a set of related outcomes that would otherwise be expected to occur.

When this happens, we suspect that there is some unknown conservation law at work that permits the first set and forbids the second. For example, we can produce an electron neutrino when a proton captures an electron:

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

We always find neutrinos in this process, but we never observe antineutrinos. Furthermore, the reaction always produces electron neutrinos and never muon or tau neutrinos.

We account for the failure to observe certain processes by proposing a conservation law for *lepton number* that is similar to the conservation law for electric charge. To each lepton we assign a lepton number +1 and to each antilepton we assign a lepton number −1. All other particles have lepton numbers of 0. The law of conservation of lepton number then states:

> *In any process, the lepton number for electron-type leptons, muon-type leptons, and tau-type leptons must each remain constant.*

As far as we know, the law of lepton conservation is strictly valid; despite careful experimental searches for violations, none has yet been found.

In the electron capture process, we assign an electron lepton number L_e of +1 to the electron and to the electron neutrino, whereas $L_e = 0$ for the proton and neutron. This process then has $L_e = +1$ on both sides and upholds the law of conservation of lepton number. If an electron *antineutrino* were produced, the right side would have $L_e = -1$, and the law would be violated. This accounts for our failure to observe this process. If another type of neutrino—for example, a muon neutrino—were produced, the process would have $L_e = -1$ on the left and $L_e = 0$ on the right. Furthermore, it would have $L_\mu = 0$ on the left and $L_\mu = +1$ on the right. The process would therefore violate conservation of both electron and muon lepton numbers, and it has never been observed.

Through the law of lepton conservation, we can account for many experimental observations. Like other conservation laws, this law proves to be of great value in analyzing decays and reactions.

SAMPLE PROBLEM 52-3. Use lepton number conservation to determine the identity of particle X in the following decay: $\mu^+ \rightarrow e^+ + \nu_e + X$.

Solution We assign electron-type lepton number L_e and muon-type lepton number L_μ to the particles as follows:

$$\begin{array}{lcccc} & \mu^+ \rightarrow & e^+ + & \nu_e + & X \\ L_e: & 0 & -1 & +1 & ? \\ L_\mu: & -1 & 0 & 0 & ? \end{array}$$

Note that electron-type leptons are assigned $L_\mu = 0$ and muon-type leptons are assigned $L_e = 0$.

Conservation of lepton number means that the net electron-type lepton number must be the same before and after the decay, and similarly for the muon-type lepton number. The electron-type lepton number is 0 before the decay and so must be 0 after the decay, which requires that particle X have $L_e = 0$. The muon-type lepton number is −1 before the decay and to make the net muon-type lepton number equal −1 after the decay, particle X must have $L_\mu = -1$.

Particle X must therefore be a lepton with $L_e = 0$ and $L_\mu = -1$. Because the other particles in the decay already satisfy conservation of electron charge, particle X must be uncharged. A glance at Table 52-3 shows that the only particle with these characteristics is the muon-type antineutrino $\bar{\nu}_\mu$.

Conservation of Baryon Number

A similar conservation law occurs in the case of baryons. To each baryon, such as the proton or neutron, we assign a baryon number B of +1, and we assign $B = -1$ to antibaryons such as the antiproton. The law of conservation of baryon number then states:

> *In any process, the total baryon number must remain constant.*

No violation of this law has yet been observed. (However, certain speculative theories, the GUTs discussed in Section 52-1, suggest that the proton can decay into nonbaryons, which would violate the law of conservation of baryon number. This decay has never been observed; if it were observed, the law of conservation of baryon number would need to be changed accordingly.)

Consider, for example, the reaction in which antiprotons are produced when a proton beam is incident on a target of protons:

$$\begin{array}{lcccccc} & p + & p \rightarrow & p + & p + & p + & \bar{p} \\ B: & +1 & +1 & +1 & +1 & +1 & -1 \end{array}$$

In this reaction, the net baryon number is +2 on both the left and the right sides.

Contrary to the case of lepton number, there is only one type of baryon number. The law of conservation of baryon number is a more general version of the rule we used in analyzing nuclear processes in Chapters 50 and 51; there we kept the total of neutrons plus protons constant in all decays and reactions, which, because neutrons and protons are baryons, is equivalent to conserving the total number of baryons.

Even though there are conservation laws for two types of particles (leptons and baryons), there is no conservation law for mesons. For example, in a reaction of protons on protons, any number of mesons can be produced (as long as the incident particles have enough kinetic energy):

$$p + p \rightarrow p + n + \pi^+,$$

$$p + p \rightarrow p + p + \pi^+ + \pi^-,$$

$$p + p \rightarrow p + n + \pi^+ + \pi^0 + \pi^0.$$

Note the conservation of electric charge in these processes.

Strangeness

There are still other processes that are difficult to understand based only on the conservation laws we have discussed so far. For example, consider the group of kaons (K mesons), which in many respects are similar to the pions. Because there is no conservation law for mesons, we might expect that any number of kaons can be produced in reactions. What we instead find is that kaons are either produced in pairs, for example,

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{K}^+ + \mathrm{K}^-,$$
$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{n} + \mathrm{K}^+ + \overline{\mathrm{K}^0},$$

or if a single kaon is produced, it is always accompanied by another "strange" particle, for example, a Λ^0,

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \Lambda^0 + \mathrm{K}^+.$$

We account for these processes (and the failure to observe others that appear to be permitted by the previously known conservation laws) by assigning to particles a new quantum number called *strangeness*, which is found to follow a new conservation law, called *conservation of strangeness*. Two kaons (K^+ and K^0) are assigned to have strangeness $S = +1$, and the other two (K^- and $\overline{\mathrm{K}^0}$) are assigned $S = -1$. All nonstrange particles (such as p, n and e) have $S = 0$. The reactions in which two kaons are produced then have $S = 0$ on the left (only nonstrange particles) and also $S = 0$ on the right. The Λ^0 baryon is assigned $S = -1$, so the reaction in which $\Lambda^0 + \mathrm{K}^+$ is produced also has $S = 0$ on both sides.

When we analyze the decays of the strange particles, the conservation of strangeness appears occasionally to break down. The kaons can decay into two (nonstrange) pions, for example,

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

Here we have $S = +1$ on the left and $S = 0$ on the right, a clear violation of the conservation of strangeness. We get a clue about how to resolve this difficulty when we measure the lifetime for this decay, which turns out to be about 10^{-8} s. The kaons and pions are strongly interacting particles, and we would expect this decay to occur with a typical strong interaction lifetime in the range of 10^{-23} s (see Table 52-1). Instead, it is slowed by 15 orders of magnitude! What could be responsible for slowing this decay?

Another clue comes from the more commonly observed decay mode of the K^+:

$$\mathrm{K}^+ \rightarrow \mu^+ + \nu_{\mu},$$

a weak-interaction process, for which the mean life of 10^{-8} s would not be unusual. It appears that *the weak interaction can change strangeness* by one unit. In either of these kaon decay modes, we have S changing by one unit. Even though it does not produce the neutrinos that usually characterize a weak-interaction process, the decay $\mathrm{K}^+ \rightarrow \pi^+ + \pi^0$ is governed by the weak interaction. In this case, the strangeness violation is a clue that it cannot be a strong-interaction process (strangeness is conserved in all strong interactions), and it must therefore be a weak-interaction decay.

Does the electromagnetic interaction conserve strangeness? To answer this question, we look for strangeness-violating electromagnetic decays, such as $\Lambda^0 \rightarrow \mathrm{n} + \gamma$. This decay apparently does not occur, and so we conclude that *the electromagnetic interaction conserves strangeness.*

We can summarize these results in the law of conservation of strangeness:

> *In processes governed by the strong or electromagnetic interactions, the total strangeness must remain constant. In processes governed by the weak interaction, the total strangeness either remains constant or changes by one unit.*

SAMPLE PROBLEM 52-4. The Ω^- baryon has $S = -3$. (*a*) It is desired to produce the Ω^- using a beam of K^- incident on protons. What other particles are produced in this reaction? (*b*) How might the Ω^- decay?

Solution (*a*) Reactions usually proceed only through the strong interaction, which conserves strangeness. We consider the reaction

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

On the left side, we have $S = -1$, $B = +1$, and $Q = 0$. On the right side, we have $S = -3$, $B = +1$, and $Q = -1$. We must therefore add to the right side particles with $S = +2$, $B = 0$, and $Q = +1$. Scanning through the tables of mesons and baryons, we find that we can satisfy these criteria with K^+ and K^0, so the reaction is

$$\mathrm{K}^- + \mathrm{p} \rightarrow \Omega^- + \mathrm{K}^+ + \mathrm{K}^0.$$

(*b*) The Ω^- cannot decay by the strong interaction, because no $S = -3$ final states are available. It must therefore decay to particles having $S = -2$ through the weak interaction, which can change S by one unit. One of the product particles must be a baryon in order to conserve baryon number. Two possibilities are

$$\Omega^- \rightarrow \Lambda^0 + \mathrm{K}^- \quad \text{and} \quad \Omega^- \rightarrow \Xi^0 + \pi^-.$$

52-4 THE QUARK MODEL

Decays and reactions involving mesons and baryons are subject to conservation laws involving two quantities: the electric charge Q and the strangeness S. It then makes sense to ask whether there is any connection between the electric charge and the strangeness of a particle. In a particular group of similar particles (the spin-0 mesons or the spin-$\frac{1}{2}$ baryons, for example), do we find all possible combinations of Q and S or only certain ones? Finding only a restricted set of combinations suggests that the particles are built according to a set of rules out of more fundamental units whose electric charge and strangeness have certain values.

To begin to answer the question about the possible internal structure of particles, we examine the connection between electric charge and strangeness by making a plot showing electric charge on one axis and strangeness on

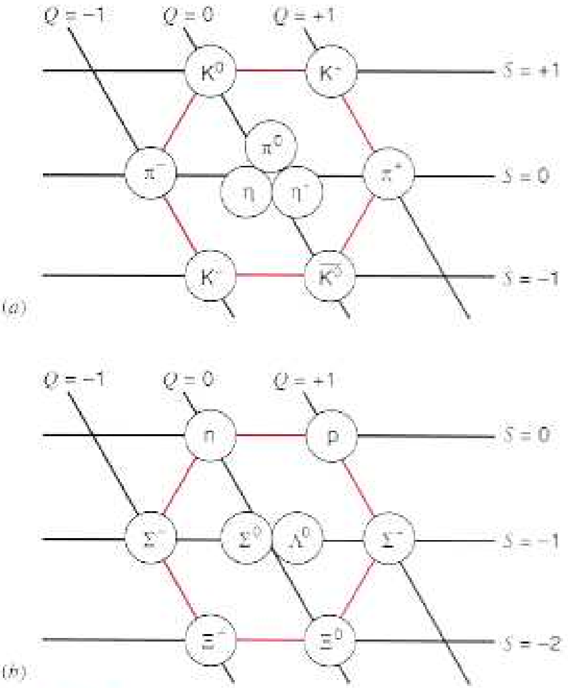

FIGURE 52-4. A chart showing *(a)* the spin-0 mesons and *(b)* the spin-$\frac{1}{2}$ baryons. Each particle is located on a grid according to its strangeness S and electric charge Q. The grid lines for electric charge have been drawn obliquely so that the patterns appear more symmetric.

another. Placing a group of nine of the spin-0 mesons (from Table 52-4) on this grid, we obtain Fig. 52-4*a*; doing the same for the spin-$\frac{1}{2}$ baryons (Table 52-5), we obtain Fig. 52-4*b*. The regularity of these patterns suggests that there may be an underlying common structure to these particles.

In 1964, it was suggested independently by Murray Gell-Mann and George Zweig that these regular patterns could be explained if it were assumed that the mesons and baryons are composed of a set of more fundamental particles called *quarks*. The original model proposed by Gell-Mann and Zweig consisted of three quarks, which are called up (u), down (d), and strange (s), along with their antiparticles (the antiquarks $\bar{\text{u}}$, $\bar{\text{d}}$, and $\bar{\text{s}}$). Their properties are listed in Table 52-7. Later it was discovered that three quarks are not sufficient to explain the properties of all mesons and baryons; a total of six quarks is needed, as we discuss below.

The quarks have two very unusual properties that make them different from other particles: (1) They have fractional electric charges, equal to (in units of the elementary charge e) $+\frac{2}{3}$ for the u quark and $-\frac{1}{3}$ for the d and s quarks. No other particle has a fractional electric charge, and no experiment has ever confirmed the existence of free particles with fractional charge. (2) The quarks also have fractional baryon numbers; all known free particles have baryon numbers of $+1$ (for baryons), -1 (for antibaryons), or 0 (for nonbaryons such as mesons or leptons). The electric charge and the baryon number for antiquarks have the same magnitude but the opposite sign as the values for the corresponding quark.

The quarks all have a spin of $\frac{1}{2}$, which means that (according to the rules for combining spins in quantum mechanics) combinations of two quarks (or a quark and an antiquark) can have a total spin of 0 or 1, and combinations of three quarks can have a total spin of $\frac{1}{2}$ or $\frac{3}{2}$. For the lighter mesons and baryons discussed here, we assume that the combinations of quarks have no orbital angular momentum; that is, in the language of Chapter 48, they combine in s states ($l = 0$). There are indeed combinations of quarks that involve p states ($l = 1$) or d states ($l = 2$), but they are more massive than the particles we are considering.

According to this model, the mesons are composed of a quark and an antiquark, and the baryons are composed of three quarks. Consider the combination $\text{u}\bar{\text{d}}$ of an up quark and an antidown quark, such that their two spins add to 0. The charge of the up quark (in units of e) is $+\frac{2}{3}$, and the charge of the antidown quark is $+\frac{1}{3}$ (the charge of an antiparticle is opposite to that of the particle). The combination $\text{u}\bar{\text{d}}$ has $Q = +1$, $S = 0$ (because both quarks have $S = 0$), and $B = 0$ (because the quark has $B = +\frac{1}{3}$ and the antiquark has $B = -\frac{1}{3}$). This combination has the same quantum numbers as the π^+ meson. Continuing in this way, we find nine possible combinations of a quark and an antiquark, which are listed in Table 52-8. These nine combinations exactly reproduce the electric charge and strangeness combinations of the spin-0 mesons.

Baryons are composed of three quarks. Since each of the quarks has a baryon number of $+\frac{1}{3}$, the total baryon number of these composite particles will be $+1$, as we expect for baryons. Consider for example the combination uud with spin $\frac{1}{2}$. The total electric charge is $Q = +\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$, and the total strangeness is 0. This matches the properties of the proton. There are a total of nine possible combinations of three quarks, which are listed in Table 52-9 along with the identification of the corresponding baryon from Table 52-5. Once again, the model has successfully accounted for the properties of this group of particles. Similar success is obtained with the spin-$\frac{3}{2}$ baryons (see Exercises 14 and 15).

TABLE 52-7 Properties of Three Quarks

Quark	*Symbol*	*Antiquark*	*Charge*[a] (e)	*Spin* $(h/2\pi)$	*Baryon Number*[a]	*Strangeness*[a]
Up	u	$\bar{\text{u}}$	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	0
Down	d	$\bar{\text{d}}$	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	0
Strange	s	$\bar{\text{s}}$	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	-1

[a] The values for charge, baryon number, and strangeness refer to the quarks. Values for the antiquarks have opposite signs.

TABLE 52-8 Quark–Antiquark Combinations

Combination	*Charge (e)*	*Baryon Number*	*Strangeness*	*Identity*
$u\bar{u}$	0	0	0	π^0, η, η'
$d\bar{d}$	0	0	0	
$s\bar{s}$	0	0	0	
$u\bar{d}$	+1	0	0	π^+
$u\bar{s}$	+1	0	+1	K^+
$d\bar{u}$	−1	0	0	π^-
$d\bar{s}$	0	0	+1	K^0
$s\bar{u}$	−1	0	−1	K^-
$s\bar{d}$	0	0	−1	$\bar{K}^0$

The quark model does far more than reproduce the simple geometrical patterns of Fig. 52-4. You should think of these patterns as ways of organizing particles with similar properties, just as the periodic table allows us to organize atoms with similar properties. Underlying the periodic table is atomic theory, which can be used to calculate properties of atoms beyond their geometrical arrangements. In a similar way, the quark model allows us to calculate properties of particles, including masses, magnetic dipole moments, decay modes, lifetimes, and reaction products. The agreement between the measured and calculated properties has been a spectacular success for the model. In fact, all known particles (hundreds of them!) have been accounted for based on this model, with a few additional quarks that we describe later.

The most unusual aspect of the quark model is the fractional electric charges of the quarks. All particles yet discovered have electric charges that can be expressed as integral multiples of the basic unit of charge e. No particle with a fractional electric charge has ever been seen. In fact, no one has ever seen a free quark, despite heroic experimental efforts to search for one. It is possible that our particle accelerators do not yet have enough energy to produce a free quark. It has also been suggested that free quarks may be forbidden to exist, so we may only observe quarks bound in mesons and baryons.

Even though free quarks have never been seen, individual *bound* quarks have been observed. Scattering experiments that probe deep inside the nucleon have revealed three pointlike objects that appear to have a spin of $\frac{1}{2}$ and a charge of $+\frac{2}{3}$ or $-\frac{1}{3}$. These experiments give direct proof of the existence of quarklike particles within the nucleon.

The Interaction between Quarks

What holds the quarks together inside a meson or a nucleon? This force is the most fundamental version of the strong force, brought about through the exchange of particles called *gluons*. Just as the electromagnetic interaction between charged particles can be regarded as an exchange of photons, the strong interaction between quarks is accomplished through the exchange of gluons. We therefore picture a nucleon as composed of three quarks mutually exchanging gluons.

The interaction between quarks has two unusual properties: (1) It takes a large (perhaps infinite) energy to separate two quarks to a distance greater than the size of a nucleon or a meson (about 1 fm). This may be the reason that no free quarks have yet been seen. When we try to pump energy into a nucleon to separate one of its quarks, the energy actually creates a quark–antiquark pair. The antiquark combines with one of the quarks to form a meson, which agrees with our

TABLE 52-9 Combinations of Three Quarks

Combination	*Charge (e)*	*Spin (h/2π)*	*Baryon Number*	*Strangeness*	*Spin $\frac{1}{2}$ Identity*
uuu	+2	$\frac{3}{2}$	+1	0	—
uud	+1	$\frac{3}{2}, \frac{1}{2}$	+1	0	p
udd	0	$\frac{3}{2}, \frac{1}{2}$	+1	0	n
uus	+1	$\frac{3}{2}, \frac{1}{2}$	+1	−1	Σ^+
uss	0	$\frac{3}{2}, \frac{1}{2}$	+1	−2	Ξ^0
uds	0	$\frac{3}{2}, \frac{1}{2}, \frac{1}{2}$	+1	−1	Λ^0, Σ^0
ddd	−1	$\frac{3}{2}$	+1	0	—
dds	−1	$\frac{3}{2}, \frac{1}{2}$	+1	−1	Σ^-
dss	−1	$\frac{3}{2}, \frac{1}{2}$	+1	−2	Ξ^-
sss	−1	$\frac{3}{2}$	+1	−3	—

observations: when we smash two nucleons together at high energies, we get our nucleons (or other baryons) back, plus some additional mesons. The more energy we put in, the more mesons we get out, but no free quark emerges. (2) Paradoxically, inside the nucleon or the meson, the quarks appear to move freely. At very short distances (less than the size of a nucleon), the force between quarks approaches zero.

This unusual behavior of quarks and gluons can be understood by comparison with electromagnetism. Two charged particles interact with one another through the exchange of photons. However, the photon itself carries no electric charge, and so the interaction between the charged particle and the exchanged photon does not result in the exchange of additional photons. A quark, on the other hand, can emit a gluon and interact with it. This interaction between the quark and the gluon can create additional gluons. When it interacts with another electron, an electron can emit a photon and still remain an electron. It does not sacrifice its "electricness" (that is, its electric charge) to emit the photon. A quark, however, gives its emitted gluon a share of its "strongness," which physicists call "color." In the interaction of quarks, color plays the same role as electric charge in the interaction of charged particles. A photon carries no electric charge, but a gluon carries color, and in doing so it changes the residual color left behind in the quark that emitted the gluon. In effect, the quark is spreading its color over a sphere the size of a nucleon (the range of the gluons), and as a result the interaction between quarks is considerably weakened at these distances.

Particle physicists have chosen amusing and whimsical names to describe the fundamental particles and their properties. Names such as quark, strangeness, gluon, or color have meaning only as labels. Gluons do provide the "glue" that binds quarks together, but it has no similarity to any other "glue" in our experience. The "color" carried by quarks and gluons has nothing to do with our ordinary use of color. It is simply easier to remember and discuss these properties if we give them familiar names.

More Quarks

In simultaneous 1974 experiments at the Brookhaven National Laboratory in New York and the Stanford Linear Accelerator Center in California, investigators discovered an unusual meson with a rest energy about three times that of the proton. This new meson, called ψ (psi), was expected to decay into lighter mesons in a strong interaction time of perhaps 10^{-23} s. Instead, it was observed to decay in a time of about 10^{-20} s, which is more characteristic of the electromagnetic interaction (see Table 52-1). Moreover, its decay products were not mesons but an electron and a positron, another signal of an electromagnetic process.

Why is the rapid, strong-interaction decay path blocked for this particle, slowing its decay by three orders of magnitude? We discussed a similar effect in the case of strangeness, a new quantum number that was introduced partly to explain certain slow decays. We accounted for those decays through a violation of the conservation of strangeness.

In a similar fashion, we assume that the decay of ψ is slowed by the violation of another conservation law, called *charm*. According to this interpretation, the ψ meson is composed of a new quark c (for charm) and its antiquark $\bar{c}$. The c quark has an electric charge of $+\frac{2}{3}$. Just as the strange quark is assigned a strangeness quantum number of $S = -1$, the charmed quark is assigned a charm of $C = +1$. The decay of the ψ meson is slowed, because the c quark must decay into other quarks (u, d, or s), all of which have $C = 0$. The decay thus involves a violation of the conservation of charm and therefore cannot occur through the strong interaction, which conserves charm. The c quark can also combine with other quarks to make a meson or a baryon; for example, the D^+ meson listed in Table 52-4 has quark content $c\bar{d}$, and the Λ_c^+ baryon listed in Table 52-5 has quark content udc.

In 1977, a similar discovery was made at the Fermi National Accelerator Laboratory near Chicago. Again, a heavy meson (in this case, ten times the proton rest energy) was discovered, which was expected to decay to other mesons in a time characteristic of the strong interaction, but instead it decayed into $e^+ + e^-$ in about 10^{-20} s. In this case, the decay was again slowed by the violation of yet another conservation rule, involving yet another new quark, called b (for bottom) and having an electric charge of $-\frac{1}{3}$. This new meson, called Υ (upsilon), is assumed to be composed of the combination $b\bar{b}$. If we assign to the b quark a new quantum number that represents bottomness, then the decay is slowed because the b quark must change into lighter quarks that lack this property; this violation of the conservation of bottomness is responsible for slowing the decay. The b quark can also combine with other quarks to make various mesons and baryons; for example, the B^+ meson listed in Table 52-4 has quark content $u\bar{b}$, and the Λ_b^0 baryon listed in Table 52-5 is composed of udb quarks.

In 1994, another quark was discovered from proton–proton collisions at Fermilab.* These high-energy collisions created a new quark and its antiquark, which rapidly decayed into a shower of secondary particles; from the momentum of these secondary particles, the existence of the original decaying particles was deduced. This new quark, with a charge of $+\frac{2}{3}$, is called the top quark t, and like the charmed and bottom quarks it has an associated property called *topness*.

A New Symmetry

Ordinary matter is composed of protons and neutrons, which are in turn made up only of u and d quarks. Ordinary matter is also composed of electrons, and in the conversion of protons to neutrons or neutrons to protons in the beta de-

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*For details of this discovery, see http://www.fnal.gov/pub/top95/top95_background.html.

cay of ordinary matter, we find electron-type neutrinos emitted along with the positron or electron.

We can therefore construct our entire world and all the phenomena we commonly observe out of two pairs of fundamental particles: u and d quarks, and e^- and ν_e leptons. Within each pair, the charges differ by one unit ($+\frac{2}{3}$ and $-\frac{1}{3}$; -1 and 0).

If we do experiments at a somewhat higher energy, we find new types of particles: a new pair of leptons (μ^- and its neutrino ν_μ) and a new pair of quarks (c and s). Once again, within each pair the electric charges differ by one unit. At still higher energies, we find a new pair of leptons (τ and ν_τ) and a new pair of quarks (t and b).

It therefore seems that the truly fundamental particles, the quarks and leptons, appear in pairs, and that a pair of quarks and a pair of leptons can be combined into a "generation," as follows:

$$\text{1st generation:} \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} u \\ d \end{pmatrix}$$

$$\text{2nd generation:} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

$$\text{3rd generation:} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Properties of these six quarks and leptons are summarized in Appendix F.

The model of the structure of the elementary particles that we have described so far has come to be known as the *Standard Model*. In this model, there are three generations of leptons and quarks, which are considered to be elementary particles. All other material particles are composites. The particles interact through the electroweak and the strong forces (gravitation having a negligible effect on the interactions of individual particles). The electroweak force is due to the exchange of photons or the so-called weak bosons W^+, W^-, and Z^0. The six quarks each come in three varieties or colors; there are eight colored gluons that carry the color charge and are responsible for the interaction between quarks. All baryons and mesons are colorless; the three quarks in a baryon must each have a different color, and the quark and antiquark in a meson must carry one color and its anticolor.

Although the Standard Model has had remarkable success in accounting for the properties and interactions of particles, you may now be wondering if we have simply replaced one level of complexity with another. Is it possible that, instead of hundreds of mesons and baryons, our list of particles might show hundreds of leptons and quarks as we do experiments at ever greater energies? There is very strong evidence that the number of generations is exactly three, and that the list of leptons and quarks we have described is complete. One limit on the number of generations of leptons comes from the decay of certain particles. For example, the Z^0 can decay into a lepton and its antilepton, such as $e^- + e^+$ or $\mu^- + \mu^+$. The lifetime for the decay is determined by how many of these pairs into which it can decay, and from the observed lifetime it is concluded that the number of lepton generations can be no greater than three.

A very different approach to answering this question comes from examining the properties of the universe a short time after its birth. At that time, the universe was a hot gas consisting of leptons and quarks. The evolution and subsequent properties of the universe were determined by the number of generations that existed at that time. From observations of the present properties of the universe, we can again conclude that the number of generations is again three. It is therefore very likely that our list of leptons and quarks is complete.

SAMPLE PROBLEM 52-5. Analyze these processes in terms of their quark content:

$$(a)\quad p \rightarrow n + e^+ + \nu_e,$$

$$(b)\quad \Omega^- \rightarrow \Lambda^0 + K^-,$$

$$(c)\quad K^- + p \rightarrow \Omega^- + K^+ + K^0.$$

Solution (*a*) Using Table 52-9 to find the quark content of the particles, we can rewrite the decay as

$$uud \rightarrow udd + e^+ + \nu_e.$$

Canceling the common pair of ud quarks from each side, we find

$$u \rightarrow d + e^+ + \nu_e.$$

The u quark changes to a d quark by beta decay. This equation represents a fundamental interaction between quarks which we can also write as

$$u \rightarrow d + W^+ \quad \text{and} \quad W^+ \rightarrow e^+ + \nu_e.$$

(*b*) The quark content of the Ω^- is sss (because it has strangeness -3), so the decay can be written as

$$sss \rightarrow uds + s\bar{u}.$$

Canceling the common pair of s quarks from each side, we find the net process to be

$$s \rightarrow u + d + \bar{u},$$

using the quark identities for Λ^0 and K^- given in Tables 52-9 and 52-8. That is, the s quark is transformed into a d quark, and a $u\bar{u}$ pair is created from the decay energy.

(*c*) Again replacing the particles by their quark content, we can write the reaction as

$$s\bar{u} + uud \rightarrow sss + u\bar{s} + d\bar{s},$$

and removing the common quarks of u, d, and s from each side we are left with

$$u\bar{u} \rightarrow s\bar{s} + s\bar{s}.$$

The net process consists of the annihilation of the $u\bar{u}$ pair and the production of two $s\bar{s}$ pairs from the reaction energy.

These examples are typical of quark processes; the weak interaction can change one type of quark into another. The strong interaction can create or destroy quark–antiquark pairs, but it cannot change one type of quark into another.

52-5 THE BIG BANG COSMOLOGY

Since the beginning of recorded history, human beings have speculated about the origin and future of the universe, a branch of science now called *cosmology*. Until the 20th century, these speculations were made mostly by philosophers and theologians, because there was no experimental evidence of any sort that would form the basis of any scientific theory. In that century, two major experimental discoveries have pointed the way to a coherent theory that is now accepted by nearly all physicists.

The Expansion of the Universe

The first of the two great discoveries was made by astronomer Edwin Hubble (see Fig. 52-5) in the 1920s. Hubble was studying the wispy objects known previously as *nebulae*. By eventually resolving individual stars in the nebulae, Hubble was able to show that they are galaxies just like our Milky Way, composed of hundreds of billions of stars. More startling, Hubble deduced that the galaxies are moving away from one another and from us, and that the greater their distance from us, the greater is their recessional speed. That is, if d is the distance of the galaxy from Earth (or from any other point of reference in the universe) and v is the speed with which the galaxy appears to be moving away from us, Hubble's law gives

$$v = Hd, \tag{52-2}$$

where H is a proportionality constant known as the *Hubble parameter*.

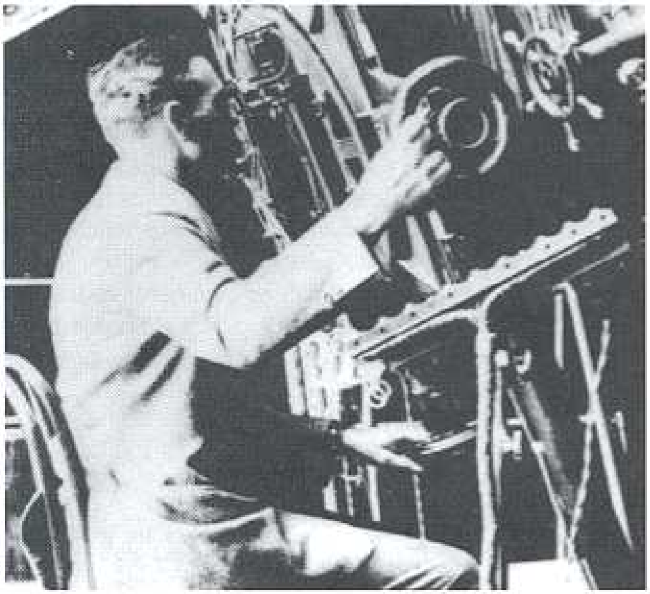

FIGURE 52-5. Edwin Hubble (1889–1953) at the controls of the 100-in. telescope on Mount Wilson, where he did much of the research that led him to propose that the universe is expanding.

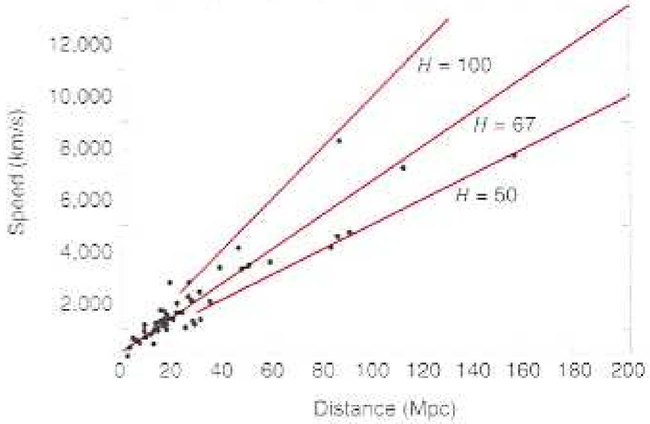

FIGURE 52-6. The relationship between speed and distance for groups and clusters of galaxies. The straight lines show the Hubble relationships for various values of the Hubble parameter H.

The Hubble parameter has the dimensions of inverse time. Its value can be learned only by experiment; we must independently deduce the distance of a galaxy from Earth and its speed relative to Earth. The recessional speeds can be measured in a straightforward way using the Doppler shift of the light from the galaxy (see Fig. 39-28), but the distance scale is difficult to determine (in fact, Hubble's early estimates were off by a factor of 10). Figure 52-6 shows an example of more recent data that confirm Hubble's law* and give a range of values of the Hubble parameter. The best set of current data gives a value of the Hubble parameter of

$$H = 72\,\frac{\text{km/s}}{\text{Mpc}},$$

where the Mpc (megaparsec) is a commonly used unit of distance on the cosmic scale:

$$\begin{aligned} 1\ \text{Mpc} = 10^6\ \text{pc} &= 3.26 \times 10^6\ \text{light-years} \\ &= 3.084 \times 10^{19}\ \text{km}. \end{aligned}$$

Because of uncertainties in the estimates of the cosmic scale of distance, the Hubble parameter is uncertain, with possible values in the range of $65 - 80\ (\text{km/s})/\text{Mpc}$.

If the universe has been expanding forever at the same rate, then H^{-1} is the age of the universe. Using the accepted value of the Hubble parameter, we would estimate the age of the universe as 14×10^9 y, with the range of uncertainty of H permitting values in the range of $12 - 15 \times 10^9$ y. However, as we shall see later, the expansion of the universe has not been constant, so the true age is less than the currently deduced value of H^{-1}.

The Cosmic Microwave Background Radiation

Although there were other explanations of the expansion of the universe, the one that gained favor was based on the assumption that, if the galaxies are presently rushing apart,

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*See "The Expansion Rate and Size of the Universe" by Wendy L. Freedman, Scientific American, November 1992. See also http://www.hubbleconstant.com/.

they must have been closer together in the distant past. If we run the cosmic clock back far enough, we find that in its early state the universe consisted of unimaginably high densities of matter and radiation. As the universe expanded, both the matter and the radiation cooled; you can think of the wavelengths of the radiant photons being stretched in the expansion. The radiation filled the entire universe in its compact state, and it continues to fill the entire universe in the expansion. We should still find that radiation present today, cooled to the extent that its most intense component is in the microwave region of the electromagnetic spectrum. This is known as the *cosmic microwave background radiation*.

This radiation was discovered in 1965 by Arno Penzias and Robert Wilson of the Bell Laboratories in New Jersey, who were testing a microwave antenna used for satellite communications (see Fig. 52-7). No matter where they pointed their antenna, they found the same annoying background "hiss." Eventually they realized that they were indeed seeing a remnant of the early universe, and they were awarded the 1978 Nobel Prize in physics for their discovery.

The microwave background radiation has a true thermal spectrum of the type we discussed in Section 45-2. Figure 52-8 shows measurements of the intensity of the background radiation at various wavelengths, and you can see how well it is fit by Planck's radiation law with a temperature of 2.725 K. The data points include recent measurements made from a satellite in Earth orbit, thereby eliminating atmospheric absorption.

Measurements of the intensity of the microwave background radiation in various directions show that the radiation has a uniform intensity in all directions; it does not appear to come from any particular source in the sky, but instead fills the entire universe uniformly, as would be expected for radiation that likewise filled the early universe. Recent observations, however, show that there are temperature fluctuations of about 10^{-5} K between different regions of the sky. These results have been interpreted as evidence for the nonuniform distribution of matter in the early universe that led ultimately to the condensation of stars and galaxies.

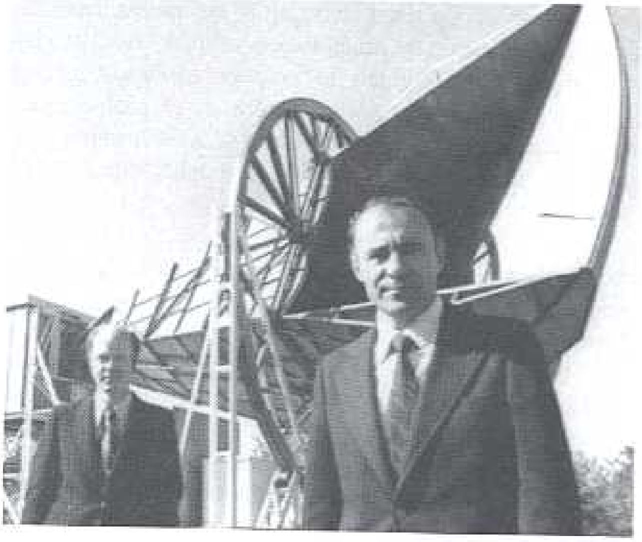

FIGURE 52-7. Arno Penzias (right) and Robert Wilson, standing in front of the large horn antenna with which they first detected the microwave background radiation.

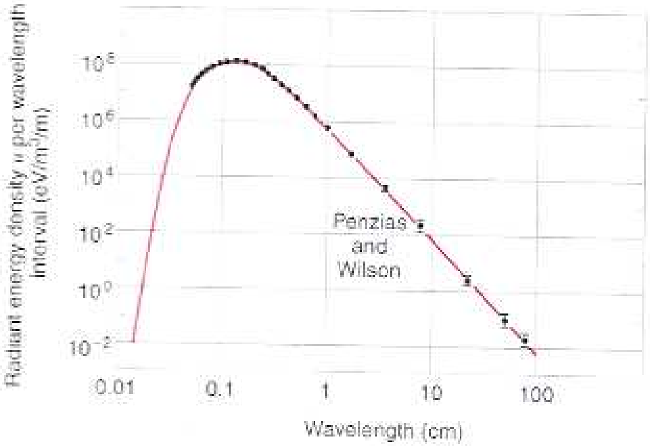

FIGURE 52-8. The spectrum of the cosmic microwave background radiation. The dots represent observations, and the solid line represents the Planck spectrum for the radiant energy corresponding to a temperature of 2.725 K. Note the excellent agreement between the data points and the theoretical curve. The data between 0.05 cm and 1.0 cm come from observations made by the COBE (COsmic Background Explorer) satellite launched in 1989.

The energy density of the radiation can be found from Planck's radiation law (Eq. 45-6). The number density of these background photons is about 400 per cm³, and the energy density is about 0.25 eV/cm³ (roughly corresponding to half the rest energy of an electron per m³). The mean energy per photon is about 0.00063 eV, which suggests why we are not ordinarily aware of the presence of these photons.

The Big Bang Cosmology

The cosmological theory that is in best agreement with these two experimental findings (the Hubble law and the background radiation) is the *big bang cosmology*. According to this theory, the universe began some 10–15 billion years ago in a state of extreme density and temperature. There were no galaxies or even clumped matter as we now know it; the "stuff" of the universe at early times was a great variety of particles and antiparticles, plus radiation. The density of radiation and matter is related to the temperature of the universe. As the universe expands, it cools (just as any expanding thermodynamic system cools). If we make some reasonable assumptions about the expansion rate, we can find a relationship between the temperature and the time after the formation of the universe:

$$T = \frac{1.5 \times 10^{10}\ \mathrm{s}^{1/2} \cdot \mathrm{K}}{t^{1/2}}, \qquad (52\text{-}3)$$

where the temperature T is in K and the time t is in seconds.

The radiation in the early universe consisted of high-energy photons, whose typical energy can be roughly estimated as kT, where k is the Boltzmann constant and T is the temperature at a particular time t, determined from Eq. 52-3. The dominant processes in the early universe can be represented as

$$\text{photons} \rightarrow \text{particle} + \text{antiparticle} \qquad (52\text{-}4a)$$

$$\text{particle} + \text{antiparticle} \rightarrow \text{photons} \qquad (52\text{-}4b)$$

Reactions of type 52-4*a* (called *pair production*) are possible only if the combined energy of the photons on the left side exceeds the total rest energy $2mc^2$ of the particle and antiparticle on the right side. If the temperature is high enough, then the two reactions are each possible; the rates of both reactions are then the same, and there is an equilibrium between the photons and the particles and antiparticles. As the universe expands and cools, the average energy of the photons decreases until at some point, for a specific type of particle, reactions of type 52-4*a* will no longer be possible. At this point no new particles and antiparticles of this type are being produced, and the equilibrium is upset because reactions of type 52-4*b* (called *annihilation*) can still proceed. As the particles and antiparticles annihilate one another, their numbers decrease.

Let us consider a specific example in the case of protons. We can represent the reactions as

$$\gamma + \gamma \rightarrow \mathrm{p} + \bar{\mathrm{p}} \quad \text{and} \quad \mathrm{p} + \bar{\mathrm{p}} \rightarrow \gamma + \gamma.$$

The rest energy of the proton is 938 MeV. For the first reaction to occur, the energy on the left side, $2E_\gamma$, must be at least as large as $2m_\mathrm{p}c^2$. If we represent the average photon energy at temperature T as kT, then the corresponding temperature is

$$T = \frac{m_\mathrm{p}c^2}{k} = \frac{938\ \text{MeV}}{8.62 \times 10^{-5}\ \text{eV/K}} = 1.1 \times 10^{13}\ \text{K}.$$

When the temperature of the universe drops below this value, the reaction $\gamma + \gamma \rightarrow \mathrm{p} + \bar{\mathrm{p}}$ will become increasingly less probable, while $\mathrm{p} + \bar{\mathrm{p}} \rightarrow \gamma + \gamma$ will continue to occur. According to Eq. 52-3, this temperature is reached at a time of

$$t = \left(\frac{1.5 \times 10^{10}\ \mathrm{s}^{1/2}\cdot\mathrm{K}}{T}\right)^2 = \left(\frac{1.5 \times 10^{10}\ \mathrm{s}^{1/2}\cdot\mathrm{K}}{1.1 \times 10^{13}\ \mathrm{K}}\right)^2$$
$$= 2 \times 10^{-6}\ \mathrm{s}.$$

That is, at times earlier than about 2 μs, the universe was hot enough to produce proton–antiproton pairs, but at later times only proton-antiproton annihilation occurs.

At very early times, with correspondingly higher temperatures, the radiation may have been hot enough to produce quark–antiquark pairs. If so, at those early times the universe consisted primarily of leptons (and antileptons), quarks (and antiquarks), and photons. The quarks may have come together to form mesons or baryons, but the radiation was sufficiently energetic to dissociate those particles as soon as they formed. Since we do not yet know the details of the interactions between free quarks (or even whether free quarks are allowed to exist), we cannot learn very much about the characteristics of the universe at that time. Instead, we begin the story at a later time, when the universe has cooled sufficiently to allow the quarks and antiquarks to form mesons and baryons.

$t = 10^{-6}$ s ($T = 1.5 \times 10^{13}$ K or $kT = 1300$ MeV). At this time, the universe consists mostly of protons, antiprotons, neutrons, antineutrons, mesons, leptons, antileptons, and photons. The rates of pair production and annihilation (Eqs. 52-4*a* and 52-4*b*) are roughly equal, so the number of each kind of particle is about equal to the number of its antiparticle. The number of photons is about equal to the number of protons, which is in turn about equal to the number of electrons.

Because the quarks and antiquarks have formed mesons and baryons, most of the influence of the strong interaction has disappeared by this time. The electromagnetic and weak interactions continue to play an important role. Electromagnetic interactions are represented by processes such as Eqs. 52-4*a*, *b*, and weak interactions can occur through such processes as

$$\mathrm{n} + \nu_e \leftrightarrows \mathrm{p} + \mathrm{e}^- \quad \text{and} \quad \mathrm{p} + \bar{\nu}_e \leftrightarrows \mathrm{n} + \mathrm{e}^+$$

and similar processes, in which neutrinos are being created and destroyed at the same rate. As long as the leptons have enough energy, the forward and reverse reaction rates are equal, which maintains the balance between the number of charged leptons (e^+ and e^-) and neutrinos. Since these reactions convert neutrons to protons and protons to neutrons with equal ease, the very early universe contained roughly equal numbers of protons and neutrons.

$t = 10^{-2}$ s ($T = 1.5 \times 10^{11}$ K or $kT = 13$ MeV). Now pair production of nucleons (protons and neutrons) no longer occurs. Nucleon–antinucleon annihilation continues to occur; because of a slight excess of matter over antimatter (which we will discuss later), all of the antinucleons disappear, leaving only the small excess of nucleons. The photons are still hot enough to produce electron–positron pairs. At this point the universe consists of protons, neutrons, electrons, positrons, neutrinos, antineutrinos, and photons. The number of protons is roughly equal to the number of neutrons.

$t = 1$ s ($T = 1.5 \times 10^{10}$ K or $kT = 1.3$ MeV). As the universe expands, the neutrinos are cooling along with the photons, and their average energy is also roughly kT. Because the neutron–proton rest energy difference is about 1.8 MeV, the neutrinos no longer have enough energy to convert protons into neutrons; neutrons can be converted to protons, however, such as by neutrino capture ($\mathrm{n} + \nu_e \rightarrow \mathrm{p} + \mathrm{e}^-$). At this point the neutrinos begin to "decouple" from the matter in the universe; that is, their interactions with matter become much less frequent, and those few remaining interactions have little influence on the properties of the neutrinos (especially their temperature or average energy). From that point until today, the neutrinos continue to fill the universe and to continue their cooling as the universe expands. Today their average energy is very small, about 0.0005 eV, and their density is about 400 per cm^3. As a result of neutrino decoupling the balance between the number of neutrons and protons is upset, and by $t = 1$ s the nucleons consist of about 73% protons and 27% neutrons.

$t = 6$ s ($T = 6 \times 10^9$ K or $kT = 0.5$ MeV). Now the photons have too little energy to produce even electron–positron pairs; electron–positron annihilation has removed all of the positrons and nearly all of the electrons. This further upsets the ability of the transformation between protons and neutrons to go in both directions; as a result, the relative number of protons continues to increase, and by this time we have about 83% protons and 17% neutrons.

At this time the universe consists of a number N protons, $0.2N$ neutrons, N electrons, and a much larger number of photons and neutrinos. At earlier times the number of photons was about equal to the number of nucleons and antinucleons, but the present number of protons represents only the slight excess of protons over antiprotons that remained following annihilation. We can deduce the ratio of photons to nucleons, because it determines the relative amounts of certain light elements such as deuterium (^{2}H) that are formed in the early universe. This number turns out to be about 10^9. That is, for every 1,000,000,001 protons and 1,000,000,000 antiprotons in the early universe, following annihilation there is just one proton and no antiprotons left.

As far as we know, the present universe contains no stars or galaxies made of antimatter. Our universe is entirely made up of the small excess of matter that remained after annihilation. Where did the slight excess of matter over antimatter originate? Evidence for this asymmetry between matter and antimatter is seen in the difference in the decay properties of the neutral K meson K^0 and its antiparticle $\bar{K}^0$. The interaction that causes this asymmetry is not yet well understood, but its effect on the distribution of particles and antiparticles may have established the slight excess of matter during an early era in the evolution of the universe when quarks and leptons were dominant. So far the K^0 is the only system that shows this effect, although it is thought that the neutral B meson B^0 and its antiparticle $\bar{B}^0$ may show a similar effect. A new acceleration and detection facility is currently under construction at the Stanford Linear Accelerator Center to test this prediction. This is another example of the way that results from particle physics have a great impact on developments in cosmology.

This description of the evolution of the universe, illustrated in Fig. 52-9, has taken us from the formation of the universe at the big bang, through hot and turbulent eras dominated by nuclear reactions, to a time of a few seconds when the composition became identical with the particles that now make up our universe. How these particles combined to form the nuclei and atoms that we observe today is discussed in the next section.

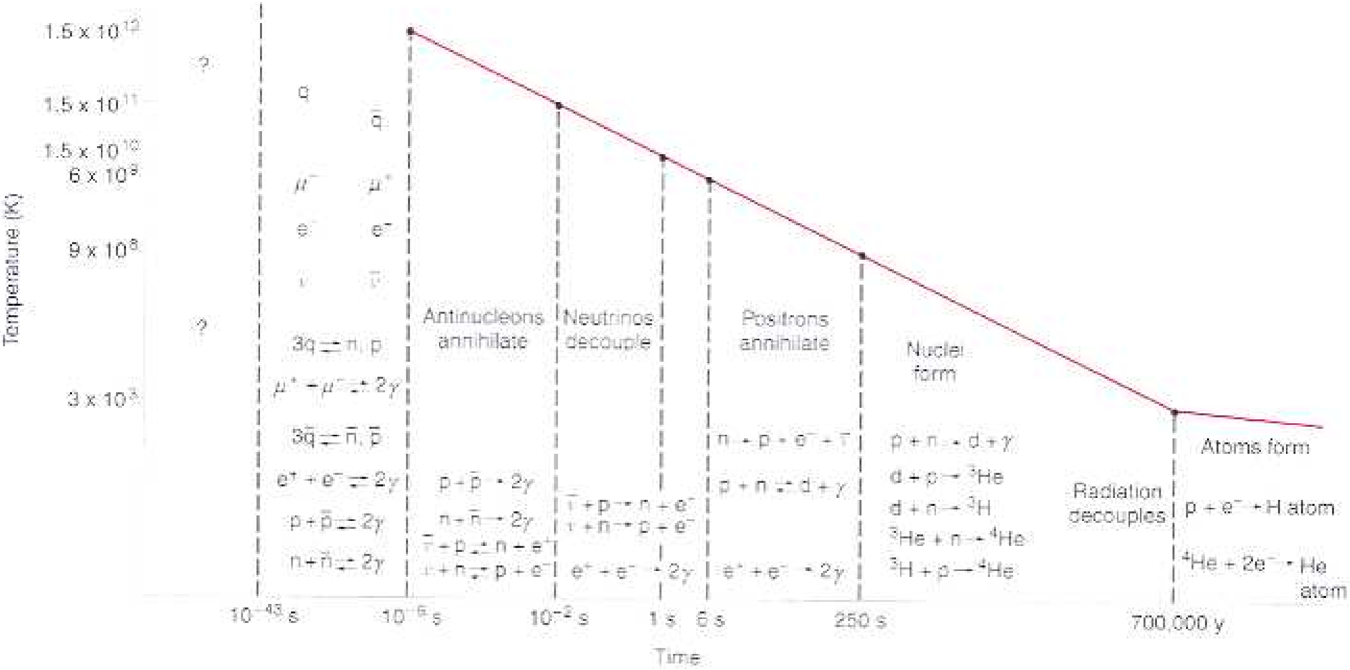

FIGURE 52-9. The evolution of the universe according to the big bang cosmology. The heavy solid line shows the relationship between temperature and time according to Eq. 52-3. The important reactions in each era are shown. (Here q and $\bar{q}$ stand for quark and antiquark, respectively.)

SAMPLE PROBLEM 52-6. When did the universe become too cool to permit the radiation to create $\mu^+ \mu^-$ pairs?

Solution The rest energy of the muon is 105.7 MeV. Photons have this mean energy at a temperature determined by

$$T = \frac{m_\mu c^2}{k} = \frac{105.7\ \text{MeV}}{8.62 \times 10^{-5}\ \text{eV/K}} = 1.23 \times 10^{12}\ \text{K}.$$

The corresponding time is found from Eq. 52-3:

$$t = \left(\frac{1.5 \times 10^{10}\ \text{s}^{1/2} \cdot \text{K}}{1.23 \times 10^{12}\ \text{K}} \right)^2 = 1.5 \times 10^{-4}\ \text{s}.$$

52-6 NUCLEOSYNTHESIS

At an age of a few seconds, the universe consisted of protons, neutrons, and electrons. Today, the composition of the universe is mostly hydrogen and helium, with a small abundance of heavier elements. How were the present nuclei and atoms produced from the big bang? The formation of the elements of the present universe is known as *nucleosynthesis*. As we shall see, observing the present abundances of the elements can give us clues about the processes that occurred during the big bang.

Big Bang Nucleosynthesis

The first step in building up complex atoms is the formation of deuterium nuclei (deuterons) from the combination of a proton and a neutron, according to

$$\text{n} + \text{p} \rightarrow \text{d} + \gamma.$$

The binding energy of the deuteron (see Section 50-2) is 2.2 MeV, which is the energy of the γ ray that is given off during the formation. The reverse reaction,

$$\text{d} + \gamma \rightarrow \text{n} + \text{p},$$

can break apart the deuterium nuclei into their constituent protons and neutrons, if the γ ray energy is at least 2.2 MeV.

If the universe is filled with energetic photons, the two reactions will take place at the same rate, and deuterium will be disassociated as quickly as it is formed. However, if the universe is sufficiently old, the photons will not have enough energy to accomplish the disassociation reaction, and deuterium can start to build up.

When we ended our story in the previous section, the universe was about 6 s old, and the mean energy of the radiation was about 0.5 MeV, which is less than what is needed to keep deuterium from forming. However, it must be remembered that the radiation has a Planck distribution of energies (see Fig. 52-10, which was discussed in Section 45-2) and that there are perhaps 10^9 photons for every proton or neutron. There is a high-energy tail in the Planck distribution, which suggests that no matter what the temperature of the radiation, there will always be some photons of energy above 2.2 MeV that can break apart deuterium nuclei. If, on the average, the number of these energetic photons is less than the number of protons and neutrons, deuterium can start to build up.

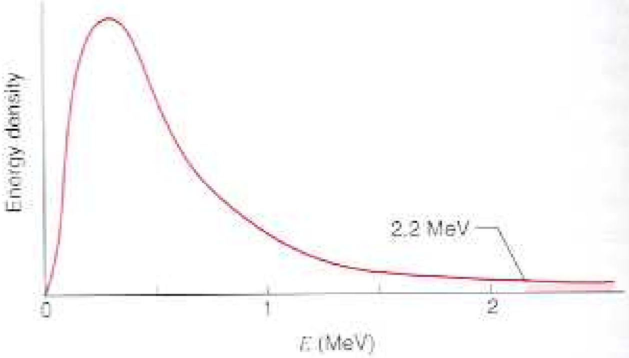

FIGURE 52-10. The energy spectrum of photons at a particular time in the evolution of the universe. Photons with energy above 2.2 MeV, which constitute a tiny fraction of the total number of photons, can dissociate deuterons.

The neutron-to-proton ratio is about 0.2 at this point in the evolution of the universe, and there are roughly 10^9 photons per nucleon, so that the ratio of neutrons to photons is about 0.2×10^{-9}. If the fraction of photons with energies above 2.2 MeV is less than 0.2×10^{-9} of the total number of photons, there will be less than one energetic photon per neutron, and deuterium formation can proceed. From the expression for the Planck distribution (obtained from Eq. 45-6), we find that the fraction of photons of energy greater than 2.2 MeV will be less than 0.2×10^{-9} when the temperature has fallen to 9×10^8 K. Equation 52-3 shows that this temperature occurs at a time of 250 s.

At a time of 250 s, the formation of deuterium nuclei begins. Because the deuterons are less abundant than protons or neutrons, the deuterons will readily react with protons and neutrons, according to the reactions

$$\text{d} + \text{n} \rightarrow {}^3\text{H} + \gamma \quad \text{and} \quad \text{d} + \text{p} \rightarrow {}^3\text{He} + \gamma.$$

Finally, the ^{3}H and ^{3}He will also react with protons and neutrons, as given by

$${}^3\text{H} + \text{p} \rightarrow {}^4\text{He} + \gamma \quad \text{and} \quad {}^3\text{He} + \text{n} \rightarrow {}^4\text{He} + \gamma.$$

For all four of these reactions, the binding energy of the final particle is greater than that of the deuteron. Thus if the radiation is too feeble to prevent the formation of deuterons, it will certainly be too feeble to prevent the succeeding reactions. We can therefore assume that nearly all the deuterons are eventually converted into ^{4}He, so that the end products of this stage of the evolution of the universe are protons and α particles. Because there are no stable nuclei with a mass number of 5, these reactions cannot continue beyond ^{4}He.

To find the relative number of ^{4}He nuclei, we must find the number of available neutrons at $t = 250$ s, when deuterons begin to form. At $t = 6$ s, about 17% of the nucleons are neutrons, but as a result of the radioactive decay of the neutron, some neutrons will be converted into protons between $t = 6$ s and $t = 250$ s. Using the half-life of the neutron (about 11 min), we find that at $t = 250$ s the nucleons will consist of about 12.5% neutrons and 87.5% protons. That is, out of every 10,000 nucleons there will be 1250 neutrons and 8750 protons. These neutrons will combine with 1250 protons to form 625 ^{4}He nuclei, leaving $8750 - 1250 = 7500$ protons. Of the total number of nuclei in the universe at this time, 7.7% are ^{4}He and 92.3% are protons. In terms of mass, the ^{4}He constitutes a fraction of the total mass of the universe given by

$$\frac{4 \times 625}{7500 + 4 \times 625} = 0.25 \text{ or } 25\%.$$

The abundance of ^{4}He in the present universe should equal this value, if we neglect the burning of hydrogen to helium that takes place in stars. The measured helium abundance in a variety of systems, including stars, gaseous nebulae, and planetary nebulae, turns out to be $24 \pm 1\%$, which agrees with our estimate and indicates that our description is certainly reasonable.

The final step in the production of matter in the big bang is the formation of neutral atoms of hydrogen and helium when the protons and ^{4}He nuclei combine with electrons. As in the case of deuteron formation, this cannot occur when there are enough photons in the high-energy tail of the Planck distribution to break apart any neutral atoms that may form. In this case, we want the relative fraction of photons with energies above 13.6 eV (the binding energy of atomic hydrogen) to be less than about 10^{-9}. This occurs for a temperature of about 6000 K, which corresponds to an age of the universe of around 200,000 y. (As the radiation cools, the energy density of the universe becomes less dominated by radiation and more by matter. In this case Eq. 52-3, which assumes a radiation-dominated universe, is not quite correct. Taking this effect into account, the temperature of the universe when hydrogen atoms begin to form is closer to 3000 K, corresponding to an age of around 700,000 y.)

Once neutral atoms have formed, there are essentially no free charged particles left in the universe. This is the time of decoupling of the matter and the radiation field. The universe becomes transparent to the radiation, which can travel long distances without interacting with matter. This radiation, which has been traveling since the decoupling time, is observed today as the microwave background. The expansion of the universe has reduced the radiation temperature by a factor of 1000 since the decoupling time.

The story of the evolution of the universe as described by the big bang cosmology is a remarkable one. It integrates modern experiments in nuclear and particle physics with quantum physics and classical thermodynamics. It yields results that can be tested in the present universe, including the helium abundance, the microwave background radiation, and a small abundance of left-over deuterium that did not get "cooked" into mass-3 nuclei. It is a story that depends in critical ways on the strengths of nuclear or subnuclear forces and on the variety of particles that took part in the early universe. For example, if there were a fourth generation of leptons, the reaction rates of weak-interaction processes would be greater, and more neutrons would be formed, thereby increasing the abundance of ^{4}He. The observed present abundance of ^{4}He is regarded by many cosmologists as limiting the number of generations of leptons to three.

Formation of Heavy Elements

After the decoupling of matter and radiation, the matter (consisting of hydrogen and helium) was subject only to the gravitational force. Recent precise observations of the microwave background have shown that the distribution of matter at the decoupling time was slightly nonuniform. Regions of slightly higher density began to condense into clouds of ever increasing density. As each cloud contracted under its own gravity, its temperature rose until it became hot enough to initiate fusion reactions. This is how first-generation stars formed.

We have seen in Chapter 51 that stars convert hydrogen into helium by means of fusion reactions. After a star has used up its supply of hydrogen and becomes mostly helium, it can again begin to contract, which increases its temperature. (This increase in temperature causes an increased radiation pressure, which causes the radius of the star to increase. The surface area increases more rapidly than the temperature, so that the energy per unit area of the surface actually decreases, and the color of the star goes from bright yellow to red. This is the *red giant* phase of the evolution of the star.) Eventually, the temperature is high enough that the Coulomb barrier between two ^{4}He nuclei can be successfully breached by their thermal motion, and helium fusion can occur. The simple helium fusion reaction

$$^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be}$$

does not contribute to the fusion in a star, because ^{8}Be is unstable and breaks apart as rapidly as it forms. Helium fusion requires a third ^{4}He to participate, so that the net reaction is

$$^4\text{He} + {}^4\text{He} + {}^4\text{He} \rightarrow {}^{12}\text{C} + \gamma.$$

Once ^{12}C forms, we can have additional ^{4}He reactions, such as

$$^{12}\text{C} + {}^4\text{He} \rightarrow {}^{16}\text{O} + \gamma,$$

$$^{16}\text{O} + {}^4\text{He} \rightarrow {}^{20}\text{Ne} + \gamma,$$

$$^{20}\text{Ne} + {}^4\text{He} \rightarrow {}^{24}\text{Mg} + \gamma,$$

and so on. These reactions have increasingly high Coulomb barriers and therefore require increasing temperatures.

When the helium fuel is exhausted, contraction sets in again to increase the temperature, so that other reactions can occur, such as carbon burning:

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{24}\text{Mg} + \gamma.$$

Eventually, these reactions reach the peak of the binding energy curve (Fig. 50-6) at about $A = 56$. Beyond this point, energy is no longer released in fusion reactions.

Figure 52-11 shows the abundance of nuclei in this mass range. The relative abundances support this scenario for producing the elements in fusion reactions. Note that C is more than five orders of magnitude more abundant than Li, Be, and B, which are not produced in these processes. Also note that the even-Z nuclei are, on the average, more than an order of magnitude more abundant than their odd-Z neighbors. The fusion reactions with ^{4}He produce only even-Z products, so the observed higher abundances of these products are consistent with this explanation of their formation.

Note also the last point in Fig. 52-11, which indicates that the *total* abundance of the 50 elements beyond the nuclei in the mass-56 range is less than the abundance of all but one of the individual elements in the region from C to Zn. It certainly appears that most of the matter we know about was produced in fusion processes.

The elements beyond $A = 56$ cannot be produced through fusion reactions in stars. Instead, they are produced through neutron-capture processes. A nucleus in the interior of a star can capture neutrons until its neutron excess is sufficient for it to want to convert an extra neutron to a proton by beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$, thereby increasing the number of protons by one. In this way the atomic number increases one step at a time up to the heaviest nuclei found in nature. For example, the process begins in this way with Fe ($Z = 26$):

$$^{56}\text{Fe} + n \rightarrow {}^{57}\text{Fe} + \gamma$$

$$^{57}\text{Fe} + n \rightarrow {}^{58}\text{Fe} + \gamma$$

$$^{58}\text{Fe} + n \rightarrow {}^{59}\text{Fe} + \gamma$$

Both ^{57}Fe and ^{58}Fe are stable, but ^{59}Fe is radioactive and beta decays with a half-life of 45 days to ^{59}Co ($Z = 27$). The process continues as ^{59}Co can capture a neutron to become ^{60}Co, which is radioactive and beta decays to ^{60}Ni ($Z = 28$). Continuing in this way we can produce all of the heavier elements through the neutron capture–beta decay process.

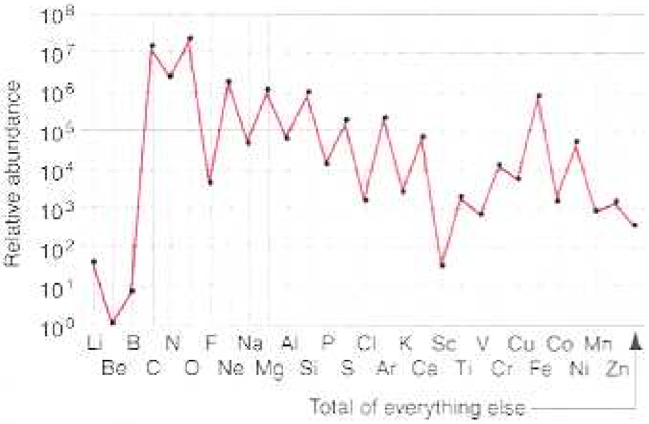

FIGURE 52-11. Relative abundances (by mass) of the elements beyond helium in the solar system.

There is a small density of neutrons in the interiors of stars, and so this process happens slowly during the lifetime of a star. It is therefore known as *s-process* (s for slow) nucleosynthesis. In an explosive supernova, on the other hand, the density of neutrons may be 10^{10}–10^{20} times larger, and the entire process may happen very quickly (seconds or minutes). In this case it is known as *r-process* (r for rapid) nucleosynthesis. Many radioactive nuclei are formed very quickly in the r process and then decay to the stable elements found in nature.

Following either s-process or r-process nucleosynthesis, the resulting elements are distributed into space. The elements beyond mass 56 found on Earth were produced this way in first-generation stars. The planets of our solar system (and in fact we ourselves) are made of the recycled ashes of burnt-out stars.

52-7 THE AGE OF THE UNIVERSE

In Section 50-7, we discussed the use of radioactive dating methods to determine the age of the Earth. By examining the relative amounts of parent and daughter isotopes in certain radioactive decay processes having half-lives in the range $10^8 - 10^9$ y (for example, $^{238}\text{U} \rightarrow {}^{206}\text{Pb}$, $^{87}\text{Rb} \rightarrow {}^{87}\text{Sr}$, and $^{40}\text{K} \rightarrow {}^{40}\text{Ar}$), it has been determined that the age of the oldest rocks on Earth is about 4.5×10^9 y. An identical value is obtained for meteorites and for rocks from the Moon. We can therefore be fairly certain that this value represents the time since the condensation of the solar system.

We know that the universe must be much older than this value, because the solar system formed out of elements that were created in the interiors of stars or in supernovas. The present chemical composition of the solar system was determined during a previous era of nucleosynthesis, which occurred in a previous generation of stars. To find the true age of the universe, we must determine the time interval needed for the elements to be produced.

The total time from the big bang to the present can be divided into four periods: (1) from the big bang until the formation of neutral H and He atoms (t_1); (2) the condensation of galaxies and the formation of first-generation stars (t_2); (3) nucleosynthesis in stars and supernovas, leading to the present chemical elements (t_3); and (4) formation and evolution of the solar system from the debris of earlier stars (t_4). The present age of the universe is the sum of these four terms:

$$t = t_1 + t_2 + t_3 + t_4. \tag{52-5}$$

We know from our discussion of the big bang cosmology that the time t_1 from the big bang until neutral atoms formed is no more than 10^6 y. The time t_2 for galaxies to condense from hydrogen and helium produced in the big bang is not precisely known but has been estimated to be in the range 1–2 × 10^9 y. Since t_4 is known to be 4.5 × 10^9 y, the age of the universe can be determined if we can find the time t_3 associated with nucleosynthesis.

This time must be estimated from the relative abundances of the products that remain at the end of nucleosynthesis. For example, consider the isotopes ^{235}U and ^{238}U, which at present have a relative abundance of 0.72% (see the discussion in connection with the natural fission reactor in Section 51-5). Both ^{235}U and ^{238}U have been decaying during the interval since the formation of the solar system. Their ratio 4.5 × 10^9 years ago is (see Sample Problem 51-4)

$$
\begin{aligned}
R(0) &= R(t)e^{(\lambda_5 - \lambda_8)t} \\
&= (0.0072)e^{(0.984 - 0.155 \times 10^{-9}\,\mathrm{y}^{-1})(4.5 \times 10^9\,\mathrm{y})} = 0.30.
\end{aligned}
$$

During the interval t_3, both isotopes were being formed more or less continuously through the r process, while the relative decay of course also took place. Because of the production of both isotopes during this time, the ratio of their abundances in this period did not change as rapidly as it did during the free decay in the interval t_4; see Fig. 52-12. Evidence from the uranium abundance suggests that t_3 is in the range 4–9 × 10^9 y; the analysis of the abundances of other r-process nuclei gives similar but slightly larger values. The best estimate for t_3 is about 8 × 10^9 y, with a range of 4–12 × 10^9 y.

Combining these results, we have as our estimate for the age of the universe

$$
\begin{aligned}
t &= t_1 + t_2 + t_3 + t_4 \\
&= 10^6\ \mathrm{y} + 1\text{–}2 \times 10^9\ \mathrm{y} + 8 \times 10^9\ \mathrm{y} + 4.5 \times 10^9\ \mathrm{y} \\
&= 14 \times 10^9\ \mathrm{y}.
\end{aligned}
$$

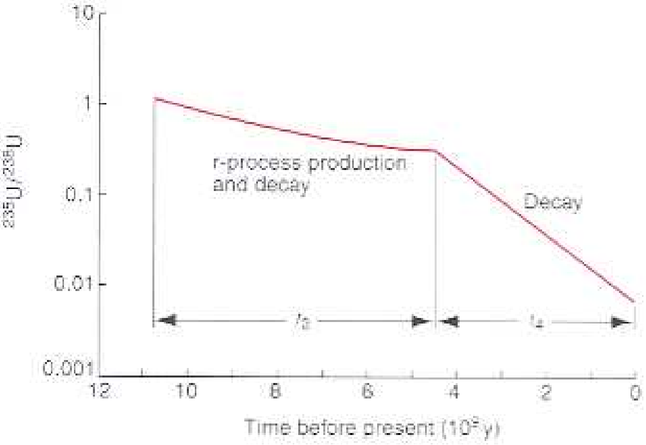

FIGURE 52-12. The change in the ^{235}U/^{238}U ratio with time. During the life of the solar system (the time t_4), the ratio changes due only to the relative decays, eventually reaching the present value of 0.0072. During the interval t_3, production by the r process occurs along with the decay. The duration deduced for the interval t_3 depends on the value that we take for the initial ratio, which must be determined from calculation.

This number is somewhat uncertain as a result of the range of values in the estimate for t_3. Taking this uncertainty into account, we obtain

$$t = 10\text{–}18 \times 10^9\ \mathrm{y}.$$

Consider the enormous amount of physics contained in this simple result. To determine t_1, we used the cumulative knowledge of particle physics, electromagnetism, thermal physics, and atomic and nuclear physics to trace the formation of matter as we know it. The interval t_2 is determined from calculations using thermodynamics and gravitational theory to analyze the condensation of cold matter into hot stars. Our estimate for t_3 is based on our knowledge of r-process and s-process nucleosynthesis based on nuclear physics studies in laboratories on Earth, and the interval t_4 is based on further experiments in nuclear physics and research in geochemistry.

Cosmological Determination of the Age

If we make the rough but not quite correct assumption that the universe has been expanding at the same rate since its formation, then the separation d between typical galaxies should be related to the age of the universe roughly according to

$$d = vt,$$

where v is the (assumed constant) speed of separation. Comparing this result with Eq. 52-2 shows that the age t of the universe is simply the inverse of the Hubble parameter:

$$t = H^{-1}. \tag{52-6}$$

The present best estimate for the Hubble parameter, H = 72 (km/s)/Mpc, gives a value for the age of the universe of

$$t = 14 \times 10^9\ \mathrm{y},$$

in remarkably good agreement with the value obtained from the nucleosynthesis calculation. The range of uncertainty of the Hubble parameter, 65–80 (km/s)/Mpc, gives a corresponding range in ages of

$$t = 12\text{–}15 \times 10^9\ \mathrm{y},$$

which overlaps with the range determined from nucleosynthesis.

Our assumption about the constant separation speed of the galaxies is almost certainly incorrect. The mutual gravitational attraction of the galaxies has been slowing their separation since the big bang, so that at earlier times the speed of separation may have been greater than it is at present. Figure 52-13 shows a representation of a typical intergalactic separation distance as a function of the time. If the "constant-speed" model were valid, the age of the universe would be $t = H^{-1}$. If the speed has been decreasing since the big bang, the deduced age depends on the rate of deceleration. Since humans have not been observing long enough to detect any change in the separation rate, we must

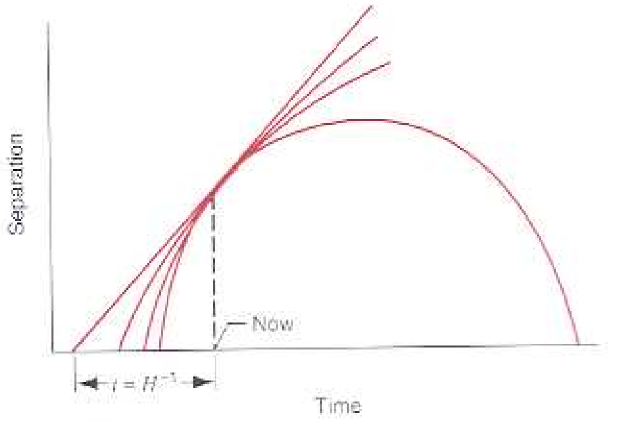

FIGURE 52-13. The dependence of a typical galactic separation distance on time during the evolution of the universe according to different models. If the universe has been expanding at a constant rate (straight line), we can extrapolate backward to zero separation (the big bang) at a time of H^{-1} before the present. If the expansion has been slowing due to the gravitational interaction (a more reasonable scenario), the big bang occurred at a time less than H^{-1} before the present. If the gravitational interaction is strong enough, the expansion may eventually become a contraction.

rely on two indirect methods to determine the deceleration: (1) we can measure the red shifts and thereby deduce the speeds of the most distant (and therefore the oldest) objects we can observe with telescopes, or (2) we can calculate the deceleration based on the gravitational effects of the total amount of matter in the universe.

Somewhat surprisingly, recent measurements of the red shifts of the most distant galaxies suggest that the expansion is *accelerating* rather than decelerating. That is, the expansion rate in the era of these ancient galaxies was slower than we would expect based on extrapolating the current expansion rate. This effect, which has as yet no convincing explanation, has been accounted for through the presence throughout the universe of a "dark energy" that drives the acceleration.

Calculations of the decelerating effect of the matter in the universe are difficult because we don't know how much matter the universe contains. Measurements suggest that the observable matter is not even sufficient to explain the gravitational attraction within galaxies or clusters of galaxies. Astrophysicists have postulated the existence of "dark matter" that is not visible but must be present to produce the gravitational attractions. The amount of this "dark matter" and its form (anything from known or exotic types of elementary particles to burnt-out stars) are uncertain, but it may account for as much as 90% of the mass of the universe.

Various cosmological models have been proposed that give curves in Fig. 52-13 of differing curvatures and therefore different ages of the universe. For example, some of these give an age that is one-half or two-thirds of H^{-1}, or $6-10 \times 10^9$ y. Although we do not know which (if any) of these models is correct, it seems clear that both the nucleosynthesis and cosmological estimates for the age of the universe are consistent with values in the range $10-15 \times 10^9$ y.

It is a source of great frustration for physicists not to be able to view the history of the universe with more certainty, because our ability to look forward is similarly limited. Will the expansion continue forever, or is there enough matter present to reverse the expansion? Figure 52-13 shows several possible outcomes. Perhaps cosmologists of later eras will observe the galaxies rushing together as the universe "heats up" and the galaxies come together, eventually reaching a single point (a "big crunch") that may be followed by another big bang. Or perhaps the expansion continues forever, until the universe is cold and dark. If the solution to this fundamental problem is to be found, it will require vigorous investigations at the forefronts of astrophysics, nuclear physics, and particle physics.

MULTIPLE CHOICE

52-1 Particle Interactions

1. Identify the interaction responsible for the following decays (decay lifetimes are given):
(a) $\Delta^{*} \rightarrow p + \pi^-$ (10^{-23} s); *(b)* $K^0 \rightarrow \pi^+ + \pi^-$ (10^{-10} s); *(c)* $\eta \rightarrow \gamma + \gamma$ (10^{-18} s).
(A) Strong (B) Electromagnetic
(C) Weak (D) Gravitational

52-2 Families of Particles

2. Given the spin and decay products, to which family does each of these particles belong?
(a) Spin $\frac{1}{2}$, decay products are only leptons and/or antileptons.
(b) Integer spin, decay products are only leptons and/or antileptons.
(c) Spin $\frac{1}{2}$, decay products include one baryon and some mesons.
(d) Integer spin, decay products are only mesons.
(e) Spin $\frac{1}{2}$, decay products are only mesons.
(A) Lepton (B) Meson
(C) Baryon (D) Not possible

52-3 Conservation Laws

3. Name the conservation law violated in each of the following decays:
(a) $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$; *(b)* $\pi^+ \rightarrow e^- + \gamma$; *(c)* $\mu^- \rightarrow \pi^+ + \bar{\nu}_\mu$.
(A) Electric charge (B) Lepton number
(C) Energy (D) Baryon number

4. Name the conservation law violated in each of the following decays:
(*a*) $\Omega^- \rightarrow \Sigma^- + \pi^0$; (*b*) $\Lambda^0 \rightarrow \pi^+ + \pi^-$;
(*c*) $\Lambda^0 \rightarrow p + K^-$.
(A) Energy (B) Strangeness
(C) Baryon number (D) Meson number

52-4 The Quark Model

5. If q = quark and $\overline{q}$ = antiquark, which two of the following combinations might be possible?
(A) $qq\overline{q}$ (B) $qq\overline{q}\overline{q}$ (C) $q\overline{q}\overline{q}$ (D) $qqqq\overline{q}$ (E) $qq\overline{q}\overline{q}\overline{q}$

52-5 The Big Bang Cosmology

6. The energy density of the very early universe ($t < 10^{-6}$ s) was dominated by ________, and the energy density of the present universe is dominated by ________.
(A) radiation, radiation (B) radiation, matter
(C) matter, radiation (D) matter, matter

52-6 Nucleosynthesis

52-7 The Age of the Universe

QUESTIONS

1. The ratio of the gravitational force between the electron and the proton in the hydrogen atom to the magnitude of the electromagnetic force of attraction between them is about 10^{-39}. If the gravitational force is so very much weaker than the electromagnetic force, how was it that the gravitational force was discovered first and is so much more apparent to us?

2. What is really meant by an elementary particle? In arriving at an answer, consider such properties as lifetime, mass, size, decays into other particles, fusion to make other particles, and reactions.

3. Why do particle physicists want to accelerate particles to higher and higher energies?

4. Name two particles that have neither mass nor charge. What properties do these particles have?

5. Why do neutrinos leave no tracks in detecting chambers?

6. Neutrinos have no mass (presumably) and travel with the speed of light. How, then, can they carry varying amounts of energy?

7. Do all particles have antiparticles? What about the photon?

8. In the beta decay of an antineutron to an antiproton, which is emitted—a neutrino or an antineutrino?

9. Photons and neutrinos are alike in that they have zero charge, zero mass, and travel with the speed of light. What are the differences between these particles? How would you produce them? How do you detect them?

10. Explain why we say that the π^0 meson is its own antiparticle.

11. An electron cannot decay by disintegrating into two neutrinos. Why not?

12. Why is the electron stable? That is, why does it not decay spontaneously into other particles?

13. A resting electron cannot emit a single gamma-ray photon and disappear. Why? Could a moving electron do so?

14. A neutron is massive enough to decay by the emission of a proton and two neutrinos. Why does it not do so?

15. A positron invariably finds an electron and they annihilate each other. How then can we call a positron a stable particle?

16. What is the mechanism by which two electrons exert forces on each other?

17. Why are particles not grouped into families on the basis of their mass?

18. A particle that responds to the strong force is either a meson or a baryon. You can tell which it is by allowing the particle to decay until only stable end products remain. If there is a proton among these products, the original particle was a baryon. If there is no proton, the original particle was a meson. Explain this classification rule.

19. How many kinds of stable leptons are there? Stable mesons? Stable baryons? In each case, name them.

20. Most particle physics reactions are endothermic rather than exothermic. Why?

21. What is the lightest strongly interacting particle? What is the heaviest particle unaffected by the strong interaction?

22. For each of the following particles, state which of the four basic forces are influential: (*a*) electron, (*b*) neutrinos, (*c*) neutron, (*d*) pion.

23. Just as x rays are used to discover internal imperfections in a metal casting caused by gas bubbles, so cosmic-ray muons have been used in an attempt to discover hidden burial chambers in Egyptian pyramids. Why were muons used?

24. Are strongly interacting particles affected by the weak interaction?

25. Do all weak-interaction decays produce neutrinos?

26. Mesons and baryons are each sensitive to the strong force. In what ways are they different?

27. By comparing Tables 52-3 and 52-7, point out as many similarities between leptons and quarks as you can and also as many differences.

28. What is the experimental evidence for the existence of quarks?

29. We can explain the "ordinary" world around us with two leptons and two quarks. Name them.

30. The neutral pion has the quark structure $u\overline{u}$ and decays with a mean life of only 8.3×10^{-17} s. The charged pion, on the other hand, has a quark structure of $u\overline{d}$ and decays with a mean life of 2.6×10^{-8} s. Explain, in terms of their quark structure, why the mean life of the neutral pion should be so much shorter than that of the charged pion. (*Hint:* Think of annihilation.)

31. Do leptons contain quarks? Do mesons? Do photons? Do baryons?

32. The Δ^{++} baryon can have an electric charge of $+2e$ (see Table 52-5). Based on the quark model, do we expect to find mesons with charge $+2e$? Baryons with charge $-2e$?

33. The Σ^- baryon decays with a mean life characteristic of the weak interaction (see Table 52-5). It should be able to decay to the Λ^0 baryon by the strong interaction without changing strangeness. Why does it not?

34. Why can we not find the center of the expanding universe? Are we looking for it?

35. Due to the effect of gravity, the rate of expansion of the universe must have decreased in time following the big bang. Show that this implies that the age of the universe is less than $1/H$.

36. It is not possible, using telescopes that are sensitive in any part of the electromagnetic spectrum, to "look back" any farther than about 500,000 y from the big bang. Why?

37. How does one arrive at the conclusion that visible matter may account for only about 10% of the matter in the universe?

38. Are we always looking back in time as we observe a distant galaxy? Does the direction in which we look make a difference?

39. Can you think of any possible explanation for the expanding universe other than a big bang?

EXERCISES

52-1 Particle Interactions

1. *(a)* An electron and a positron are separated by a distance r. Find the ratio of the gravitational force to the electrostatic force between them. What do you conclude from the result concerning the forces acting between particles detected in a bubble chamber or similar detector? *(b)* Repeat for a proton–antiproton pair.

2. Some of the GUTs predict the following possible decay schemes for the proton:

$$p \rightarrow e^+ + \gamma,$$

$$p \rightarrow e^+ + \pi^0.$$

(a) Calculate the Q-values for these decays. *(b)* Show that the decays do not violate the conservation laws of charge, relativistic energy, or linear momentum. The rest energy of a proton is 938.27 MeV, of an electron is 0.511 MeV, and of a neutral pion is 135 MeV.

3. An electron and a proton are placed a distance apart equal to one Bohr radius a_0. Find the radius R of a lead sphere that must be placed directly behind the electron so that the gravitational force on the electron just overcomes the electrostatic attraction between the proton and the electron; see Fig. 52-14. Assume that Newton's law of gravitation holds, and that the density of the sphere equals the density of lead on the Earth.

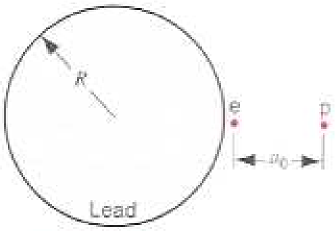

FIGURE 52-14. Exercise 3.

52-2 Families of Particles

4. A neutral pion decays into two gamma rays: $\pi^0 \rightarrow \gamma + \gamma$. Calculate the wavelengths of the gamma rays produced by the decay of a neutral pion at rest.

5. The rest energy of many short-lived particles cannot be measured directly, but must be inferred from the measured momenta and known rest energies of the decay products. Consider the ρ^0 meson, which decays by $\rho^0 \rightarrow \pi^+ + \pi^-$. Calculate the rest energy of the ρ^0 meson given that each of the oppositely directed momenta of the created pions has magnitude 358.3 MeV/c. See Table 52-4 for the rest energies of the pions.

6. Observations of neutrinos emitted by the supernova SN1987a in the Large Magellanic Cloud, see Figs. 52-3 and 52-15, place an upper limit on the rest energy of the electron neutrino of 20 eV. Suppose that the rest energy of the neutrino, rather than being zero, is in fact equal to 20 eV. How much slower than light is a 1.5-MeV neutrino, emitted in a β-decay, moving?

FIGURE 52-15. Exercise 6.

7. Calculate the range of the weak force between two neighboring protons. Assume that the Z^0 boson is the field particle; see Table 52-6.

8. Identify the interaction responsible for each of the following decays: *(a)* $\pi^0 \rightarrow \gamma + \gamma$; *(b)* $K^+ \rightarrow \mu^+ + \nu_\mu$; *(c)* $\eta' \rightarrow \eta + \pi^+ + \pi^-$; *(d)* $\Sigma^+ \rightarrow p + \pi^0$.

52-3 Conservation Laws

9. Use the conservation laws to identify the particle labeled x in the following reactions, which proceed by means of the strong interaction: (*a*) $p + p \rightarrow p + \Lambda^0 + x$; (*b*) $p + \bar{p} \rightarrow n + x$; (*c*) $\pi^- + p \rightarrow \Xi^0 + K^0 + x$.

10. The reaction $\pi^+ + p \rightarrow p + p + \bar{n}$ proceeds by the strong interaction. By applying the conservation laws, deduce the charge, baryon number, and strangeness of the antineutron.

11. By examining strangeness, determine which of the following decays or reactions proceed via the strong interaction: (*a*) $K^0 \rightarrow \pi^+ + \pi^-$; (*b*) $\Lambda^0 + p \rightarrow \Sigma^+ + n$; (*c*) $\Lambda^0 \rightarrow p + \pi^-$; (*d*) $K^- + p \rightarrow \Lambda^0 + \pi^0$. See Tables 52-4 and 52-5 for values of S.

12. In addition to the decay mode listed in Table 52-4, give four other possible decays of the K^+ meson that satisfy the conservation laws.

13. Give one possible decay mode for (*a*) $\overline{\Lambda^0}$, (*b*) $\bar{n}$, (*c*) π^-, (*d*) K^-.

52-4 The Quark Model

14. Make a chart similar to Fig. 52-4 for the 10 spin-$\frac{3}{2}$ baryons listed in Table 52-5.

15. Identify the 10 spin-$\frac{3}{2}$ baryons with the three-quark combinations listed in Table 52-9.

16. Using the up, down, and strange quarks only, construct, if possible, a baryon (*a*) with $Q = -1$ and $S = -2$; (*b*) with $Q = +2$ and $S = 0$.

17. There is no known meson with $Q = +1$ and $S = -1$ or with $Q = -1$ and $S = +1$. Explain why, in terms of the quark model.

18. The quark composition of the proton and the neutron are uud and udd, respectively. What are the quark compositions of (*a*) the antiproton and (*b*) the antineutron?

19. (*a*) List the seven possible quark–antiquark combinations of u, d, c, and s quarks that contain at least one c quark or antiquark. Give the electric charge, strangeness, and charm for each combination. (*b*) Identify the spin-0 mesons in the following table with the quark–antiquark combinations in your list.

Particle	*Antiparticle*	Q	S	C
η_c	η_c	0	0	0
D^+	D^-	+1	0	+1
D^0	$\overline{D^0}$	0	0	+1
D_s^+	D_s^-	+1	+1	+1

20. Analyze the following decays or reactions in terms of the quark content of the particles: (*a*) $\Sigma^- \rightarrow n + \pi^-$; (*b*) $K^0 \rightarrow \pi^+ + \pi^-$; (*c*) $\pi^+ + p \rightarrow \Sigma^+ + K^+$; (*d*) $\gamma + n \rightarrow \pi^- + p$.

52-5 The Big Bang Cosmology

21. By choosing two points on each line of Fig. 52-6 and calculating the slopes, verify the given numerical values of the Hubble parameter.

22. If Hubble's law can be extrapolated to very large distances, at what distance would the recessional speed become equal to the speed of light?

23. Why is the observed wavelength of the 656.3-nm H_α line of hydrogen emitted by a galaxy at a distance of 2.4×10^8 pc?

24. In the laboratory, one of the lines of sodium is emitted at a wavelength of 590.0 nm. When observing the light from a particular galaxy, however, this line is seen at a wavelength of 602.0 nm. Calculate the distance to the galaxy, assuming that Hubble's law holds.

25. (*a*) What is the minimum temperature of the universe necessary for the photons to produce $\pi^+\pi^-$ pairs? (*b*) At what age did the universe have this temperature?

26. (*a*) Estimate the peak wavelength of the microwave background radiation from Fig. 52-8. (*b*) Find the frequency and photon energy corresponding to that wavelength.

27. (*a*) What was the age of the universe when its temperature was 5000 K? In which era did this occur (Fig. 52-9)? (*b*) Estimate the average photon energy at that time. (*c*) If there were 10^9 photons per nucleon at that time, estimate the ratio of the energy of the radiation to the rest energy of the matter.

52-6 Nucleosynthesis

52-7 The Age of the Universe

PROBLEMS

1. A neutral pion has a rest energy of 135 MeV and a mean life of 8.4×10^{-17} s. If it is produced with an initial kinetic energy of 80 MeV and it decays after one mean lifetime, what is the longest possible track that this particle could leave in a bubble chamber? Take relativistic time dilation into account.

2. A positive tau (τ^+, rest energy = 1777 MeV) is moving with 2200 MeV of kinetic energy in a circular path perpendicular to a uniform 1.2-T magnetic field. (*a*) Calculate the momentum of the tau in kg · m/s. Relativistic effects must be considered. (*b*) Find the radius of the circular path. (*Hint:* See Section 32-3.)

3. The wavelength of the photons at which a radiation field of temperature T radiates most intensely is given by $\lambda_{max} = (2898\ \mu m \cdot K)/T$ (see Eq. 45-4). (*a*) Show that the energy E in MeV of such a photon can be computed from

$$E = (4.28 \times 10^{-10}\ \text{MeV/K})T.$$

(*b*) At what minimum temperature can this photon create an electron–positron pair?

4. The recessional speeds of galaxies and quasars at great distances are close to the speed of light, so that the relativistic Doppler shift formula (see Section 39-6) must be used. The redshift is reported as z, where $z = \Delta\lambda/\lambda_0$ is the (fractional) red shift. (*a*) Show that, in terms of z, the recessional speed parameter $\beta = v/c$ is given by

$$\beta = \frac{z^2 + 2z}{z^2 + 2z + 2}.$$

(*b*) One of the most distant quasars detected has $z = 4.43$. Calculate its speed parameter. (*c*) Find the distance to the quasar, assuming that Hubble's law is valid to these distances.

5. Due to the presence everywhere of the microwave radiation background, the minimum possible temperature of a gas in interstellar or intergalactic space is not 0 K but 2.7 K. This implies that a significant fraction of the molecules in space that possess excited states of low excitation energy may, in fact, be in those excited states. Subsequent de-excitation leads to the emission of radiation that could be detected. Consider a (hypothetical) molecule with just one excited state. (*a*) What would the excitation energy have to be in order that 23% of the molecules be in the excited state? (*Hint:* see Section 48-9.) (*b*) Find the wavelength of the photon emitted in a transition to the ground state.

6. Will the universe continue to expand forever? To attack this question, make the (reasonable?) assumption that the recessional speed v of a galaxy a distance r from us is determined only by the matter that lies inside a sphere of radius r centered on us; see Fig. 52-16. If the total mass inside this sphere is M, the escape speed v_e is given by $v_e = \sqrt{2GM/r}$ (see Section 14-6). (*a*) Show that the average density ρ inside the sphere must be at least equal to the value given by

$$\rho = 3H^2/8\pi G$$

to prevent unlimited expansion. (*b*) Evaluate this "critical density" numerically; express your answer in terms of H-atoms/m^3. Measurements of the actual density are difficult and complicated by the presence of dark matter.

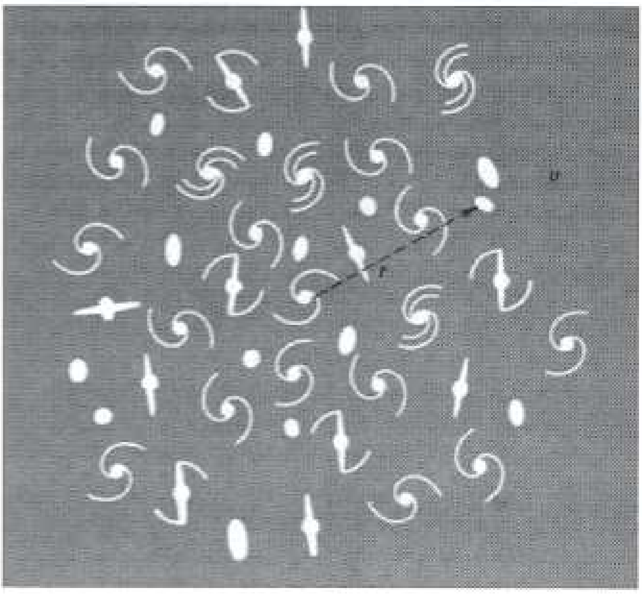

FIGURE 52-16. Problem 6.

7. The existence of dark (i.e., nonluminous) matter in a galaxy (such as our own) can be inferred by determining through observation the variation with distance in the orbital period of revolution of stars about the galactic center. This is then compared with the variation derived on the basis of the distribution of matter as indicated by the luminous material (mostly stars). Any significant deviation implies the existence of dark matter. For example, suppose that the matter (stars, gas, dust) of a particular galaxy, total mass M, is distributed uniformly throughout a sphere of radius R. A star, mass m, is revolving about the center of the galaxy in a circular orbit of radius $r < R$. (*a*) Show that the orbital speed v of the star is given by

$$v = r\sqrt{GM/R^3},$$

and therefore that the period T of revolution is

$$T = 2\pi\sqrt{R^3/GM},$$

independent of r. (*b*) What is the corresponding formula for the orbital period assuming that the mass of the galaxy is strongly concentrated toward the center of the galaxy, so that essentially all of the mass is at distances from the center less than r? These considerations applied to our own Milky Way galaxy indicate that substantial quantities of dark matter are present.

8. Find the temperature at which the fraction of photons with energy greater than 2.2 MeV in the Planck distribution is 0.2×10^{-9}. (Hint: Use Eq. 45-6.)

(*b*) One of the most distant quasars detected has $z = 4.43$. Calculate its speed parameter. (*c*) Find the distance to the quasar, assuming that Hubble's law is valid to these distances.

5. Due to the presence everywhere of the microwave radiation background, the minimum possible temperature of a gas in interstellar or intergalactic space is not 0 K but 2.7 K. This implies that a significant fraction of the molecules in space that possess excited states of low excitation energy may, in fact, be in those excited states. Subsequent de-excitation leads to the emission of radiation that could be detected. Consider a (hypothetical) molecule with just one excited state. (*a*) What would the excitation energy have to be in order that 23% of the molecules be in the excited state? (*Hint:* see Section 48-9.) (*b*) Find the wavelength of the photon emitted in a transition to the ground state.

6. Will the universe continue to expand forever? To attack this question, make the (reasonable?) assumption that the recessional speed v of a galaxy a distance r from us is determined only by the matter that lies inside a sphere of radius r centered on us; see Fig. 52-16. If the total mass inside this sphere is M, the escape speed v_e is given by $v_e = \sqrt{2GM/r}$ (see Section 14-6). (*a*) Show that the average density ρ inside the sphere must be at least equal to the value given by

$$\rho = 3H^2/8\pi G$$

to prevent unlimited expansion. (*b*) Evaluate this "critical density" numerically; express your answer in terms of H-atoms/m^3. Measurements of the actual density are difficult and complicated by the presence of dark matter.

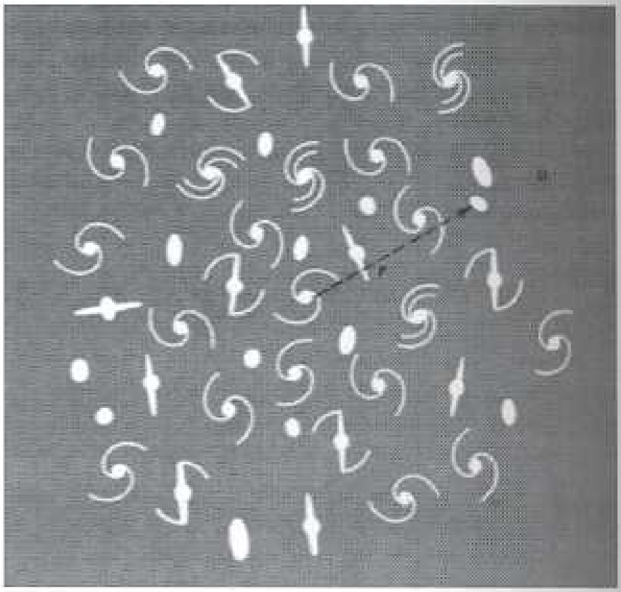

FIGURE 52-16. Problem 6.

7. The existence of dark (i.e., nonluminous) matter in a galaxy (such as our own) can be inferred by determining through observation the variation with distance in the orbital period of revolution of stars about the galactic center. This is then compared with the variation derived on the basis of the distribution of matter as indicated by the luminous material (mostly stars). Any significant deviation implies the existence of dark matter. For example, suppose that the matter (stars, gas, dust) of a particular galaxy, total mass M, is distributed uniformly throughout a sphere of radius R. A star, mass m, is revolving about the center of the galaxy in a circular orbit of radius $r < R$. (*a*) Show that the orbital speed v of the star is given by

$$v = r\sqrt{GM/R^3},$$

and therefore that the period T of revolution is

$$T = 2\pi\sqrt{R^3/GM},$$

independent of r. (*b*) What is the corresponding formula for the orbital period assuming that the mass of the galaxy is strongly concentrated toward the center of the galaxy, so that essentially all of the mass is at distances from the center less than r? These considerations applied to our own Milky Way galaxy indicate that substantial quantities of dark matter are present.

8. Find the temperature at which the fraction of photons with energy greater than 2.2 MeV in the Planck distribution is 0.2×10^{-9}. (Hint: Use Eq. 45-6.)