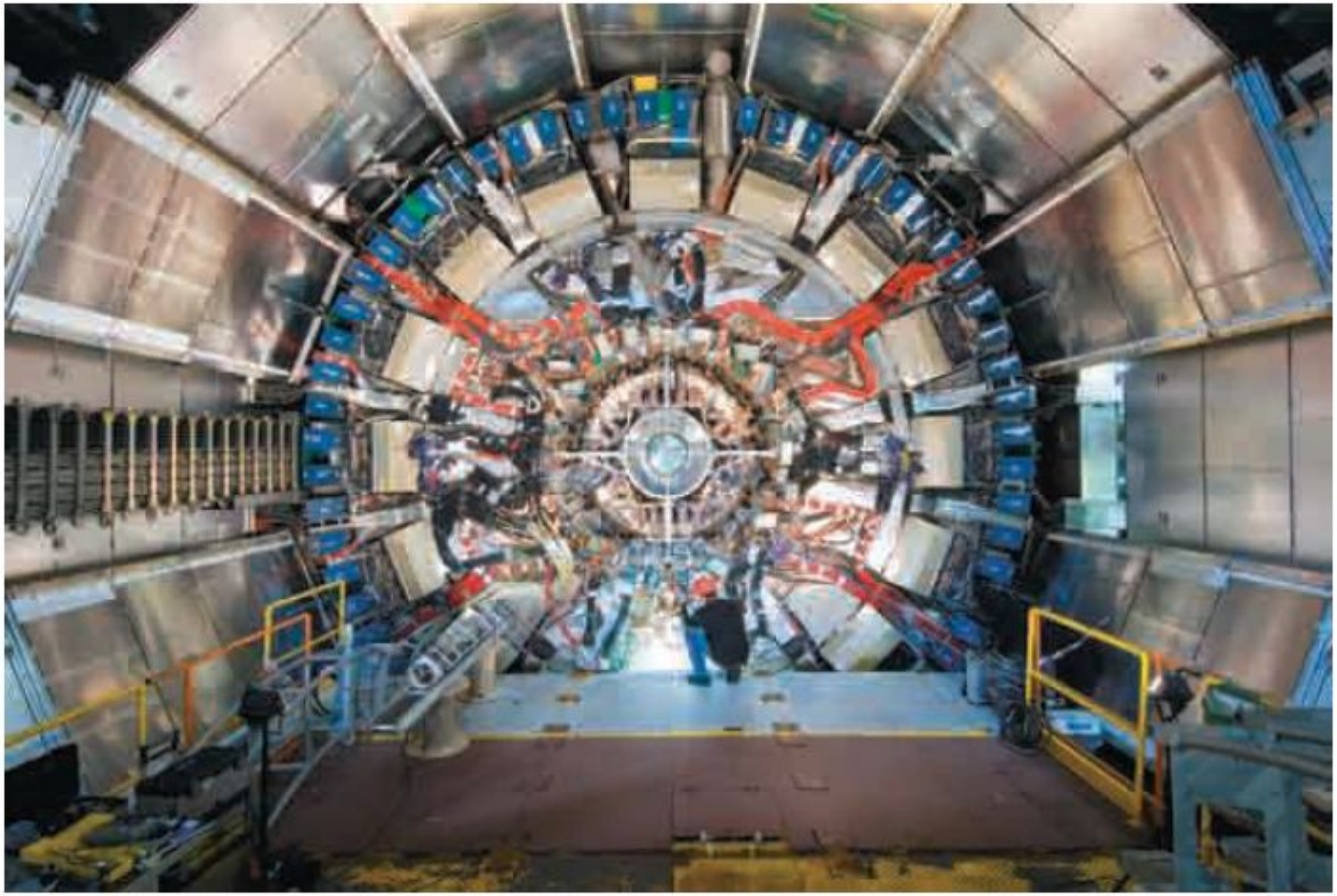
Chapter 44

Quarks, Leptons, and The Big Bang

44.2: Particles, Particles, Particles:



One of the detectors at the Large Hadron Collider at CERN, where the Standard Model of the elementary particles will be put to the test. (© *CERN Geneva*)

44.2: Particles, Particles, Particles: Fermion or Boson?

Fermions obey the Pauli exclusion principle, which asserts that only a single particle can be assigned to a given quantum state. Bosons *do not* obey this principle. Any number of bosons can occupy a given quantum state.

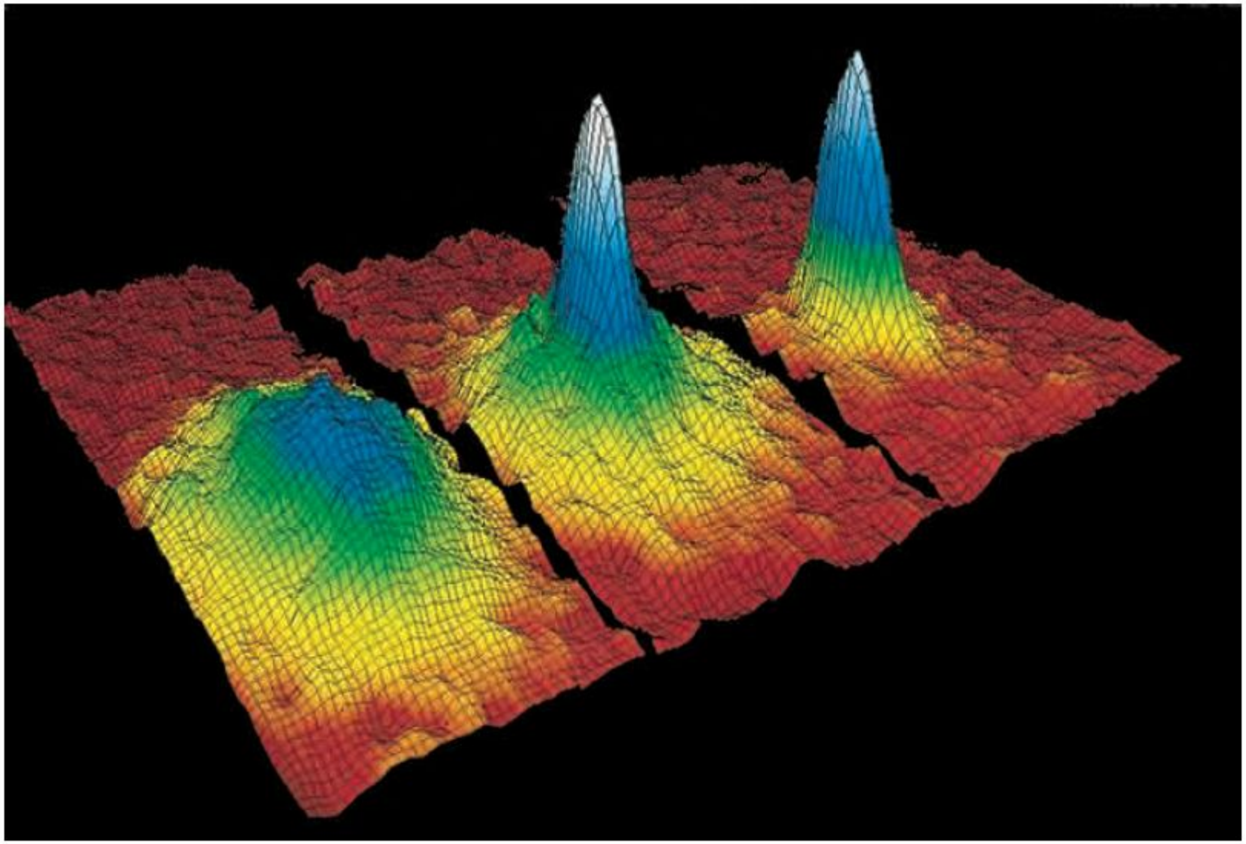
All particles have an intrinsic angular momentum called spin. The component of spin in any direction (assume the component to be along a *z axis)* is:

$$S_z = m_s\hbar \qquad \text{for } m_s = s, s-1, \ldots, -s, \qquad \hbar \text{ is } h/2\pi.$$

Particles with half-integer spin quantum numbers (like electrons) are called ***fermions***, after Enrico Fermi. Like electrons, protons and neutrons also have and are fermions.

Particles with zero or integer spin quantum numbers are called ***bosons,*** after Indian physicist Satyendra Nath Bose. Photons, which have *s=1*.

44.2: Particles, Particles, Particles: Fermion or Boson?



(a) (b) (c)

Fig. 44-1 Three plots of the particle speed distribution in a vapor of rubidium-87 atoms. The temperature of the vapor is successively reduced from plot (*a*) to plot (*c*). Plot (*c*) shows a sharp peak centered around zero speed; that is, all the atoms are in the same quantum state. The achievement of such a Bose–Einstein condensate, often called the Holy Grail of atomic physics, was finally recorded in 1995.
(Courtesy Michael Mathews)

44.2: Particles, Particles, Particles: Hadron or Lepton?

Particles on which the strong force acts are called ***hadrons*****.** Protons, neutrons, and pions are hadrons.

Particles on which the strong force does not act, leaving the weak force as the dominant force, are called ***leptons*****.** Electrons and neutrinos are leptons.

One can make a further distinction among the hadrons because some of them are bosons (called ***mesons***); the pion is an example.

The other hadrons are fermions (we call them ***baryons***); the proton is an example.

44.2: Particles, Particles, Particles: Particle or Antiparticle?

- In 1928 Dirac predicted that the electron e^- should have a positively charged counterpart of the same mass and spin. The counterpart, the *positron* e^+, *was* discovered in cosmic radiation in 1932 by Carl Anderson.

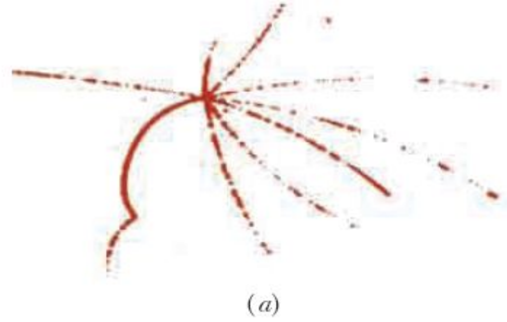
- Physicists then gradually realized that *every particle has a corresponding* ***antiparticle.*** The members of such pairs have the same mass and spin but opposite signs of electric charge (if they are charged) and opposite signs of quantum numbers.

- When a particle meets its antiparticle, the two can *annihilate* each other. The particle and antiparticle disappear and their combined energies reappear in other forms. For an electron annihilating with a positron, this energy reappears as two gamma-ray photons:

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

- An assembly of antiparticles, such as an antihydrogen atom, is often called *antimatter* to distinguish it from an assembly of common particles (matter).

44.3: An Interlude:



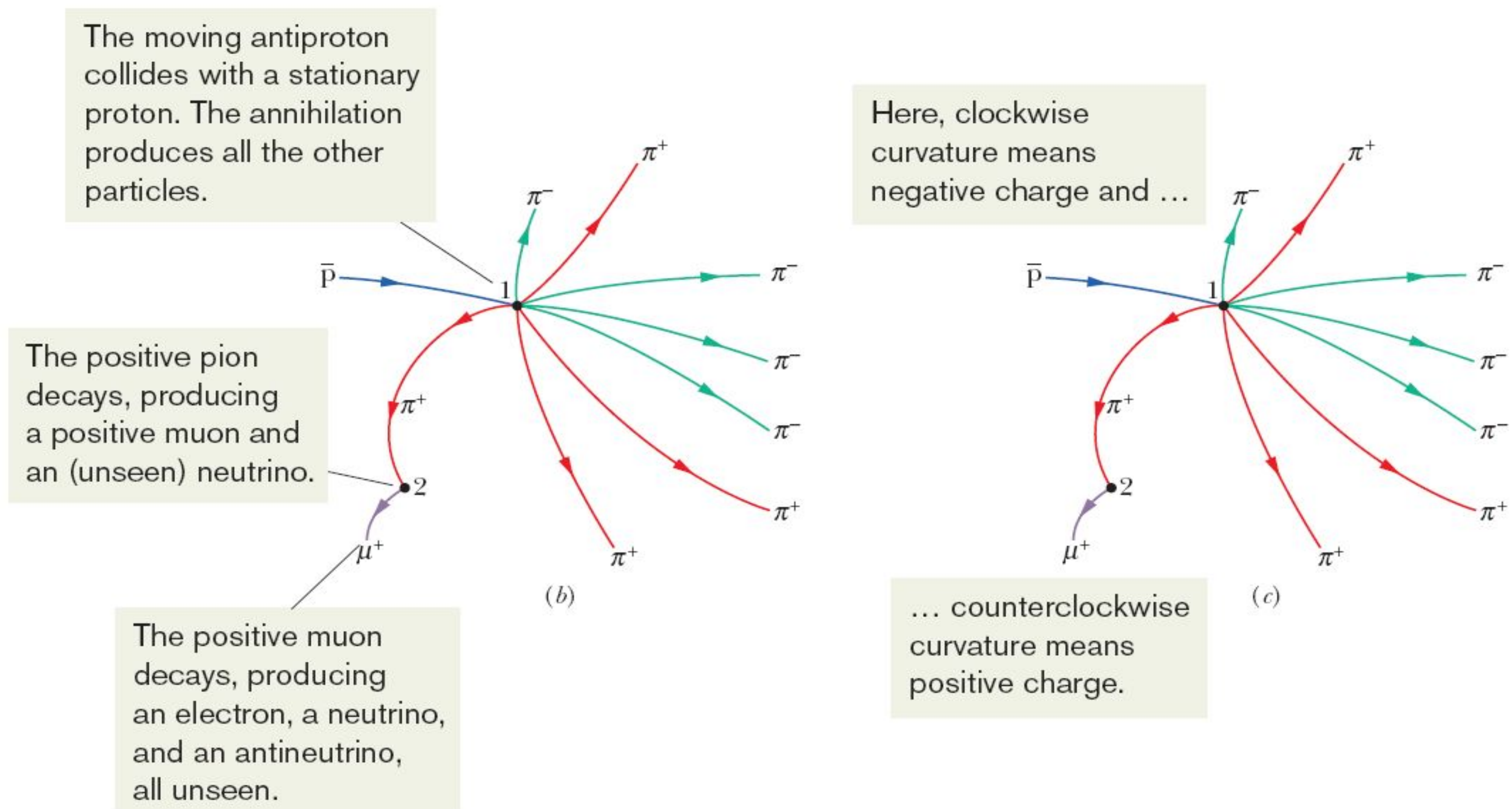


Fig. 44-2 (*a*) A bubble-chamber photograph of a series of events initiated by an antiproton that enters the chamber from the left. (*b*) The tracks redrawn and labeled for clarity. (*c*) The tracks are curved because a magnetic field present in the chamber exerts a deflecting force on each moving charged particle. *(Courtesy Lawrence Berkeley Laboratory)*

44.3: An Interlude:

In the previous figure, there are three separate subevents:

1. ***Proton – Antiproton Annihilation.*** The initiating antiproton (blue track) slams into a proton of the liquid hydrogen in the chamber, and the result is mutual annihilation. From the principle of conservation of linear momentum, the incoming antiproton must have had a forward momentum when it underwent annihilation. Further, because the particles are charged and moving through a magnetic field, the curvature of the paths reveal whether the particles are negatively charged (like the incident antiproton) or positively charged (Fig. 44-2*c).*

The total energy involved in the collision of the antiproton and the proton is the sum of the antiproton's kinetic energy and the two (identical) rest energies of those two particles (2x 938.3 MeV, or 1876.6 MeV). The annihilation produces four positive pions (red tracks in Fig. 44-2b*)* and four negative pions (green tracks).

$$\mathrm{p} + \bar{\mathrm{p}} \rightarrow 4\pi^{+} + 4\pi^{-}.$$

44.3: An Interlude:

The second subevent is:

2. *Pion Decay.* Pions are unstable particles and decay with a mean lifetime of 2.6 x10^{-8} s. At point 2 in Fig. 44-2*b,* one of the positive pions comes to rest in the chamber and decays spontaneously into an antimuon m (purple track) and a neutrino ν:

$$\pi^+ \rightarrow \mu^+ + \nu.$$

The neutrino, being uncharged, leaves no track. Both the antimuon and the neutrino are leptons; that is, they are particles on which the strong force does not act. Thus, the decay process is governed by the weak force, and is described as a *weak interaction.*

The spin angular momentum is conserved in the process, as are the net spin component S_z and the net charge.

The rest energy of an antimuon is 105.7 MeV and the rest energy of a neutrino is approximately 0. Since the pion is at rest when it decays, its energy is just its rest energy, 139.6 MeV. Thus, an energy of 139.6 MeV -105.7 MeV, or 33.9 MeV, is available to share between the antimuon and the neutrino as kinetic energy.

44.3: An Interlude:

The third subevent is:

3. ***Muon Decay.*** Muons (whether μ^- or μ^+) are also unstable, decaying with a mean life of 2.2x 10^{-6} s. Although the decay products are not shown in Fig. 44-2, the antimuon produced in the reaction of Eq. 44-7 comes to rest and decays spontaneously according to

$$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}.$$

The rest energy of the antimuon is 105.7 MeV, and that of the positron is only 0.511 MeV, leaving 105.2 MeV to be shared as kinetic energy among the three particles produced in the decay process.

44.3: An Interlude:

Table 44-1

The Particles or Antiparticles Involved in the Event of Fig. 44-2

Particle	Symbol	Charge q	Mass (MeV/c^2)	Spin Quantum Number s	Identity	Mean Life (s)	Antiparticle
Neutrino	ν	0	$\approx 1 \times 10^{-7}$	$\frac{1}{2}$	Lepton	Stable	$\bar{\nu}$
Electron	e^-	-1	0.511	$\frac{1}{2}$	Lepton	Stable	e^+
Muon	μ^-	-1	105.7	$\frac{1}{2}$	Lepton	2.2×10^{-6}	μ^+
Pion	π^+	$+1$	139.6	0	Meson	2.6×10^{-8}	π^-
Proton	p	$+1$	938.3	$\frac{1}{2}$	Baryon	Stable	$\bar{p}$

Example, Momentum and kinetic energy in a pion decay :

A stationary positive pion can decay according to

$$\pi^+ \rightarrow \mu^+ + \nu.$$

What is the kinetic energy of the antimuon μ^+? What is the kinetic energy of the neutrino?

KEY IDEA

The pion decay process must conserve both total energy and total linear momentum.

Energy conservation: Let us first write the conservation of total energy (rest energy mc^2 plus kinetic energy K) for the decay process as

$$m_\pi c^2 + K_\pi = m_\mu c^2 + K_\mu + m_\nu c^2 + K_\nu.$$

Because the pion was stationary, its kinetic energy K_π is zero. Then, using the masses listed for m_π, m_μ, and m_ν in Table 44-1, we find

$$\begin{aligned} K_\mu + K_\nu &= m_\pi c^2 - m_\mu c^2 - m_\nu c^2 \\ &= 139.6 \text{ MeV} - 105.7 \text{ MeV} - 0 \\ &= 33.9 \text{ MeV}, \end{aligned} \tag{44-9}$$

where we have approximated m_ν as zero.

Momentum conservation: We cannot solve Eq. 44-9 for either K_μ or K_ν separately, and so let us next apply the principle of conservation of linear momentum to the decay process. Because the pion is stationary when it decays, that principle requires that the muon and neutrino move in opposite directions after the decay. Assume that their motion is along an axis. Then, for components along that axis, we can write the conservation of linear momentum for the decay as

$$p_\pi = p_\mu + p_\nu,$$

which, with $p_\pi = 0$, gives us

$$p_\mu = -p_\nu. \tag{44-10}$$

Relating p and K: We want to relate these momenta p_μ and $-p_\nu$ to the kinetic energies K_μ and K_ν so that we can solve for the kinetic energies. Because we have no reason to believe that classical physics can be applied, we use Eq. 37-54, the momentum–kinetic energy relation from special relativity:

$$(pc)^2 = K^2 + 2Kmc^2. \tag{44-11}$$

From Eq. 44-10, we know that

$$(p_\mu c)^2 = (p_\nu c)^2. \tag{44-12}$$

Substituting from Eq. 44-11 for each side of Eq. 44-12 yields

$$K_\mu^2 + 2K_\mu m_\mu c^2 = K_\nu^2 + 2K_\nu m_\nu c^2.$$

Approximating the neutrino mass to be $m_\nu = 0$, substituting $K_\nu = 33.9 \text{ MeV} - K_\mu$ from Eq. 44-9, and then solving for K_μ, we find

$$\begin{aligned} K_\mu &= \frac{(33.9 \text{ MeV})^2}{(2)(33.9 \text{ MeV} + m_\mu c^2)} \\ &= \frac{(33.9 \text{ MeV})^2}{(2)(33.9 \text{ MeV} + 105.7 \text{ MeV})} \\ &= 4.12 \text{ MeV}. \end{aligned} \qquad \text{(Answer)}$$

The kinetic energy of the neutrino is then, from Eq. 44-9,

$$\begin{aligned} K_\nu &= 33.9 \text{ MeV} - K_\mu = 33.9 \text{ MeV} - 4.12 \text{ MeV} \\ &= 29.8 \text{ MeV}. \end{aligned} \qquad \text{(Answer)}$$

We see that, although the magnitudes of the momenta of the two recoiling particles are the same, the neutrino gets the larger share (88%) of the kinetic energy.

Example, Q in a proton-pion reaction:

The protons in the material filling a bubble chamber are bombarded with energetic antiparticles known as negative pions. At collision points, a proton and a pion transform into a negative kaon and a positive sigma:

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

The rest energies of these particles are

π^-	139.6 MeV	K^-	493.7 MeV
p	938.3 MeV	Σ^+	1189.4 MeV

What is the Q of the reaction?

KEY IDEA

The Q of a reaction is

$$Q = \begin{pmatrix}\text{initial total}\\ \text{mass energy}\end{pmatrix} - \begin{pmatrix}\text{final total}\\ \text{mass energy}\end{pmatrix}.$$

Calculation: For the given reaction, we find

$$\begin{aligned} Q &= (m_\pi c^2 + m_\mathrm{p} c^2) - (m_\mathrm{K} c^2 + m_\Sigma c^2) \\ &= (139.6\ \mathrm{MeV} + 938.3\ \mathrm{MeV}) \\ &\quad -(493.7\ \mathrm{MeV} + 1189.4\ \mathrm{MeV}) \\ &= -605\ \mathrm{MeV}. \end{aligned} \qquad \text{(Answer)}$$

The minus sign means that the reaction is *endothermic;* that is, the incoming pion (π^-) must have a kinetic energy greater than a certain threshold value if the reaction is to occur. The threshold energy is actually greater than 605 MeV because linear momentum must be conserved. (The incoming pion has momentum.) This means that the kaon (K^-) and the sigma (Σ^+) not only must be created but also must be given some kinetic energy. A relativistic calculation whose details are beyond our scope shows that the threshold energy for the reaction is 907 MeV.

44.4: The Leptons:

Table 44-2

The Leptons[a]

Family	Particle	Symbol	Mass (MeV/c^2)	Charge q	Antiparticle
Electron	Electron	e^-	0.511	-1	e^+
	Electron neutrino[b]	ν_e	$\approx 1 \times 10^{-7}$	0	$\bar{\nu}_e$
Muon	Muon	μ^-	105.7	-1	μ^+
	Muon neutrino[b]	ν_μ	$\approx 1 \times 10^{-7}$	0	$\bar{\nu}_\mu$
Tau	Tau	τ^-	1777	-1	τ^+
	Tau neutrino[b]	ν_τ	$\approx 1 \times 10^{-7}$	0	$\bar{\nu}_\tau$

[a]All leptons have spin quantum numbers of $\frac{1}{2}$ and are thus fermions.
[b]The neutrino masses have not been well determined.

44.4: The Leptons: The Conservation of Lepton Number

In all particle interactions, the net lepton number *for each family* is separately conserved.

Particle interactions involving leptons obey a conservation law for a quantum number called the ***lepton number L.*** Each (normal) particle is assigned *L=1,* and each antiparticle is assigned *L=-1.* All other particles, which are not leptons, are assigned *L=0.*

There are actually three lepton numbers L_e, L_μ, L_τ, and the net of each must remain unchanged during any particle interaction.

For example, in the process: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu.$

the net lepton number is *-1* on either side.

44.5: The Hadrons:

Baryons and mesons are hadrons, whose interaction are govered by the strong force.

A new quantum can be introduced, called the *baryon number*, B. The conservation law of B is given as:

To every baryon we assign $B = +1$. To every antibaryon we assign $B = -1$. To all particles of other types we assign $B = 0$. A particle process cannot occur if it changes the net baryon number.

Example, Proton decay: conservation of quantum numbers, energy, and momentum:

Determine whether a stationary proton can decay according to the scheme

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

Properties of the proton and the π^+ pion are listed in Table 44-1. The π^0 pion has zero charge, zero spin, and a mass energy of 135.0 MeV.

KEY IDEA

We need to see whether the proposed decay violates any of the conservation laws we have discussed.

Electric charge: We see that the net charge quantum number is initially +1 and finally 0 + 1, or +1. Thus, charge is conserved by the decay. Lepton number is also conserved, because none of the three particles is a lepton and thus each lepton number is zero.

Linear momentum: Because the proton is stationary, with zero linear momentum, the two pions must merely move in opposite directions with equal magnitudes of linear momentum (so that their total linear momentum is also zero) to conserve linear momentum. The fact that linear momentum *can* be conserved means that the process does not violate the conservation of linear momentum.

Energy: Is there energy for the decay? Because the proton is stationary, that question amounts to asking whether the proton's mass energy is sufficient to produce the mass energies and kinetic energies of the pions. To answer, we evaluate the Q of the decay:

$$\begin{aligned} Q &= \begin{pmatrix} \text{initial total} \\ \text{mass energy} \end{pmatrix} - \begin{pmatrix} \text{final total} \\ \text{mass energy} \end{pmatrix} \\ &= m_p c^2 - (m_0 c^2 + m_+ c^2) \\ &= 938.3 \text{ MeV} - (135.0 \text{ MeV} + 139.6 \text{ MeV}) \\ &= 663.7 \text{ MeV}. \end{aligned}$$

The fact that Q is positive indicates that the initial mass energy exceeds the final mass energy. Thus, the proton *does* have enough mass energy to create the pair of pions.

Spin: Is spin angular momentum conserved by the decay? This amounts to determining whether the net component S_z of spin angular momentum along some arbitrary z axis can be conserved by the decay. The spin quantum numbers s of the particles in the process are $\frac{1}{2}$ for the proton and 0 for both pions. Thus, for the proton the component S_z can be either $+\frac{1}{2}\hbar$ or $-\frac{1}{2}\hbar$ and for each pion it is $0\hbar$. We see that there is no way that S_z can be conserved. Hence, spin angular momentum is not conserved, and the proposed decay of the proton cannot occur.

Baryon number: The decay also violates the conservation of baryon number: The proton has a baryon number of $B = +1$, and both pions have a baryon number of $B = 0$. Thus, nonconservation of baryon number is another reason the proposed decay cannot occur.

Example, Xi-minus decay: conservation of quantum numbers:

A particle called xi-minus and having the symbol Ξ^- decays as follows:

$$\Xi^- \rightarrow \Lambda^0 + \pi^-.$$

The Λ^0 particle (called lambda-zero) and the π^- particle are both unstable. The following decay processes occur in *cascade* until only relatively stable products remain:

$$\Lambda^0 \rightarrow p + \pi^- \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e.$$

(a) Is the Ξ^- particle a lepton or a hadron? If the latter, is it a baryon or a meson?

KEY IDEAS

(1) Only three families of leptons exist (Table 44-2) and none include the Ξ^- particle. Thus, the Ξ^- must be a hadron. (2) To answer the second question we need to determine the baryon number of the Ξ^- particle. If it is $+1$ or -1, then the Ξ^- is a baryon. If, instead, it is 0, then the Ξ^- is a meson.

Baryon number: To see, let us write the overall decay scheme, from the initial Ξ^- to the final relatively stable products, as

$$\Xi^- \rightarrow p + 2(e^- + \bar{\nu}_e) + 2(\nu_\mu + \bar{\nu}_\mu). \qquad (44\text{-}15)$$

On the right side, the proton has a baryon number of $+1$ and each electron and neutrino has a baryon number of 0. Thus, the net baryon number of the right side is $+1$. That must then be the baryon number of the lone Ξ^- particle on the left side. We conclude that the Ξ^- particle is a baryon.

(b) Does the decay process conserve the three lepton numbers?

KEY IDEA

Any process must separately conserve the net lepton number for each lepton family of Table 44-2.

Lepton number: Let us first consider the electron lepton number L_e, which is $+1$ for the electron e^-, -1 for the anti-electron neutrino $\bar{\nu}_e$, and 0 for the other particles in the overall decay of Eq. 44-15. We see that the net L_e is 0 before the decay and $2[+1 + (-1)] + 2(0 + 0) = 0$ after the decay. Thus, the net electron lepton number *is* conserved. You can similarly show that the net muon lepton number and the net tau lepton number are also conserved.

(c) What can you say about the spin of the Ξ^- particle?

KEY IDEA

The overall decay scheme of Eq. 44-15 must conserve the net spin component S_z.

Spin: We can determine the spin component S_z of the Ξ^- particle on the left side of Eq. 44-15 by considering the S_z components of the nine particles on the right side. All nine of those particles are spin-$\frac{1}{2}$ particles and thus can have S_z of either $+\frac{1}{2}\hbar$ or $-\frac{1}{2}\hbar$. No matter how we choose between those two possible values of S_z, the net S_z for those nine particles must be a *half-integer* times $\hbar$. Thus, the Ξ^- particle must have S_z of a *half-integer* times $\hbar$, and that means that its spin quantum number s must be a half-integer. (It is $\frac{1}{2}$.)

44.6: Still Another Conservation Law:

Certain particles possess a certain property called strangeness, with its own quantum number S and its own conservation law.

The proton, neutron, and pion have $S = 0$ (they are not *“strange”*). It was proposed, however, that the kaon particle (K^+) has strangeness $S=1$ and that the sigma particle (Σ) has $S=-1$.

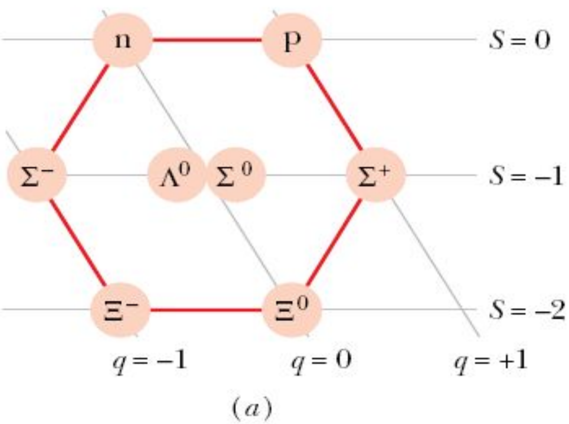
This may explain why K^+ and Σ are always produced in pairs: $\pi^+ + p \rightarrow K^+ + \Sigma^+$

In this reaction, the net strangeness is initially zero and also finally zero.

The conservation of strangeness thus follows as:

Strangeness is conserved in interactions involving the strong force.

44.7: The Eightfold Way:



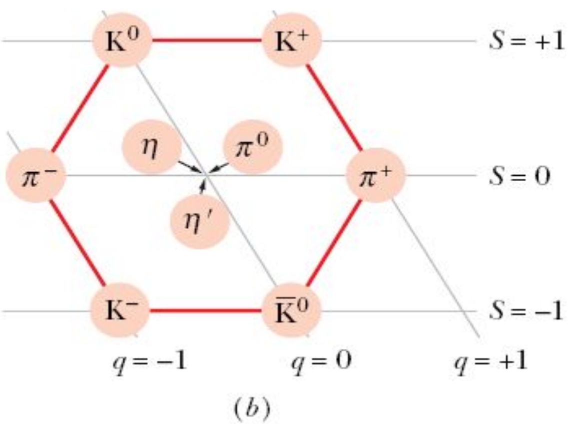


Fig. 44-3 (*a*) The eightfold way pattern for the eight spin-$\frac{1}{2}$ baryons listed in Table 44-3. The particles are represented as disks on a strangeness–charge plot, using a sloping axis for the charge quantum number. (*b*) A similar pattern for the nine spin-zero mesons listed in Table 44-4.

Table 44-3

Eight Spin-$\frac{1}{2}$ Baryons

Particle	Symbol	Mass (MeV/c^2)	Quantum Numbers	
			Charge q	Strangeness S
Proton	p	938.3	+1	0
Neutron	n	939.6	0	0
Lambda	Λ^0	1115.6	0	−1
Sigma	Σ^+	1189.4	+1	−1
Sigma	Σ^0	1192.5	0	−1
Sigma	Σ^-	1197.3	−1	−1
Xi	Ξ^0	1314.9	0	−2
Xi	Ξ^-	1321.3	−1	−2

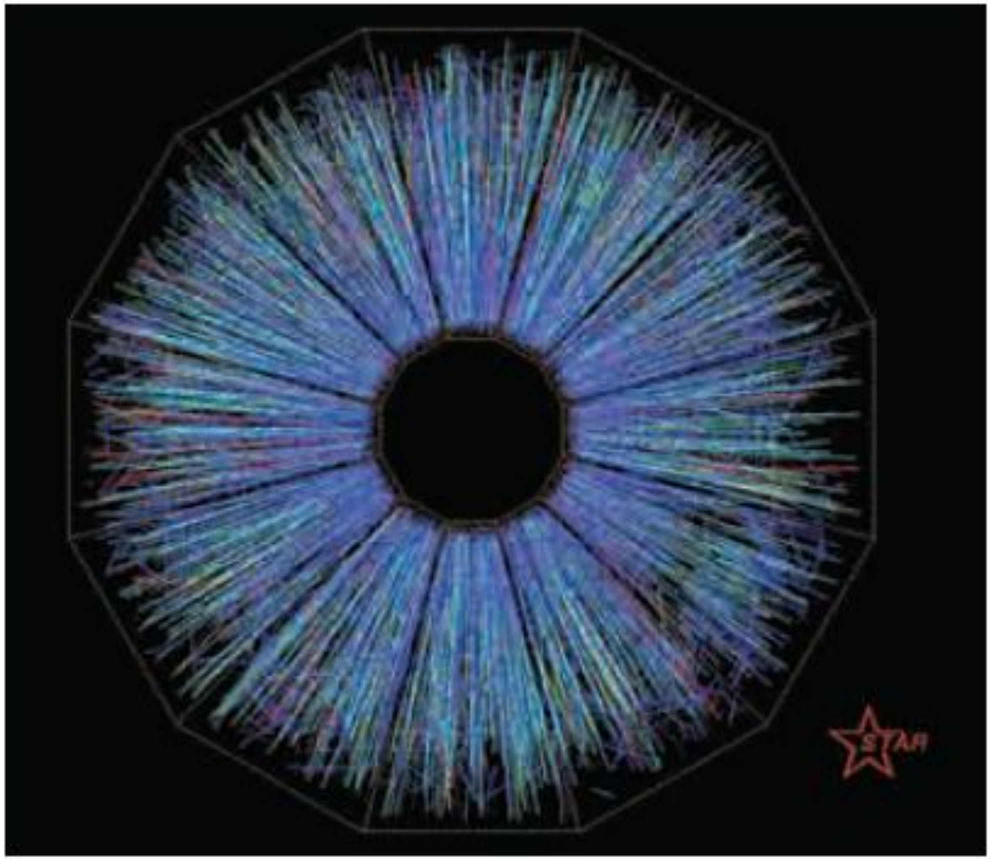
Table 44-4

Nine Spin-Zero Mesons[a]

Particle	Symbol	Mass (MeV/c^2)	Quantum Numbers	
			Charge q	Strangeness S
Pion	π^0	135.0	0	0
Pion	π^+	139.6	+1	0
Pion	π^-	139.6	−1	0
Kaon	K^+	493.7	+1	+1
Kaon	K^-	493.7	−1	−1
Kaon	K^0	497.7	0	+1
Kaon	$\overline{K}^0$	497.7	0	−1
Eta	η	547.5	0	0
Eta prime	η'	957.8	0	0

[a] All mesons are bosons, having spins of 0, 1, 2, ... The ones listed here all have a spin of 0.

44.8: The Quark Model:



The violent head-on collision of two 30 GeV beams of gold atoms in the RHIC accelerator at the Brookhaven National Laboratory. In the moment of collision, a gas of individual quarks and gluons was created. *(Courtesy Brookhaven National Laboratory)*

44.8: The Quark Model:

In 1964 Gell-Mann and George Zweig independently pointed out that the eightfold way patterns can be understood in a simple way if the mesons and the baryons are built up out of subunits that Gell-Mann called ***quarks*.**

Table 44-5

The Quarks[a]

			Quantum Numbers			
Particle	Symbol	Mass (MeV/c^2)	Charge q	Strangeness S	Baryon Number B	Antiparticle
Up	u	5	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\bar{u}$
Down	d	10	$-\frac{1}{3}$	0	$+\frac{1}{3}$	$\bar{d}$
Charm	c	1500	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\bar{c}$
Strange	s	200	$-\frac{1}{3}$	-1	$+\frac{1}{3}$	$\bar{s}$
Top	t	175 000	$+\frac{2}{3}$	0	$+\frac{1}{3}$	$\bar{t}$
Bottom	b	4300	$-\frac{1}{3}$	0	$+\frac{1}{3}$	$\bar{b}$

[a]All quarks (including antiquarks) have spin $\frac{1}{2}$ and thus are fermions. The quantum numbers q, S, and B for each antiquark are the negatives of those for the corresponding quark.

44.8: The Quark Model:

Quarks and Mesons:

Mesons are quark–antiquark pairs; this is consistent with the fact that mesons are not baryons, and have a baryon number $B = 0$. The baryon number for a quark is +⅓ and for an antiquark is -⅓; thus, the combination of baryon numbers in a meson is zero.

The meson π^+, consists of an up quark and an antidown quark; the charge quantum number of the up quark is +⅔ and that of the antidown quark is +⅓. This adds to a charge quantum number +1 for the π^+ meson.

A New Look at Beta Decay:

A neutron (udd) can change into a proton (uud) by changing a down quark into an up quark. We can view the fundamental beta-decay process as $\mathrm{d} \rightarrow \mathrm{u} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$.

Still More Quarks:

There are three more quarks: the *charm quark c, the top quark t, and the bottom quark b.* These quarks are exceptionally massive, the most massive of them (top) being almost 190 times more massive than a proton. To generate particles that contain such quarks, with such large mass energies, one must go to higher and higher energies.

Example, Quark composition of a xi-minus particle:

The Ξ^- (xi-minus) particle is a baryon with a spin quantum number s of $\frac{1}{2}$, a charge quantum number q of -1, and a strangeness quantum number S of -2. Also, it does not contain a bottom quark. What combination of quarks makes up Ξ^-?

Reasoning: Because the Ξ^- is a baryon, it must consist of three quarks (not two as for a meson).

Let us next consider the strangeness $S = -2$ of the Ξ^-. Only the strange quark s and the antistrange quark $\bar{s}$ have nonzero values of strangeness (see Table 44-5). Further, because only the strange quark s has a *negative* value of strangeness, Ξ^- must contain that quark. In fact, for Ξ^- to have a strangeness of -2, it must contain two strange quarks.

To determine the third quark, call it x, we can consider the other known properties of Ξ^-. Its charge quantum number q is -1, and the charge quantum number q of each strange quark is $-\frac{1}{3}$. Thus, the third quark x must have a charge quantum number of $-\frac{1}{3}$, so that we can have

$$\begin{aligned} q(\Xi^-) &= q(\mathrm{ssx}) \\ &= -\tfrac{1}{3} + (-\tfrac{1}{3}) + (-\tfrac{1}{3}) = -1. \end{aligned}$$

Besides the strange quark, the only quarks with $q = -\frac{1}{3}$ are the down quark d and bottom quark b. Because the problem statement ruled out a bottom quark, the third quark must be a down quark. This conclusion is also consistent with the baryon quantum numbers:

$$\begin{aligned} B(\Xi^-) &= B(\mathrm{ssd}) \\ &= \tfrac{1}{3} + \tfrac{1}{3} + \tfrac{1}{3} = +1. \end{aligned}$$

Thus, the quark composition of the Ξ^- particle is ssd.

44.9: The Basic Forces and Messenger Particles:

Electromagnetic Forces:

At the atomic level, Coulomb's Law explains the electromagnetic force that two electrons exert on each other.

At a deeper level, this interaction is described by ***quantum electrodynamics (QED)*.**
It is assumed that each electron senses the presence of the other by exchanging photons with it.

These photons, called ***virtual photons***, cannot be detected since they are emitted by one electron and absorbed by the other a very short time later. These are also called *messenger particles*.

If a stationary electron emits a photon and remains itself unchanged, energy is not conserved. The principle of conservation of energy is saved, by the uncertainty principle, written in the form

$$\Delta E \cdot \Delta t \approx \hbar.$$

When electron *A* emits a virtual photon, the overdraw in energy is quickly set right when that electron receives a virtual photon from electron *B*, within a time frame given by the above relation.

44.9: The Basic Forces and Messenger Particles:

The Weak Force:

A theory of the weak force, which acts on all particles, was developed by analogy with the theory of the electromagnetic force.

The messenger particles that transmit the weak force between particles, however, are not (massless) photons but massive particles, identified by the symbols W and Z.

The theory was so successful that it revealed the electromagnetic force and the weak force as being different aspects of a single ***electroweak force*.**

Particle	Charge	Mass
W	$\pm e$	$80.4\ \mathrm{GeV}/c^2$
Z	0	$91.2\ \mathrm{GeV}/c^2$

44.9: The Basic Forces and Messenger Particles:

The Strong Force:

The messenger particles in this case are massless, and are called ***gluons*****.**

The theory assumes that each “flavor” of quark comes in three varieties, labeled *red, yellow, and blue.* Thus, there are three up quarks, one of each color, and so on. The antiquarks also come in three colors, which we call *antired, antiyellow, and antiblue.*

The force acting between quarks is called a ***color force*** and the underlying theory is called ***quantum chromodynamics (QCD).***

Apparently, quarks can be assembled only in combinations that are *color-neutral.*

The color force not only acts to bind together quarks as baryons and mesons, but it also acts between such particles, in which case it has traditionally been called the strong force. Hence, not only does the color force bind together quarks to form protons and neutrons, but it also binds together the protons and neutrons to form nuclei.

44.9: The Basic Forces and Messenger Particles:

Einstein's Dream:

The unification of the fundamental forces of nature into a single force occupied Einstein's attention for much of his later life.

The weak force has been successfully combined with electromagnetism so that they may be jointly viewed as aspects of a single *electroweak force.*

The *grand unification theories (GUTs)* attempt to add the strong force to this combination, and are being pursued actively.

Theories that seek to add gravity, sometimes called *theories of everything (TOE),* are at an encouraging but speculative stage at this time.

44.10: A Pause for Reflection:

Once upon a time the temperature everywhere *was high enough to provide* energies in the GeV and TeV range. That time of extremely high temperatures occurred in the **big bang** beginning of the universe, when the universe (and both space and time) came into existence.

One reason scientists study particles at high energies is to understand what the universe was like just after it began.

All of space within the universe was initially tiny in extent, and the temperature of the particles within that space was incredibly high. With time, the universe expanded and cooled to lower temperatures, eventually to the size and temperature we see today.

The phrase "we see today" is complicated: When we look out into space, we are looking back in time because the light from the stars and galaxies has taken a long time to reach us.

The most distant objects that we can detect are ***quasars*** (***quasistellar objects***), which are the extremely bright cores of galaxies that are as much as 13 $\times 10^9$ ly from us. Each such core contains a gigantic black hole. As material (gas and even stars) is pulled into one of those black holes, the material heats up and radiates a tremendous amount of light, enough for us to detect in spite of the huge distance. Therefore, we "see" a quasar not as it looks today but as it once was, when that light began its journey to us billions of years ago.

44.11: The Universe is Expanding:

If we look at distant galaxies, beyond our immediate galactic neighbors, we find that they are *all moving* away (receding) from us!

In 1929 Edwin P. Hubble connected the recession speed v of a galaxy and its distance r from us—they are directly proportional:

$$v = Hr \qquad \text{(Hubble's law)}, \qquad H = 71.0 \text{ km/s} \cdot \text{Mpc} = 21.8 \text{ mm/s} \cdot \text{ly}.$$

H is called the ***Hubble constant.*** The value of H is usually measured in the unit kilometers per second-megaparsec (km/s Mpc), where the megaparsec is a length unit commonly used in astrophysics and astronomy:

$$1 \text{ Mpc} = 3.084 \times 10^{19} \text{ km} = 3.260 \times 10^{6} \text{ ly}.$$

The Hubble constant H has not had the same value since the universe began. Hubble's law is consistent with the hypothesis that the universe began with the big bang and has been expanding ever since.

If H is assumed constant, then the age of the universe, T, can be approximated as:

$$T = \frac{r}{v} = \frac{r}{Hr} = \frac{1}{H} \qquad \text{(estimated age of universe)}.$$

$$= \qquad 13.7 \times 10^{9} \text{ y}.$$

Example, Using Hubble's law to relate distance and recessional speed:

The wavelength shift in the light from a particular quasar indicates that the quasar has a recessional speed of 2.8×10^8 m/s (which is 93% of the speed of light). Approximately how far from us is the quasar?

KEY IDEA

We assume that the distance and speed are related by Hubble's law.

Calculation: From Eqs. 44-19 and 44-21, we find

$$r = \frac{v}{H} = \frac{2.8 \times 10^8 \text{ m/s}}{21.8 \text{ mm/s} \cdot \text{ly}}(1000 \text{ mm/m})$$
$$= 12.8 \times 10^9 \text{ ly.} \qquad \text{(Answer)}$$

This is only an approximation because the quasar has not always been receding from our location at the same speed v; that is, H has not had its current value throughout the time during which the universe has been expanding.

Example, Using Hubble's law to relate distance and Doppler shift:

A particular emission line detected in the light from a galaxy has a detected wavelength $\lambda_{det} = 1.1\lambda$, where λ is the proper wavelength of the line. What is the galaxy's distance from us?

KEY IDEAS

(1) We assume that Hubble's law ($v = Hr$) applies to the recession of the galaxy. (2) We also assume that the astronomical Doppler shift of Eq. 37-36 ($v = c\,\Delta\lambda/\lambda$, for $v \ll c$) applies to the shift in wavelength due to the recession.

Calculations: We can then set the right side of these two equations equal to each other to write

$$Hr = \frac{c\,\Delta\lambda}{\lambda}, \tag{44-23}$$

which leads us to

$$r = \frac{c\,\Delta\lambda}{H\lambda}. \tag{44-24}$$

In this equation,

$$\Delta\lambda = \lambda_{det} - \lambda = 1.1\lambda - \lambda = 0.1\lambda.$$

Substituting this into Eq. 44-24 then gives us

$$r = \frac{c(0.1\lambda)}{H\lambda} = \frac{0.1c}{H}$$

$$= \frac{(0.1)(3.0 \times 10^8\ \text{m/s})}{21.8\ \text{mm/s}\cdot\text{ly}}(1000\ \text{mm/m})$$

$$= 1.4 \times 10^9\ \text{ly}. \qquad \text{(Answer)}$$

44.12: The Cosmic Background Radiation:

Cosmic background radiation is generated in the early universe and is filling all space almost uniformly. The cosmic background radiation is now known to be light that has been in flight across the universe since shortly after the universe began billions of years ago.

Currently this radiation has a maximum intensity at a wavelength of 1.1 mm, which lies in the microwave region of electromagnetic radiation. The wavelength distribution of this radiation matches the wavelength distribution of light that would be emitted by a laboratory enclosure with walls at a temperature of 2.7 K.

When the universe was even younger than when cosmic radiation originated, light could scarcely go any significant distance without being scattered by all the individual, high-speed particles along its path.

If a light ray started from, say, point *A,* it would be scattered in so many directions that if you could have intercepted part of it, you would have not been able to tell that it originated at point *A*.

However, after the particles began to form atoms, the scattering of light greatly decreased. A light ray from point *A* might then be able to travel for billions of years without being scattered. This light is the cosmic background radiation.

44.13: Dark Matter:

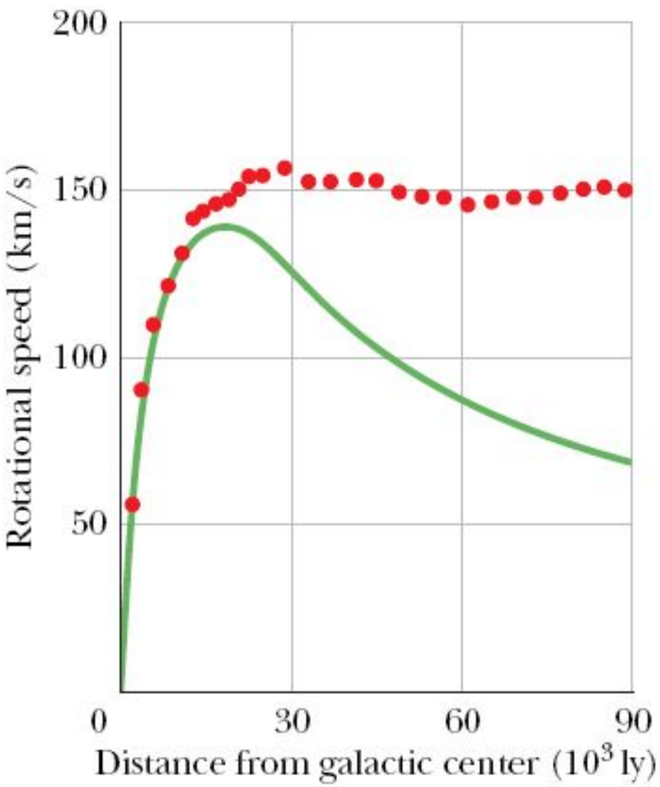


Fig. 44-5 The rotational speed of stars in a typical galaxy as a function of their distance from the galactic center. The theoretical solid curve shows that if a galaxy contained only the mass that is visible, the observed rotational speed would drop off with distance at large distances. The dots are the experimental data, which show that the rotational speed is approximately constant at large distances.

The only explanation for the findings that is consistent with Newtonian mechanics is that a typical galaxy contains much more matter than what we can actually see. The visible portion of a galaxy represents only about 5 to 10% of the total mass of the galaxy.

In addition to these studies of galactic rotation, many other observations lead to the conclusion that the universe abounds in matter that we cannot see.

This unseen matter is called ***dark matter*** because either it does not emit light or its light emission is too dim for us to detect.

This dark normal matter is only a small part of the total dark matter. The rest is called ***nonbaryonic dark matter*** because it does not contain protons and neutrons.

44.14: The Big Bang:

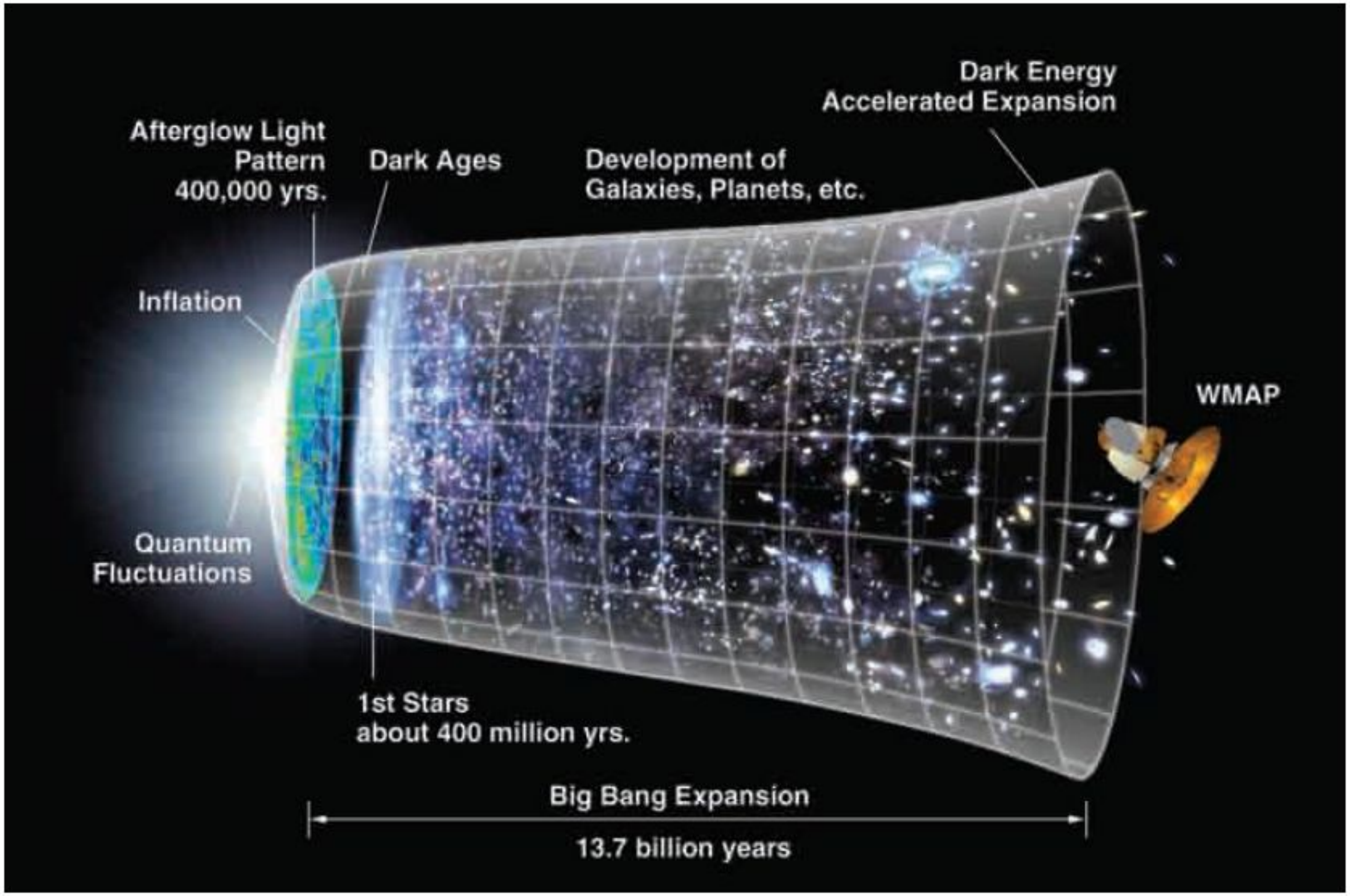


Fig. 44-6 An illustration of the universe from the initial quantum fluctuations just after $t = 0$ (at the left) to the current accelerated expansion, 13.7×10^9 y later (at the right). Don't take the illustration literally—there is no such *"external view"* of the universe because there is no exterior to the universe. *(Courtesy NASA)*

44.14: The Big Bang:

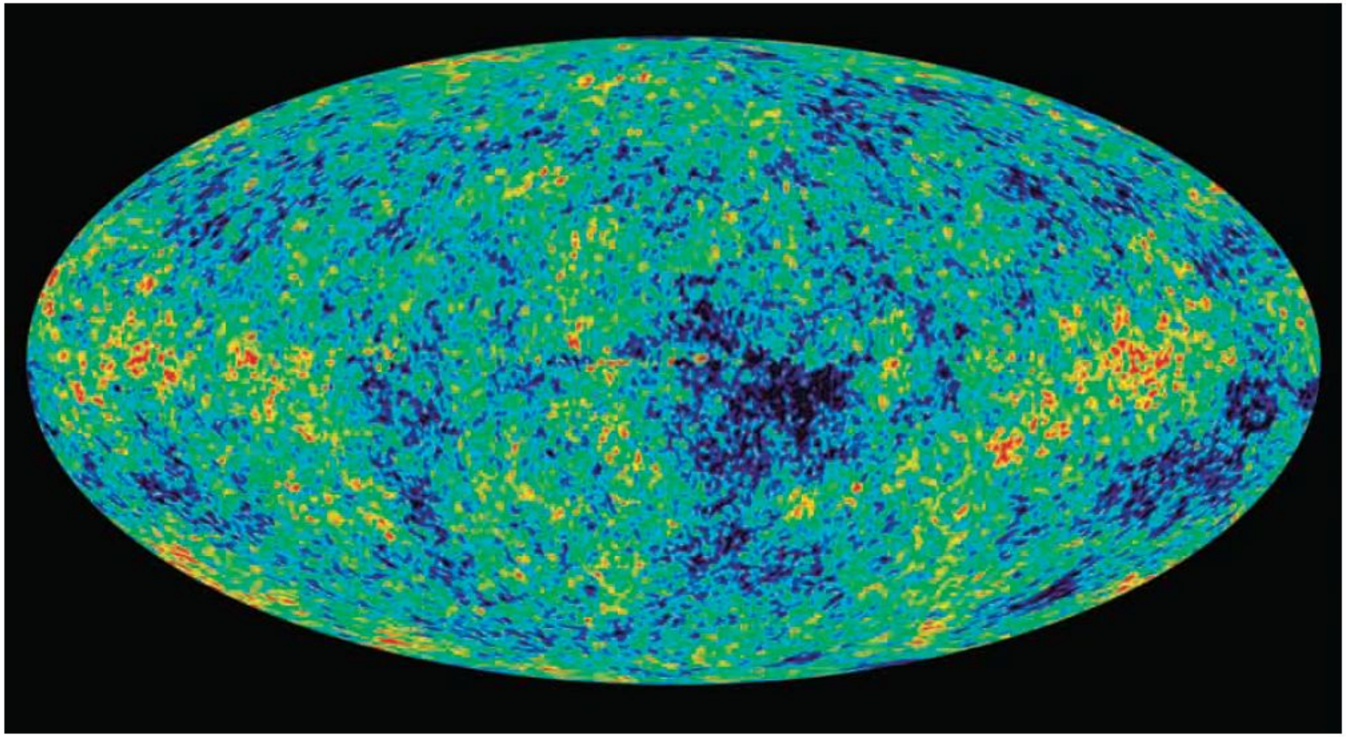


Fig. 44-7 This color-coded image is effectively a photograph of the universe when it was only 379 000 y old, which was about 13.7 $\times 10^9$ y ago. This is what you would have seen then as you looked away in all directions (the view has been condensed to this oval). Patches of light from collections of atoms stretch across the "sky," but galaxies, stars, and planets have not yet formed. *(Courtesy WMAP Science Team/NASA)*

44.15: A Summing Up:

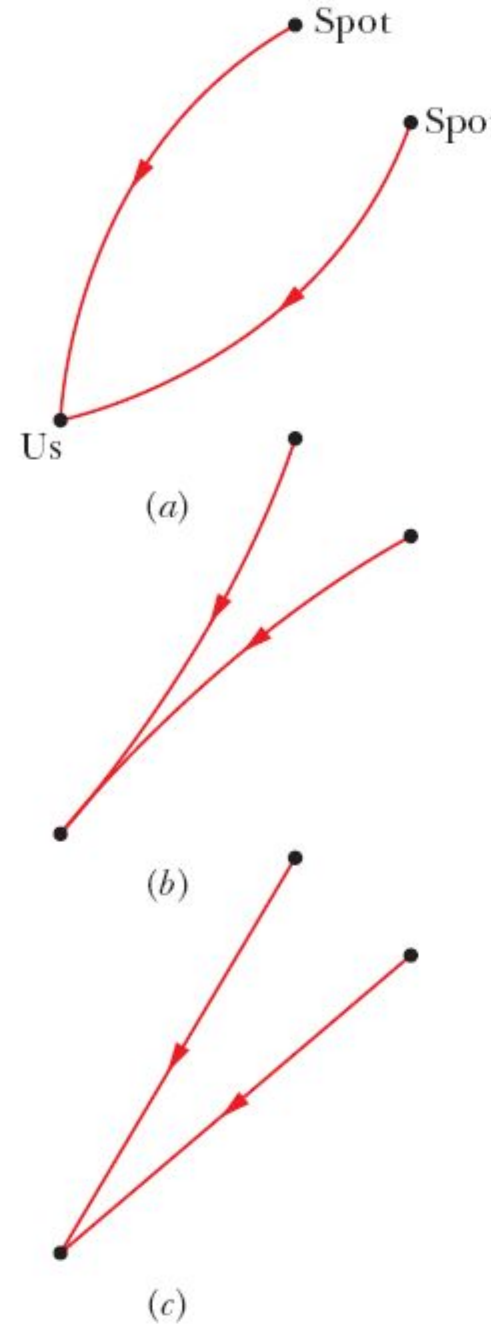


Fig. 44-8 Light rays from two adjacent spots in our view of the cosmic background radiation would reach us at an angle (*a*) greater than 1° or (*b*) less than 1° if the space along the light-ray paths through the universe were curved. (*c*) An angle of 1° means that the space is not curved.