

## Chapter 6: Elementary Particle Physics and The Unification of The Forces

“Three quarks for Muster Mark!  
Sure he hasn’t got much of a bark  
and sure any he has it’s all beside the mark”  
James Joyce, *Finnegan’s Wake*

### 6.1 Introduction

Man has always searched for simplicity in nature. Recall that the ancient Greeks tried to describe the entire physical world in terms of the four quantities of earth, air, fire, and water. These, of course, have been replaced with the fundamental quantities of length, mass, charge, and time in order to describe the physical world of space, matter, and time. We have seen that space and time are not independent quantities, but rather are a manifestation of the single quantity — spacetime — and that mass and energy are interchangeable, so that energy could even be treated as one of the fundamental quantities. We also found that energy is quantized and therefore, matter should also be quantized. What is the smallest quantum of matter? That is, what are the fundamental or elementary building blocks of matter? What are the forces that act on these fundamental particles? Is it possible to combine these forces of nature into one unified force that is responsible for all the observed interactions? We shall attempt to answer these questions in this chapter.

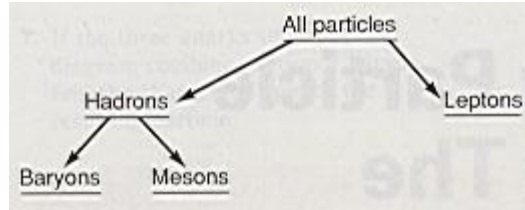
### 6.2 Particles and Antiparticles

As mentioned in chapter 20, the Greek philosophers Leucippus and Democritus suggested that matter is composed of fundamental or elementary particles called atoms. The idea was placed on a scientific foundation with the publication, by John Dalton, of *A New System of Chemical Philosophy* in 1808, in which he listed about 20 chemical elements, each made up of an atom. By 1896 there were about 60 known elements. It became obvious that there must be a way to arrange these different atoms in an orderly way in order to make sense of what was quickly becoming chaos. In 1869 the Russian chemist, Dimitri Mendeleev, developed the periodic table of the elements based on the chemical properties of the elements. Order was brought to the chaos of the large diversity of elements. In fact, new chemical elements were predicted on the basis of the blank spaces found in the periodic table. Later with the discovery of the internal structure of the atom, the atom could no longer be considered as elementary

By 1932, only four elementary particles were known; the electron, the proton, the neutron, and the photon. Things looked simple again. But this simplicity was not to last. Other particles were soon discovered in cosmic rays. Cosmic rays are particles from outer space that impinge on the top of the atmosphere. Some of them make it to the surface of the earth, whereas others decay into still other particles before they reach the surface. Other new particles were found in the large

accelerating machines made by man. Today, there are hundreds of such particles. Except for the electron, proton, and neutron, most of these elementary particles decay very quickly. We are again in the position of trying to make order out of the chaos of so many particles.

The first attempt at order is the classification of particles according to the scheme shown in figure 6.1. All the elementary particles can be grouped into particles called hadrons or leptons.



**Figure 6.1** First classification of the elementary particles.

## Leptons

The **Leptons** are particles that are not affected by the strong nuclear force. They are very small in terms of size, in that they are less than  $10^{-19}$  m in diameter. They all have spin  $\frac{1}{2}$  in units of  $\hbar$ . There are a total of six leptons: the electron,  $e^-$ , the muon,  $\mu^-$  and the tauon,  $\tau^-$ , each with an associated neutrino. They can be grouped in the form

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad (6.1)$$

There are thus three neutrinos: the neutrino associated with the electron,  $\nu_e$ ; the neutrino associated with the muon,  $\nu_\mu$ ; and the neutrino associated with the tauon,  $\nu_\tau$ . The muon is very much like an electron but it is much heavier. It has a mass about 200 times greater than the electron. It is not stable like the electron but decays in about  $10^{-6}$  s.

Originally the word lepton, which comes from the Greek word *leptos* meaning small or light in weight, signified that these particles were light. However, in 1975 the  $\tau$  lepton was discovered and it has twice the mass of the proton. That is, the  $\tau$  lepton is a heavy lepton, certainly a misnomer.

Leptons are truly elementary in that they apparently have no structure. That is, they are not composed of something still smaller. Leptons participate in the weak nuclear force, while the charged leptons,  $e^-$ ,  $\mu^-$ ,  $\tau^-$ , also participate in the electromagnetic interaction.

The muon was originally thought to be Yukawa's meson that mediated the strong nuclear force, and hence it was called a  $\mu^-$  meson. This is now known to be a misnomer, since the muon is not a meson but a lepton.

## Hadrons

**Hadrons** are particles that are affected by the strong nuclear force. There are hundreds of known hadrons. Hadrons have an internal structure, composed of what appears to be truly elementary particles called quarks. The hadrons can be further broken down into two subgroups, the baryons and the mesons.

1. **Baryons.** Baryons are heavy particles that, when they decay, contain at least one proton or neutron in the decay products. The baryons have half-integral spin, that is,  $1/2 \hbar$ ,  $3/2 \hbar$ , and so on. We will see in a moment that all baryons are particles that are composed of three quarks.

2. **Mesons.** Originally, mesons were particles of intermediate-sized mass between the electron and the proton. However many massive mesons have since been found, so the original definition is no longer appropriate. A meson is now defined as any particle whose decay products do not include a baryon. We will see that mesons are particles that are composed of a quark-antiquark pair. All mesons have integral spin, that is, 0, 1, 2, 3, and so on. The mass of the meson increases with its spin. A list of some of the elementary particles is shown in table 6.1.

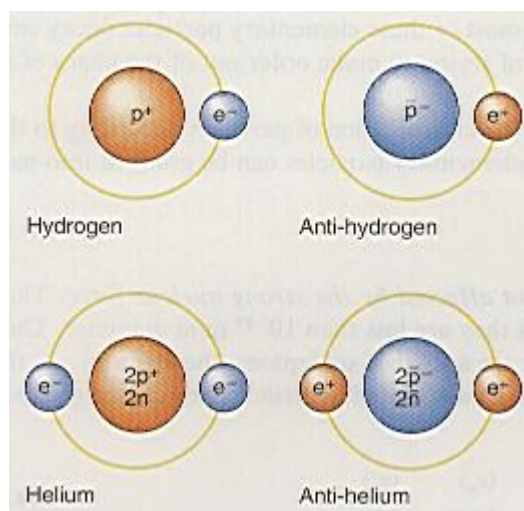
Table 6.1 List of Some of the Elementary Particles		
Leptons	electron, muon, tauon, neutrinos,	$e^-$ $\mu^-$ $\tau^-$ $\nu_e, \nu_\mu, \nu_\tau$
Hadrons		
Baryons	proton, neutron, delta, lambda, Sigma, Hyperon, Omega	p n $\Delta$ $\lambda$ $\Sigma$ $\Lambda$ $\Omega$
Mesons	pi, eta, rho, omega, delta, phi	$\pi$ $\eta$ $\rho$ $\Omega$ $\delta$ $\phi$

In 1928, Paul Dirac merged special relativity with the quantum theory to give a relativistic theory of the electron. A surprising result of that merger was that his equations predicted two energy states for each electron. One is associated with

the electron, whereas the other is associated with a particle, like the electron in every way, except that it carries a positive charge. This new particle was called the *antielectron* or the *positron*. This was the first prediction of the existence of antimatter. The positron was found in 1932.

*For every particle in nature there is associated an **antiparticle**. The antiparticle of the proton is the antiproton.* It has all the characteristics of the proton except that it carries a negative charge. Some purely neutral particles such as the photon and the  $\pi^0$  meson are their own antiparticles. Antiparticles are written with a bar over the symbol for the particle. Hence,  $\bar{p}$  is an antiproton and  $\bar{n}$  is an antineutron.

*Matter consists of electrons, protons and neutrons, whereas **antimatter** consists of antielectrons (positrons), antiprotons, and antineutrons.* Figure 6.2 shows atoms of matter and antimatter. The same electric forces that hold matter



**Figure 6.2** Matter and antimatter.

together, hold antimatter together. (Note that the positive and negative signs are changed in antimatter.) The antihelium nucleus has already been made in high-energy accelerators.

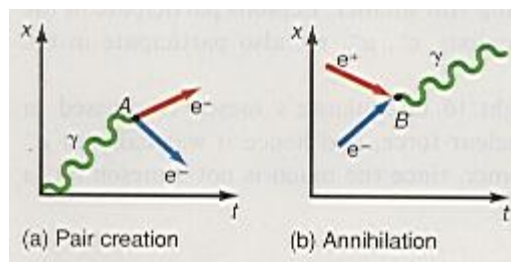
*Whenever particles and antiparticles come together they annihilate each other and only energy is left.* For example, when an electron comes in contact with a positron they annihilate according to the reaction

$$e^- + e^+ \rightarrow 2\gamma \quad (6.2)$$

where the  $2\gamma$ 's are photons of electromagnetic energy. (Two gamma rays are necessary in order to conserve energy and momentum.) This energy can also be used to create other particles. Conversely, particles can be created by converting the energy in the photon to a particle-antiparticle pair such as

$$\gamma \rightarrow e^- + e^+ \quad (6.3)$$

Creation or annihilation can be shown on a spacetime diagram, called a *Feynman diagram*, after the American physicist Richard Feynman (1918-1988), such as in figure 6.3. Figure 6.3(a) shows the creation of an electron-positron pair. A



**Figure 6.3** Creation and annihilation of particles.

photon  $\gamma$  moves through spacetime until it reaches the spacetime point A, where the energy of the photon is converted into the electron-positron pair. Figure 6.3(b) shows an electron and positron colliding at the spacetime point B where they annihilate each other and only the photon  $\gamma$  now moves through spacetime. (In order to conserve momentum and energy in the creation process, the presence of a relatively heavy nucleus is required.)

### 6.3 The Four Forces of Nature

In the study of nature, four forces that act on the particles of matter are known. They are:

1. *The Gravitational Force.* The gravitational force is the oldest known force. It holds us to the surface of the earth and holds the entire universe together. It is a long-range force, varying as  $1/r^2$ . Compared to the other forces of nature it is by far the weakest force of all.
2. *The Electromagnetic Force.* The electromagnetic force was the second force known. In fact, it was originally two forces, the electric force and the magnetic force, until the first unification of the forces tied them together as a single electromagnetic force. The electromagnetic force holds atoms, molecules, solids, and liquids together. Like gravity, it is a long-range force varying as  $1/r^2$ .
3. *The Weak Nuclear Force.* The weak nuclear force manifests itself not so much in holding matter together, but in allowing it to disintegrate, such as in the decay of the neutron and the proton. The weak force is responsible for the fusion process occurring in the sun by allowing a proton to decay into a neutron such as given in equation 5.21. The proton-proton cycle then continues until helium is formed and large quantities of energy are given off. The nucleosynthesis of the chemical elements also occurred because of the weak force. Unlike the gravitational and electromagnetic force, the weak nuclear force is a very short range force.
4. *The Strong Nuclear Force.* The strong nuclear force is responsible for holding the nucleus together. It is the strongest of all the forces but is a very short range force.

That is, its effects occur within a distance of about  $10^{-15}$  m, the diameter of the nucleus. At distances greater than this, there is no evidence whatsoever for its very existence. The strong nuclear force acts only on the hadrons.

Why should there be four forces in nature? Einstein, after unifying space and time into spacetime, tried to unify the gravitational force and the electromagnetic force into a single force. Although he spent a lifetime trying, he did not succeed. The hope of a unification of the forces has not died, however. In fact, we will see shortly that the electromagnetic force and the weak nuclear force have already been unified theoretically into the electroweak force by Glashow, Weinberg, and Salam, and experimentally confirmed by Rubbia. A grand unification between the electroweak and the strong force has been proposed. Finally an attempt to unify all the four forces into one superforce is presently underway.

## 6.4 Quarks

In the attempt to make order out of the very large number of elementary particles, Murray Gell-Mann and George Zweig in 1964, independently proposed that the hadrons were not elementary particles but rather were made of still more elementary particles. Gell-Mann called these particles, **quarks**. He initially assumed there were only three such quarks, but with time the number has increased to six. The six quarks are shown in table 6.2. *The names of the quarks are: up, down, strange, charmed, bottom, and top.* One of the characteristics of these

Table 6.2 The Quarks			
Name (Flavor)	Symbol	Charge	Spin
up	u	2/3	1/2
down	d	-1/3	1/2
strange	s	-1/3	1/2
charmed	c	2/3	1/2
bottom	b	-1/3	1/2
top	t	2/3	1/2

quarks is that they have fractional electric charges. That is, the up, charmed, and top quark has 2/3 of the charge found on the proton, whereas the down, strange, and bottom quark has 1/3 of the charge found on the electron. They all have spin 1/2, in units of  $\hbar$ . Each quark has an antiquark, which is the same as the original quark except it has an opposite charge. The antiquark is written with a bar over the letter, that is  $\bar{q}$ .

We will now see that all of the hadrons are made up of quarks. The baryons are made up of three quarks:

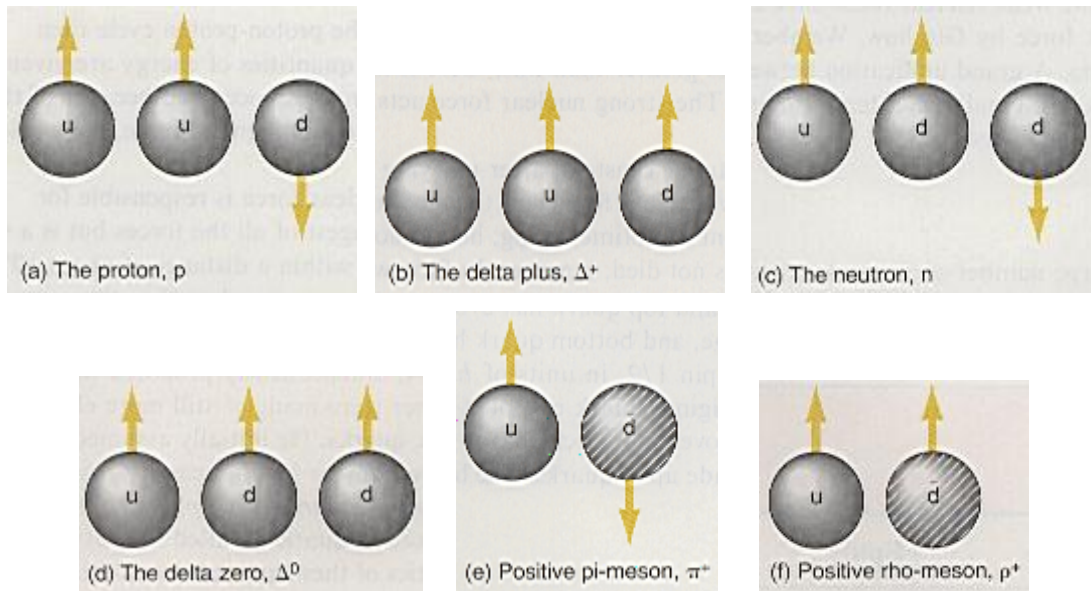
$$\text{Baryon} = qq\bar{q} \quad (6.4)$$



While the mesons are made up of a quark-antiquark pair:

$$\text{Meson} = q\bar{q} \quad (6.5)$$

As an example of the formation of a baryon from quarks, consider the proton. The proton consists of two up quarks and one down quark, as shown in figure 6.4(a).



**Figure 6.4** Some quark configurations of baryons and mesons.

The electric charge of the proton is found by adding the charges of the constitutive quarks. That is, since the  $u$  quark has a charge of  $2/3$ , and the  $d$  quark has a charge of  $-1/3$ , the charge of the proton is

$$2/3 + 2/3 - 1/3 = 1$$

which is exactly as expected. Now the proton should have a spin of  $1/2$  in units of  $\hbar$ . In figure 6.4(a), we see the two up quarks as having their spin up by the direction of the arrow on the quark. The down quark has its arrow pointing down to signify that its spin is down. Because each quark has spin  $1/2$ , the spin of the proton is found by adding the spins of the quarks as

$$1/2 + 1/2 - 1/2 = 1/2$$

We should note that the names up and down for the quarks are just that, a name, and have nothing to do with the direction of the spin of the quark. For example, the delta plus  $\Delta^+$  baryon is made from the same three quarks as the proton, but their spins are all aligned in the same direction, as shown in figure 6.4(b). Thus, the spin of the  $\Delta^+$  particle is

$$1/2 + 1/2 + 1/2 = 3/2$$

That is, the  $\Delta^+$  particle has a spin of  $3/2$ . Since it takes more energy to align the spins in the same direction, when quark spins are aligned, they have more energy. This manifests itself as an increased mass by Einstein's equivalence of mass and energy ( $E = mc^2$ ). Thus, we see that the mass of the  $\Delta^+$  particle has a larger mass than the proton. Hence, in the formation of particles from quarks, we not only have to know the types of quarks making up the particle but we must also know the direction of their spin.

Figure 6.4(c) shows that a neutron is made up of one up quark and two down quarks. The total electric charge is

$$2/3 - 1/3 - 1/3 = 0$$

While its spin is

$$1/2 + 1/2 - 1/2 = 1/2$$

Again note that the delta zero  $\Delta^0$  particle is made up of the same three quarks, figure 6.4(d), but their spins are all aligned.

As an example of the formation of a meson from quarks, consider the pi plus  $\pi^+$  meson in figure 6.4(e). It consists of an up quark and an antidown quark. Its charge is found as

$$2/3 + [ -(-1/3) ] = 2/3 + 1/3 = 1$$

That is, the d quark has a charge of  $-1/3$ , so its antiquark  $\bar{d}$  has the same charge but of opposite sign  $+1/3$ . The spin of the  $\pi^+$  is

$$1/2 - 1/2 = 0$$

Thus, the  $\pi^+$  meson has a charge of  $+1$  and a spin of zero.

If the spins of these same two quarks are aligned, as in figure 6.4(f), the meson is the positive rho-meson  $\rho^+$ , with electric charge of  $+1$  and spin of  $1$ .

The quark structure of some of the baryons is shown in table 6.3, whereas table 6.4 shows the quark structure for some mesons.

Particles that contain the strange quark are called strange particles. The reason for this name is because these particles took so much longer to decay than the other elementary particles, that it was considered strange.

If a proton or neutron consists of quarks, we would like to "see" them. Just as Rutherford "saw" inside the atom by bombarding it with alpha particles, we can "see" inside a proton by bombarding it with electrons or neutrinos. In 1969, at the Stanford Linear Accelerator Center (SLAC), protons were bombarded by high-energy electrons. *It was found that some of these electrons were scattered at very large angles, just as in Rutherford scattering, indicating that there are small constituents within the proton.* Figure 6.5 shows the picture of a proton as

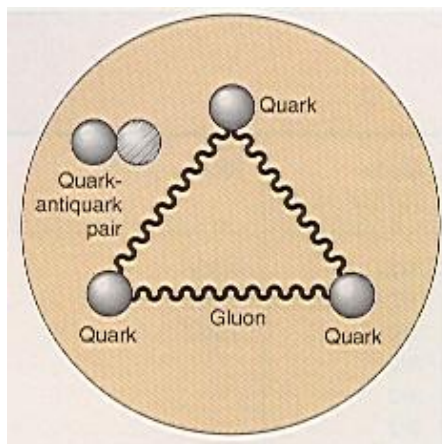


Table 6.3 Quark Structure of Some of the Baryons					
Name	Symbol	Structure	Charge (units of e)	Spin (units of $\hbar$ )	Mass (GeV)
Proton	p	u u d	1	1/2	0.938
Neutron	n	u d d	0	1/2	0.94
Delta plus plus	$\Delta^{++}$	u u u	2	3/2	1.232
Delta plus	$\Delta^+$	u u d	1	3/2	
Delta zero	$\Delta^0$	u d d	0	3/2	
Delta minus	$\Delta^-$	d d d	-1	3/2	
Lambda zero	$\Lambda^0$	u d s	0	1/2	1.116
Positive sigma	$\Sigma^{*+}$	u u s	1	3/2	1.385
Positive sigma	$\Sigma^+$	u u s	1	1/2	1.189
Neutral sigma	$\Sigma^{*0}$	u d s	0	3/2	1.385
Neutral sigma	$\Sigma^0$	u d s	0	1/2	1.192
Negative sigma	$\Sigma^{*-}$	d d s	-1	3/2	1.385
Negative sigma	$\Sigma^-$	d d s	-1	1/2	1.197
Negative xi	$\Xi^-$	s d s	-1	1/2	1.321
Neutral xi	$\Xi^0$	s u s	0	1/2	1.315
Omega minus	$\Omega^-$	s s s	-1	3/2	1.672
Charmed lambda	$\Lambda_c^+$	u d c	1	1/2	2.281

Table 6.4 Quark Structure of Some Mesons					
Name	Symbol	Structure	Charge (units of e)	Spin (units of $\hbar$ )	Mass (GeV)
Positive pion	$\pi^+$	$\bar{d}$ u	1	0	0.14
Positive rho	$\rho^+$	$\bar{d}$ u	1	1	0.77
Negative pion	$\pi^-$	$\bar{u}$ d	-1	0	0.14
Negative rho	$\rho^-$	$\bar{u}$ d	-1	1	0.77
Pi zero	$\pi^0$	50%( $\bar{u}$ u) + 50% $\bar{d}$ d)	0	0	0.135
Positive kaon	$K^+$	u $\bar{s}$	1	0	0.494
Neutral kaon	$K^0$	$\bar{s}$ d	0	0	0.498
Negative kaon	$K^-$	$\bar{u}$ s	-1	0	0.494
J/Psi (charmonium)	J/ $\Psi$	c $\bar{c}$	0	1	3.097
Charmed eta	$\eta_c$	c $\bar{c}$	0	0	2.98
Neutral D	$D^0$	$\bar{u}$ c	0	0	1.863
Neutral D	$D^{*0}$	$\bar{u}$ c	0	1	
Positive D	$D^+$	$\bar{d}$ c	1	0	1.868
Zero B-meson	$B^0$	$\bar{d}$ b	0		5.26
Negative B-meson	$B^-$	$\bar{u}$ b	-1		5.26
Upsilon	$\psi$	$\bar{b}$ b	0	1	9.46
Phi-meson	$\Phi$	s $\bar{s}$	0	1	1.02
F-meson	$F^+$	c $\bar{s}$	0	1	2.04

observed by scattering experiments. The scattering appears to come from particles with charges of  $+2/3$  and  $-1/3$  of the electronic charge. (Recall that the up quark has a charge of  $+2/3$ , whereas the down quark has a charge of  $-1/3$ .) *There is thus, experimental evidence for the quark structure of the proton.* Similar experiments have also been performed on neutrons with the same success. The scattering also confirmed the existence of some quark-antiquark pairs within the proton. Recall that quark-antiquark pairs are the constituents of mesons. The experiments also showed the existence of other particles within the nucleons, called *gluons*. The gluons are the exchange particles between the quarks that act to hold the quarks together. They are the nuclear glue.

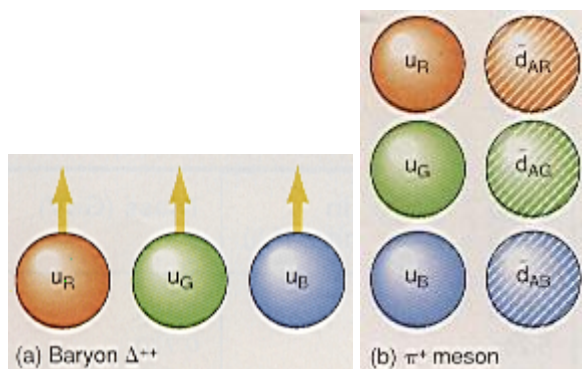
The one difficulty with the quark model at this point is that there seems to be a violation of the Pauli exclusion principle. Recall that the Pauli exclusion principle stated that no two electrons can have the same quantum numbers at the same time. The Pauli exclusion principle is actually more general than that, in that it applies not only to electrons, but to any particles that have half-integral spin, such as  $1/2$ ,  $3/2$ ,  $5/2$ , and so on. *Particles that have half-integral spin are called fermions.* Because quarks have spin  $1/2$ , they also must obey the Pauli exclusion principle. But the  $\Delta^{++}$  particle is composed of three up quarks all with the same spin, and the  $\Omega^-$  particle has three strange quarks all with the same spin. *Thus, there must be an additional characteristic of each quark, that is different for each quark, so that the Pauli exclusion principle will not be violated. This new attribute of the quark is called “color.”*



**Figure 6.5** Structure of the proton. (From D. H. Perkins, “Inside the Proton” in *The Nature of Matter*, Clarendon Press, Oxford. 1981)

*Quarks come in three colors: red, green, and blue.* We should note that these colors are just names and have no relation to the real colors that we see everyday with our eyes. The words are arbitrary. As an example, they could just as easily have been called A, B, and C. We can think of color in the same way as electric charges. Electric charges come in two varieties, positive and negative. Color charges come in three varieties: red, green, and blue. *Thus, there are three types of up*

quarks; a red-up quark  $u_R$ , a green-up quark  $u_G$ , and a blue-up quark  $u_B$ . Hence the delta plus-plus particle  $\Delta^{++}$  can be represented as in figure 6.6(a). In this way there is no violation of the Pauli exclusion principle since each up quark is different.



**Figure 6.6** Colored quarks.

All baryons are composed of red, green, and blue quarks. Just as the primary colors red, green, and blue add up to white, the combination of a red, green, and blue quark is said to make up the color white. All baryons are, therefore, said to be white, or colorless. Just as a quark has an antiquark, each color of quark has an anticolor. Hence, a red-up quark has an up antiquark that carries the color antired, and is called an antired-up quark. The varieties of quarks are called flavors, such as up, down, strange, and so on. Hence, each flavor of quark comes in three colors to give a total of six flavors times three colors equals 18 quarks. Associated with the 18 quarks are 18 antiquarks. Mesons, like baryons, must also be white or colorless. Hence, one colored quark of a meson must always be associated with an anticolor, since a color plus its anticolor gives white. Thus, possible formations of a  $\pi^+$  meson are shown in figure 6.6(b). That is, a red-up quark  $u_R$  combines with an antidown quark that carries the color antired  $\bar{d}_{AR}$  to form the white  $\pi^+$  meson. (The anticolor quark is shown with the hatched lines in figure 6.6.) Similarly the  $\pi^+$  meson can be made out of green and antigreen  $u_G\bar{d}_{AG}$  and blue and antiblue quarks  $u_B\bar{d}_{AB}$  and a linear combination of them, such as  $u_R\bar{d}_{AR} + u_G\bar{d}_{AG} + u_B\bar{d}_{AB}$ . We can rewrite equations 6.4 and 6.5 as

$$\text{Baryon} = \text{q} \quad \text{q} \quad \text{q}$$

(6.6)

$$\text{Meson} = \text{q} \quad \bar{\text{q}} + \text{q} \quad \bar{\text{q}} + \text{q} \quad \bar{\text{q}}$$

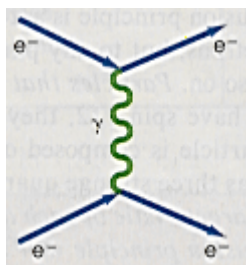
(6.7)

*The force between a quark carrying a color and its antiquark carrying anticolor is always attractive. Similarly the force between three quarks each of a different color is also attractive. All other combinations of colors gives a repulsive force. We will say more about colored quarks when we discuss the strong nuclear force in section 6.8.*

## 6.5 The Electromagnetic Force

The electromagnetic force has been discussed in some detail in your previous general physics course. To summarize the results from there, Coulomb's law gave the electric force between charged particles, and the electric field was the mediator of that force. The relation between electricity and magnetism was first discovered by Ampère when he found that a current flowing in a wire produced a magnetic field. Faraday found that a changing magnetic field caused an electric current. James Clerk Maxwell synthesized all of electricity with all of magnetism into his famous equations of electromagnetism. That is, the separate force of electricity and the force of magnetism were unified into one electromagnetic force.

*The merger of electromagnetic theory with quantum mechanics has led to what is now called **quantum electrodynamics**, which is abbreviated **QED**. In QED the electric force is transmitted by the exchange of a virtual photon. That is, the force between two electrons can be visualized as in figure 6.7. Recall from chapter 3 that the Heisenberg uncertainty relation allows for the creation of a virtual particle as long as the energy associated with the mass of the virtual particle is repaid in a time interval  $\Delta t$  that satisfies equation 3.56. In figure 6.7, two electrons approach each other. The first electron emits a virtual photon and recoils as shown.*



**Figure 6.7** The electric force as an exchange of a virtual photon.

When the second electron absorbs that photon it also recoils as shown, leading to the result that the exchange of the photon caused a force of repulsion between the two electrons. As pointed out in chapter 3, this exchange force is strictly a quantum mechanical phenomenon with no real classical analogue. So it is perhaps a little more difficult to visualize that the exchange of a photon between an electron and a proton produces an attractive force between them. *The exchanged photon is the mediator or transmitter of the force. All of the forces of nature can be represented by an exchanged particle.*

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Because the rest mass of a photon is equal to zero, the range of the electric force is infinite. This can be shown with the help of a few equations from chapter 3. The payback time for the uncertainty principle was

$$\Delta t = \frac{\hbar}{\Delta E} \quad (3.56)$$

While the energy  $\Delta E$  was related to the mass  $\Delta m$  of the virtual particle by

$$\Delta E = (\Delta m)c^2$$

Substituting this into equation 3.56, gave for the payback time

$$\Delta t = \frac{\hbar}{(\Delta m)c^2} \quad (3.57)$$

The distance a virtual particle could move and still return during that time  $\Delta t$ , was given as

$$d = c \frac{\Delta t}{2} \quad (3.58)$$

This distance is called the *range* of the virtual particle. Substituting equation 3.57 into 3.58 gives for the range

$$\begin{aligned} d &= \frac{c \hbar}{2(\Delta m)c^2} \\ d &= \frac{\hbar}{2c} \frac{1}{\Delta m} \end{aligned} \quad (6.8)$$

For a photon, the rest mass  $\Delta m$  is equal to zero. So as the denominator of a fraction approaches zero, the fraction approaches infinity. Hence, the range  $d$  of the particle goes to infinity. Thus, the electric force should extend to infinity, which, of course, it does.

### 6.6 The Weak Nuclear Force

The weak nuclear force is best known for the part it plays in radioactive decay. Recall from chapter 5 on nuclear physics that the initial step in beta  $\beta^-$  decay is for a neutron in the nucleus to decay according to the relation

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (6.9)$$

Whereas the proton inside the nucleus decays as

$$p \rightarrow n + e^+ + \nu_e \quad (6.10)$$

and is the initial step in the beta  $\beta^+$  decay. Finally, the radioactive disintegration caused by the capture of an electron by the nucleus (electron capture), is initiated by the reaction

$$e^- + p \rightarrow n + \nu_e \quad (6.11)$$

These three reactions are just some of the reactions that are mediated by the weak nuclear force.

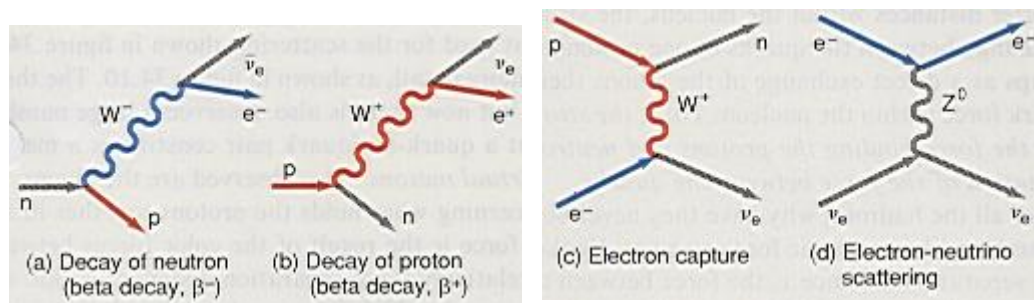
*The **weak nuclear force** does not exert the traditional push or pull type of force known in classical physics. Rather, it is responsible for the transmutation of the subatomic particles. The weak nuclear force is independent of electric charge and acts between leptons and hadrons and also between hadrons and hadrons. The range of the weak nuclear force is very small, only about  $10^{-17}$  m. The decay time is relatively large in that the weak decay occurs in about  $10^{-10}$  seconds, whereas decays associated with the strong interaction occur in approximately  $10^{-23}$  seconds.*

*The weak nuclear force is the weakest force after gravity. A product of weak interactions is the neutrino. The neutrinos are very light particles. Some say they have zero rest mass while others consider them to be very small, with an upper limit of about  $10^{-30}$  eV for the  $\nu_e$  neutrino. The neutrino is not affected by the strong or electromagnetic forces, only by the weak force. Its interaction is so weak that it can pass through the earth or the sun without ever interacting with anything.*

## 6.7 The Electroweak Force

Steven Weinberg, Abdus Salam, and Sheldon Glashow proposed a unification of the electromagnetic force with the weak nuclear force and received the Nobel Prize for their work in 1979. This force is called the **electroweak force**. Just as a virtual photon mediates the electromagnetic force between charged particles, it became obvious that there should also be some particle to mediate the weak nuclear force. The new electroweak force is mediated by four particles: the photon and three intermediate *vector bosons* called  $W^+$ ,  $W^-$ , and  $Z^0$ . The photon mediates the electromagnetic force, whereas the vector bosons mediate the weak nuclear force. In terms of the exchange particles, the decay of a neutron, equation 6.9, is shown in figure 6.8(a). *A neutron decays by emitting a  $W^-$  particle, thereby converting the neutron into a proton. The  $W^-$  particle subsequently decays within  $10^{-26}$  s into an electron and an antineutrino.* The decay of the proton in a radioactive nucleus, equation 6.10, is shown in figure 6.8(b). *The proton emits the positive intermediate vector boson,  $W^+$ , and is converted into a neutron. The  $W^+$  subsequently decays into a positron and a neutrino.* An electron capture, equation 6.11, is shown in figure 6.8(c) as a collision between a proton and an electron. The proton emits a  $W^+$  and is converted into a neutron. The  $W^+$  then combines with the electron forming a neutrino. The  $Z^0$  particle is observed in electron-neutrino scattering, as shown in figure 6.8(d).





**Figure 6.8** Examples of the electroweak force.

The vector bosons,  $W^+$  and  $W^-$ , were found experimentally in proton-antiproton collisions at high energies, at the European Center for Nuclear Research (CERN), in January 1983, by a team headed by Carlo Rubbia of Harvard University. The  $Z^0$  was found a little later in May 1983. The mass of the  $W^\pm$  was around 80 GeV, while the mass of the  $Z^0$  was about 90 GeV. Referring to equation 6.8, we see that for such a large mass,  $\Delta m$  in that equation gives a very short range  $d$  for the weak force, as found experimentally.

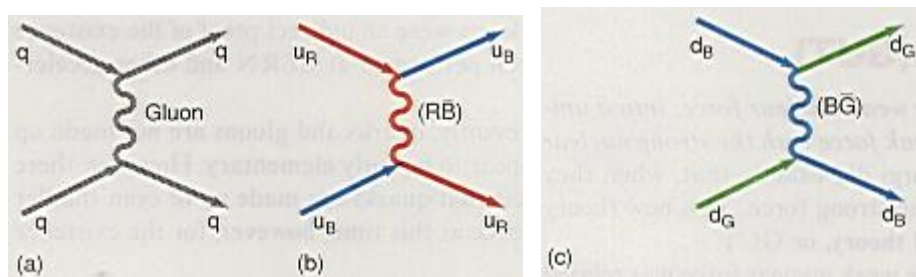
*At very high energies, around 100 GeV, the electromagnetic force and the weak nuclear force merge into one electroweak force that acts equally between all particles: hadrons and leptons, charged and uncharged.*

## 6.8 The Strong Nuclear Force

As mentioned previously, the **strong nuclear force** is responsible for holding the protons and neutrons together in the nucleus. The strong nuclear force must indeed be very strong to overcome the enormous electrical force of repulsion between the protons. Yukawa proposed that an exchange of mesons between the nucleons was the source of the nuclear force. But the nucleons are themselves made up of quarks. What holds these quarks together?

*In quantum electrodynamics (QED), the electric force was caused by the exchange of virtual photons. One of the latest theories in elementary particle physics is called **quantum chromodynamics (QCD)** and the force holding quarks together is caused by the exchange of a new particle, called a “gluon.”* That is, a gluon is the nuclear glue that holds quarks together in a nucleon. Figure 6.9(a) shows the force between quarks as the exchange of a virtual gluon. Gluons, like quarks, come in colors and anticolors. *A gluon interacting with a quark changes the color of a quark.* As an example, figure 6.9(b) shows a red-up quark  $u_R$  emitting a red-antiblue gluon ( $R\bar{B}$ ). The up quark loses its red color and becomes blue. That is, *in taking away an anticolor, the color itself must remain.* Hence, taking away an antiblue from the up quark, the color blue must remain. When the first blue- up quark



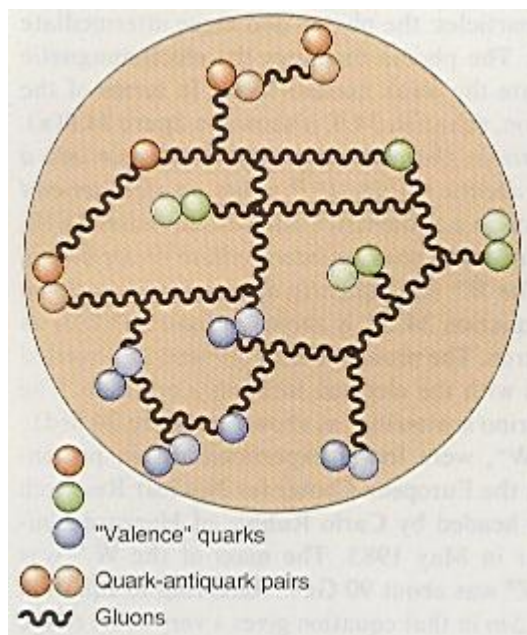


**Figure 6.9** Exchange of gluons between quarks.

receives the red-antiblue gluon ( $R\bar{B}$ ), the blue of the up quark combines with the antiblue of the gluon canceling out the color blue. (A color and its anticolor always gives white.) The red color of the gluon is now absorbed by the up quark turning it into a red-up quark. *Thus, in the process of exchanging the gluon, the quarks changed color.* Figure 6.9(c) shows a blue-down quark emitting a blue-antigreen gluon ( $B\bar{G}$ ), changing the blue-down quark into a green-down quark. When the first green-down quark absorbs the ( $B\bar{G}$ ) gluon, the color green cancels and the down quark becomes a blue-down quark.

All told, there are eight different gluons and each gluon has a mass. Each gluon always carries one color and one anticolor. Occasionally a gluon can transform to a quark-antiquark pair.

At energies greater than that used for the scattering shown in figure 6.5, scattering from protons reveals even more detail, as shown in figure 6.10. The three valence quarks are shown as before, but now there is also observed a large



**Figure 6.10** More detailed structure of the proton. (After D. H. Perkins, "The Nature of Matter", Oxford University Press)

number of quark-antiquark pairs. Recall that a quark-antiquark pair constitutes a meson. *Hence, the proton is seething with virtual mesons.* Also observed are the gluons. To answer the traditional questions concerning what holds the protons together in the nucleus, we can say that the strong force is the result of the color forces between the quarks within the nucleons. At relatively large separation distances within the nucleus, the quark-antiquark pair (meson), which is created by the gluons, is exchanged between the nucleons. At shorter distances within the nucleus, the strong force can be explained either as an exchange between the quarks of one proton and the quarks of another proton, or perhaps as a direct exchange of the gluons themselves, which give rise to the quark-quark force within the nucleon. *Thus, the strong force originates with the quarks, and the force binding the protons and neutrons together in the nucleus is the manifestation of the force between the quarks.*

If quarks are the constituents of all the hadrons, why have they never been isolated? The quark-quark force is something like an elastic force given by Hooke's law,  $F = kx$ . For small values of the separation distance  $x$ , the force between the quarks is small and the quarks are relatively free to move around within the particle. However, if we try to separate the quarks through a large separation distance  $x$ , then the force becomes very large, so large, in fact, that the quarks cannot be separated at all. *This condition is called the confinement of quarks. Thus, quarks are never seen in an isolated state because they cannot escape from the particle in which they are constituents.*

But is there any evidence for the existence of quarks? The answer is yes. Experiments were performed in the new PETRA storage ring at DESY (Deutsches Elektronen-Synchrotron) in Hamburg, Germany, in 1978. Electrons and positrons, each at an energy of 20 GeV, were fired at each other in a head-on collision. The annihilation of the electron and its antiparticle, the positron, produce a large amount of energy; it is from this energy that the quarks are produced. The experimenters found a series of "quark jets," which were the decay products of the quarks, exactly as predicted. (A quark jet is a number of hadrons flying off from the interaction in roughly the same direction.) These quark jets were an indirect proof of the existence of quarks. Similar experiments have been performed at CERN and other accelerators.

As far as can be determined presently, quarks and gluons are not made up of still smaller particles; that is, they appear to be truly elementary. However, there are some speculative theories that suggest that quarks are made up of even smaller particles called preons. There is no evidence at this time, however, for the existence of preons.

### 6.9 Grand Unified Theories (GUT)

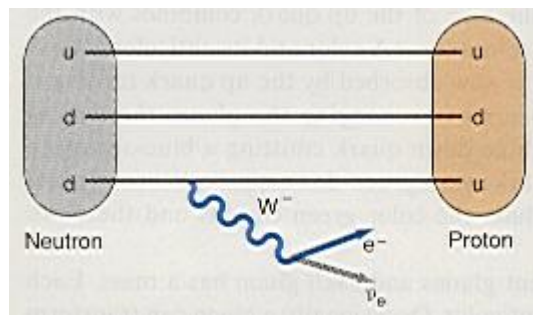
*If it is possible to merge the electric force with the weak nuclear force, into a unified electroweak force, why not merge the electroweak force with the strong nuclear force?*

In 1973 Sheldon Glashow and Howard Georgi did exactly that, when they published a theory merging the electroweak with the strong force. This new theory was the first of many to be called the **grand unified theory**, or GUT.

The first part of this merger showed how the weak nuclear force was related to the strong nuclear force. Let us consider the decay of the neutron shown in equation 6.9:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

We can now visualize this decay according to the diagram in figure 6.11. According



**Figure 6.11** The decay of the neutron.

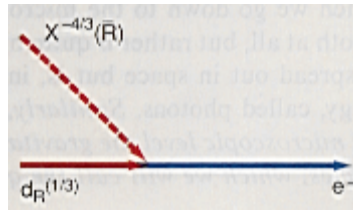
to the quark theory, a neutron is composed of one up quark and two down quarks. One of the down quarks of the neutron emits the  $W^-$  boson and is changed into an up quark, transforming the neutron into a proton. (Recall, that the proton consists of two up quarks and one down quark.) The  $W^-$  boson then decays into an electron and an antineutrino. Thus, *the weak force changes the flavor of a quark, whereas the strong force changes only the color of a quark.*

Above  $10^{15}$  GeV of energy, called the *grand unification energy*, we can no longer tell the difference between the strong, weak, and electromagnetic forces. Above this energy there is only one unified interaction or force that occurs. Of course, this energy is so large that it is greater than anything we could ever hope to create experimentally. As we shall see, however, it could have been attained in the early stages of the creation of the universe — the so-called “Big Bang.”

The strong nuclear force operates between quarks, whereas the weak nuclear force operates between quarks and leptons. If the strong and weak forces are to be combined, then the quarks and leptons should be aspects of one more fundamental quantity. That is, the grand unified force should be able to transform quarks into leptons and vice versa. In the grand unified theories, there are 24 particles that mediate the unified force and they are listed in table 6.5. In grand unified theories, the forces are unified because the forces arise through the exchange of the same family of particles. As seen before, the photon mediates the electromagnetic force; the vector bosons mediate the weak force; the gluons mediate the strong force; and there are now 12 new particles called X particles (sometimes progenitor and/or lepto-quark particles) that mediate the unified force. It is these X particles that are capable of converting hadrons into leptons by changing quarks to leptons.

Table 6.5 Family of Particles that Mediate the Unified Force		
Particle	Number	Force Mediated
Photon	1	Electromagnetic
Vector bosons ( $W^+$ , $W^-$ , $Z^0$ )	3	Weak
Gluons	8	Strong
X particles	12	Strong-electroweak

The X particles come in four different electrical charges,  $\pm 1/3$  and  $\pm 4/3$ . Thus, the X particles can be written as  $X^{1/3}$ ,  $X^{-1/3}$ ,  $X^{4/3}$ , and  $X^{-4/3}$ . Each of these X particles also comes in the three colors red, blue, and green, thereby giving the total of 12 X particles. The X particles can change a quark into a lepton, as shown in figure 6.12. An X particle carrying an electrical charge of  $-4/3$ , and a color charge



**Figure 6.12** Changing a quark to an electron.

of antired combines with a red-down quark, which carries an electrical charge of  $1/3$ . The colors red and antired cancel to give white, while the electrical charge becomes  $1/3 - 4/3 = -3/3 = -1$  and an electron is created out of a quark. This type of process is not readily seen in our everyday life because the mass of the virtual X particle must be of the order of  $10^{15}$  GeV, which is an extremely large energy. A similar analysis shows that an isolated proton should also decay. The lifetime, however, is predicted to be  $10^{32}$  yr. Experiments are being performed to look for the predicted decays. However, at the present time no such decay of an isolated proton has been found. An isolated proton seems to be a very stable particle, indicating that either more experiments are needed, or the GUT model needs some modifications.

## 6.10 The Gravitational Force and Quantum Gravity

As has been seen throughout this book, physics is a science of successive approximations to the truth hidden in nature. Newton found that celestial gravity was of the same form as terrestrial gravity and unified them into his law of universal gravitation. However, it turned out that it was not quite so universal. Einstein started the change in his special theory of relativity, which governed systems moving with respect to each other at constant velocity. As he generalized this theory to systems that were accelerated with respect to each other, he found

the equivalence between accelerated systems and gravity. The next step of course was to show that matter warped spacetime and gravitation was a manifestation of that warped spacetime. Thus, general relativity became a law of gravitation, and it was found that Newton's law of gravitation was only a special case of Einstein's theory of general relativity.

We have also seen that the quantum theory is one of the great new theories of modern physics, which seems to say that nature is quantized. There are quanta of energy, mass, angular momentum, charge, and the like. But general relativity, in its present format, is essentially independent of the quantum theory. It is, in this sense, still classical physics. It, too, must be only an approximation to the truth hidden in nature. *A more general theory should fuse quantum mechanics with general relativity — that is, we need a quantum theory of gravity.*

In order to combine quantum theory with general relativity (hereafter called Einstein's theory of gravitation), we have to determine where these two theories merge. Remember the quantum theory deals with very small quantities, because of the smallness of Planck's constant  $h$ , whereas Einstein's theory of gravitation deals with very large scale phenomena, or at least with very large masses that can significantly warp spacetime.

One of the important characteristics of the quantum theory is the wave-particle duality; waves can act as particles and particles can act as waves. And as has also been seen, waves can exist in the electromagnetic field. Let us, for the moment, compare electromagnetic fields with gravitational fields. On a large scale the electric field appears smooth. It is only when we go down to the microscopic level that we see that the electric field is not smooth at all, but rather is quite bumpy, because the energy of the electric field is not spread out in space but is, instead, stored in little bundles of electromagnetic energy, called photons. *Similarly, from the quantum theory we should expect that on a microscopic level the gravitational field should also be quantized into little particles, which we will call the quanta of the gravitational field — the **gravitons**.*

But what is a gravitational field but the warping of spacetime? Hence, a quantum of gravitation must be a quantum of spacetime itself. Thus, the graviton would appear to be a quantum of spacetime. Therefore, on a microscopic level, spacetime itself is probably not smooth but probably has a graininess or bumpiness to it. At this time, no one knows for sure what happens to spacetime on this microscopic level, but it has been conjectured that spacetime may look something like a foam that contains "wormholes."

At what point do the quantum theory and Einstein's theory of gravitation merge? The answer is to be found in Heisenberg's uncertainty principle.

$$\Delta E \Delta t \geq \hbar \tag{31.55}$$

For the electric field, small quantities of energy  $\Delta E$  of the electric field are turned into small quanta of energy, the photons. In a similar manner, small quantities of energy  $\Delta E$  of the gravitational field should be turned into little bundles or

## Chapter 6: Elementary Particle Physics and The Unification of The Forces

quantums of gravity, the gravitons. Since the range of a force is determined by the mass of the exchanged particle, and the range of the gravitational force is known to be infinite, it follows that the rest mass of the graviton must be zero. Hence, a quantum fluctuation should appear as a gravitational wave moving at the speed of light  $c$ . Therefore, if we consider a fluctuation of the gravitational field that spreads out spherically, the small time for it to move a distance  $r$  is

$$\Delta t = \frac{r}{c} \quad (6.12)$$

To obtain an order of magnitude for the energy, we drop the greater than sign in the uncertainty principle and on substituting equation 6.12 into equation 3.55 we get, for the energy of the fluctuation,

$$\Delta E \Delta t = \Delta E \frac{r}{c} = \hbar$$

and

$$\Delta E = \frac{\hbar c}{r} \quad (6.13)$$

The value of  $r$  in equation 6.13, wherein the quantum effects become important, is unknown at this point; in fact, it is one of the things that we wish to find. So further information is needed. Let us consider the amount of energy required to pull this little graviton or bundle of energy apart against its own gravity. The work to pull the graviton apart is equal to the energy necessary to assemble that mass by bringing small portions of it together from infinity. Let us first consider the problem for the electric field, and then use the analogy for the gravitational field. Recall that the electric potential for a small spherical charge is

$$V = \frac{kq}{r}$$

But the electric potential  $V$  was defined as the potential energy per unit charge, that is,

$$V = \frac{PE}{q}$$

So if a second charge  $q$  is brought from infinity to the position  $r$ , the potential energy of the system of two charges is

$$PE = qV = \frac{kq^2}{r}$$

## Chapter 6: Elementary Particle Physics and The Unification of The Forces

In a similar vein, a gravitational potential  $\Phi$  could have been derived using the same general technique used to derive the electric potential. The result for the gravitational potential would be

$$\Phi = \frac{GM}{r} \quad (6.14)$$

where  $G$ , of course, is the gravitational constant,  $M$  is the mass, and  $r$  is the distance from the mass to the point where we wish to determine the gravitational potential. The gravitational potential of a spherical mass is defined, similar to the electric potential, as the gravitational potential energy per unit mass. That is,

$$\Phi = \frac{PE}{M} \quad (6.15)$$

Hence, if another mass  $M$  is brought from infinity to the position  $r$ , the potential energy of the system of two equal masses is

$$PE = M\Phi = \frac{GM^2}{r} \quad (6.16)$$

This value of the potential energy, PE to assemble the two masses, is the same energy that would be necessary to pull the two masses apart. Applying the same reasoning to the assembly of the masses that constitutes the graviton, the potential energy given by equation 6.16 is equal to the energy that would be necessary to pull the graviton apart. This energy can be equated to the energy of the graviton found from the uncertainty principle. Thus,

$$PE = \Delta E$$

Substituting for the PE from equation 6.16 and the energy  $\Delta E$  from the uncertainty principle, equation 6.13, we get

$$\frac{GM^2}{r} = \frac{\hbar c}{r} \quad (6.17)$$

But the mass of the graviton  $M$  can be related to the energy of the graviton by Einstein's mass-energy relation as

$$\Delta E = Mc^2$$

or

$$M = \frac{\Delta E}{c^2} \quad (6.18)$$

Substituting equation 6.18 into equation 6.17 gives



$$\frac{G(\Delta E)^2}{r(c^2)^2} = \frac{\hbar c}{r}$$

Solving for  $\Delta E$ , we get

$$\Delta E = \sqrt{\frac{\hbar c^5}{G}} \quad (6.19)$$

Equation 6.19 represents the energy of the graviton.

### **Example 6.1**

*The energy of the graviton.* Find the energy of the graviton.

#### **Solution**

The energy of the graviton, found from equation 6.19, is

$$\begin{aligned} \Delta E &= \sqrt{\frac{\hbar c^5}{G}} \\ \Delta E &= \sqrt{\frac{(1.05 \times 10^{-34} \text{ J s})(3.00 \times 10^8 \text{ m/s})^5}{6.67 \times 10^{-11} \text{ (N m}^2\text{)/kg}^2}} \\ \Delta E &= 1.96 \times 10^9 \text{ J} \end{aligned}$$

This can also be expressed in terms of electron volts as

$$\begin{aligned} \Delta E &= (1.96 \times 10^9 \text{ J}) \left( \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} \right) \left( \frac{1 \text{ GeV}}{10^9 \text{ eV}} \right) \\ &= 1.20 \times 10^{19} \text{ GeV} \end{aligned}$$

This is the energy of a graviton; it is called the *Planck energy*.

From the point of view of particle physics, then, the graviton looks like a particle of mass  $10^{19} \text{ GeV}/c^2$ . This is an enormous mass and energy when compared to the masses and energies of all the other elementary particles. However, for any elementary particles of this size or larger, both quantum theory and gravitation must be taken into account. Recall that in all the other interactions of the elementary particles, gravity was ignored. From the point of view of ordinary gravity, this energy is associated with a mass of  $2 \times 10^{-5} \text{ g}$ , a very small mass.

The distance in which this quantum fluctuation occurs can now be found by equating  $\Delta E$  from equation 6.13 to  $\Delta E$  from equation 6.19, that is,

$$\Delta E = \frac{\hbar c}{r} = \Delta E = \sqrt{\frac{\hbar c^5}{G}}$$

Solving for  $r$  we get

$$\begin{aligned} r &= \frac{\hbar c}{\sqrt{\hbar c^5/G}} \\ r &= \sqrt{\frac{\hbar G}{c^3}} \end{aligned} \quad (6.20)$$

Equation 6.20 is the distance or length where quantum gravity becomes significant. This distance turns out to be the same distance that Max Planck found when he was trying to establish some fundamental units from the fundamental constants of nature, and is called the *Planck length*  $L_P$ . Hence, the Planck length is

$$L_P = \sqrt{\frac{\hbar G}{c^3}} \quad (6.21)$$

### Example 6.2

*The Planck length.* Determine the size of the Planck length.

#### Solution

The Planck length, determined from equation 6.21, is

$$\begin{aligned} L_P &= \sqrt{\frac{\hbar G}{c^3}} \\ L_P &= \sqrt{\frac{(1.05 \times 10^{-34} \text{ J s})(6.67 \times 10^{-11} \text{ (N m}^2\text{)/kg}^2\text{)})}{(3.00 \times 10^8 \text{ m/s})^3}} \\ &= 1.61 \times 10^{-35} \text{ m} = 1.61 \times 10^{-33} \text{ cm} \end{aligned}$$

Thus, quantum fluctuations of spacetime start to occur at distances of the order of  $1.61 \times 10^{-33} \text{ cm}$ . We can now find the interval of time, within which this quantum fluctuation of spacetime occurs, from equation 6.12 as

$$\Delta t = \frac{r}{c} = \frac{L_P}{c}$$

This time unit is called the *Planck time*  $T_P$  and is

$$\begin{aligned} T_P &= \frac{L_P}{c} \\ &= \frac{1.61 \times 10^{-35} \text{ m}}{3.00 \times 10^8 \text{ m/s}} \\ &= 5.37 \times 10^{-44} \text{ s} \end{aligned} \quad (6.22)$$

Thus, intervals of space and time given by the Planck length and the Planck time are the regions in which quantum gravity must be considered. This distance and time are extremely small. Recall that the size of the electron is about  $10^{-19}$  m. Thus, quantum gravity occurs on a scale much smaller than that of an atom, a nucleus, or even an electron. There is relatively little known about quantum gravity at this time, but research is underway to find more answers dealing with the ultimate structure of spacetime itself.

## 6.11 The Superforce — Unification of All the Forces

An attempt to unify all the forces into one single force — a kind of **superforce** — continues today. One of the techniques followed is called *supersymmetry*, where the main symmetry element is spin. (Recall that all particles have spin.) Those particles that obey the Pauli exclusion principle have half-integral spin, that is, spin  $\hbar/2$ ,  $3\hbar/2$ , and so on. Those particles that obey the Pauli exclusion principle are called *fermions*. All the quarks and leptons are fermions. Particles that have integral spin,  $\hbar$ ,  $2\hbar$ , and so on, do not obey the Pauli exclusion principle. These particles are called *bosons*. All the mediating particles, such as the photon,  $W^\pm$ ,  $Z^0$ , gluons, and the like, are bosons. *Hence, fermions are associated with particles of matter, whereas bosons are associated with the forces of nature, through an exchange of bosons. The new theories of supersymmetry attempt to unite bosons and fermions.*

A further addition to supersymmetry unites gravity with the electroweakstrong or GUT force into the superforce that is also called super gravity. Super gravity requires not only the existence of the graviton but also a new particle, the “gravitino,” which has spin  $3/2$ . However, this unification exists only at the extremely high energy of  $10^{19}$  GeV, an energy that cannot be produced in a laboratory. However, in the initial formation or creation of the universe, a theory referred to as the Big Bang, such energies did exist.

The latest attempt to unify all the forces is found in the *superstring theory*. The superstring theory assumes that the ultimate building blocks of nature consist of very small vibrating strings. As we saw in our study of wave motion, a string is capable of vibrating in several different modes. The superstring theory assumes that each mode of vibration of a superstring can represent a particle or a force. Because there are an infinite number of possible modes of vibration, the superstring can represent an infinite number of possible particles. The graviton, which is responsible for the gravitational interaction, is caused by the lowest vibratory mode of a circular string. (Superstrings come in two types: open strings, which have ends, and closed strings, which are circular.) The photon corresponds to the lowest mode of vibration of the open string. Higher modes of vibrations represent different particles, such as quarks, gluons, protons, neutrons, and the like. In fact, the gluon is considered to be a string that is connected to a quark at each end. In this theory, no particle is more fundamental than any other, each is just a different mode of vibration of the superstrings. The superstrings interact with other superstrings by breaking and reforming. The four forces are considered just different manifestations

of the one unifying force of the superstring. The superstring theory assumes that the universe originally existed in ten dimensions, but broke into two pieces — one of the pieces being our four-dimensional universe. Like the theories of supersymmetry and super gravity, the energies needed to test this theory experimentally are too large to be produced in any laboratory.

A simple picture of the unifications is shown in table 6.6. A great deal more work is necessary to complete this final unification.

Table 6.6 The Forces and Their Unification			
Electricity	Electromagnetism	Electroweak force	Grand unified theories (GUT)
Magnetism			
Weak force	Strong force	Superforce	
Gravity			

### **Have you ever wondered ... ?** **An Essay on the Application of Physics** **The Big Bang Theory and the** **Creation of the Universe**

Have you ever wondered how the world was created? In every civilization throughout time and throughout the world, there has always been an account of the creation of the world. Such discussions have always belonged to religion and philosophy. It might seem strange that astronomers, astrophysicists, and physicists have now become involved in the discussion of the creation of the universe. Of course, if we think about it, it is not strange at all. *Since physics is a study of the entire physical world; it is only natural that physics should try to say something about the world's birth.*

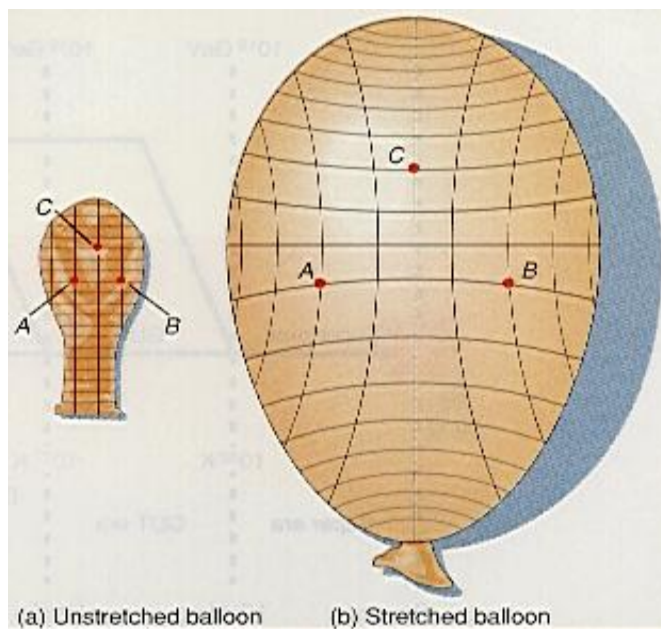
The story starts in 1923 when the American astronomer, Edwin Hubble, using the Doppler effect for light, observed that all the galactic clusters, outside our own, in the sky were receding away from the earth. When we studied the Doppler effect for sound, we saw that when a train recedes from us its frequency decreases. A decrease in the frequency means that there is an increase in the wavelength. Similarly, a Doppler effect for light waves can be derived. The equations are different than those derived for sound because, in the special theory of relativity, the velocity of light is independent of the source. However, the effect is the same. That is, a receding source that emits light at a frequency  $\nu$ , is observed by the stationary observer to have a frequency  $\nu'$ , where  $\nu'$  is less than  $\nu$ . Thus, since the

frequency decreases, the wavelength increases. Because long waves are associated with the red end of the visible spectrum, all the observed wavelengths are shifted toward the red end of the spectrum. The effect is called the *cosmological red shift*, to distinguish it from the gravitational red shift discussed in chapter 2. *Hubble found that the light from the distant galaxies were all red shifted indicating that the distant galaxies were receding from us.*

It can, therefore, be concluded that if all the galaxies are receding from us, the universe itself must be expanding. Hubble was able to determine the rate at which the universe is expanding. If the universe is expanding now, then in some time in the past it must have been closer together. If we look far enough back in time, we should be able to find when the expansion began. (Imagine taking a movie picture of an explosion showing all the fragments flying out from the position of the explosion. If the movie is run backward, all the fragments would be seen moving backward toward the source of the explosion.)

*The best estimate for the creation of the universe, is that the universe began as a great bundle of energy that exploded outward about 15 billion years ago. This great explosion has been called the **Big Bang**. It was not an explosion of matter into an already existing space and time, rather it was the very creation of space and time, or spacetime, and matter themselves.*

As the universe expanded from this explosion, all objects became farther and farther apart. A good analogy to the expansion of spacetime is the expansion of a toy balloon. A rectangular coordinate system is drawn on an unstretched balloon, as shown in figure 1(a), locating three arbitrary points, *A*, *B*, and *C*. The balloon is



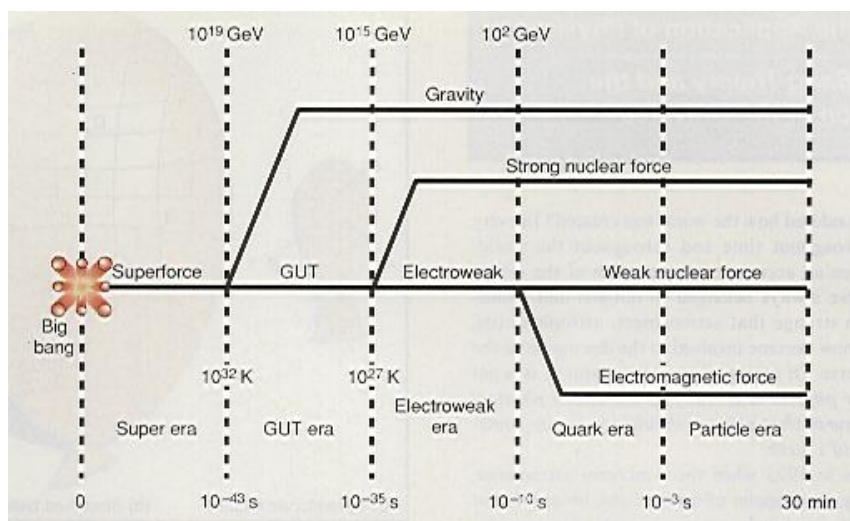
**Figure 1** An Analogy to the expanding universe.

then blown up. As the balloon expands the distance between points *A* and *B*, *A* and *C*, and *B* and *C* increases. So no matter where you were on the surface of the

balloon you would find all other points moving away from you. This is similar to the distant galaxies moving away from the earth. To complete the analogy to the expanding universe, we note that the simple flat rectangular grid in which Euclidean geometry holds now become a curved surface in which Euclidean geometry no longer holds.

If everything in the universe is spread out and expanding, the early stages of the universe must have been very compressed. To get all these masses of stars of the present universe back into a small compressed state, that compressed state must have been a state of tremendous energy and exceedingly high density and temperature. Matter and energy would be transforming back and forth through Einstein's mass-energy formula,  $E = mc^2$ . Work done by particle physicists at very high energies allows us to speculate what the universe must have looked like at these very high energies at the beginning of the universe.

The early history of the universe is sketched in figure 2. The Big Bang is shown occurring at time  $t = 0$ , which is approximately 15 billion years ago.



**Figure 2** Creation of the four forces from the superforce.

## 1. From the Big Bang to $10^{-43}$ s

Between the creation and the Planck time, 0 to  $10^{-43}$  s, the energy of the universe was enormous, dropping to about  $10^{19}$  GeV at the Planck time. The temperature was greater than  $10^{32}$  K. Relatively little is known about this era, but the extremely high energy would cause all the forces to merge into one superforce. That is, gravity, the strong force, the weak force, and the electromagnetic force would all be replaced by one single superforce. This is the era being researched by present physicists in the supersymmetry and super gravity theories. There is only one particle, a super particle, that decays into bosons and fermions, and continually converts fermions to bosons and vice versa, so that there is no real distinction between them.

### 2. *From $10^{-43}$ s to $10^{-35}$ s*

As the universe expands, the temperature drops and the universe cools to about  $10^{32}$  K. The energy drops below  $10^{19}$  GeV and the gravitational force breaks away from the superforce as a separate force, leaving the grand unified force of GUT as a separate force. Now two forces exist in nature. We are now in the GUT era, that era governed by the grand unified theories. The X particle and its antiparticle  $\bar{X}$  are in abundance. The X particles decay into quarks and leptons, whereas the  $\bar{X}$  particles decay into antiquarks and antileptons. However, the decay rate of X and  $\bar{X}$  are not the same and more particles than antiparticles are formed. This will eventually lead to the existence of more matter than antimatter in the universe. The X particles continually convert quarks into leptons and vice versa. There are plenty of quarks, electrons, neutrinos, photons, gluons, X particles, and their antiparticles present, but they have effectively lost their individuality.

### 3. *From $10^{-35}$ s to $10^{-10}$ s*

As further expansion of the universe continues, the temperature drops to  $10^{27}$  K and the energy drops to  $10^{15}$  GeV. At this low energy all the X particles disappear, and quarks and leptons start to have an individual identity of their own. No longer can they be converted into each other. The lower energy causes the strong nuclear force to break away leaving the electroweak force as the only unified force left. There are now three forces of nature: gravity, strong nuclear, and the electroweak. There are quarks, leptons, photons, neutrinos,  $W^\pm$  and  $Z^0$ , and gluon particles present. It is still too hot for the quarks to combine.

### 4. *From $10^{-10}$ s to $10^{-3}$ s*

As the universe continues to expand, it cools down to an energy of  $10^2$  GeV. The  $W^\pm$  and  $Z^0$  particles disappear because there is not enough energy to form them anymore. The weak nuclear force breaks away from the electroweak force, leaving the electromagnetic force. There are now present the four familiar forces of nature: gravity, strong nuclear, weak nuclear, and electromagnetic. Quarks now combine to form baryons, qqq, and mesons,  $q\bar{q}$ . The familiar protons and neutrons are now formed. Because of the abundance of quarks over antiquarks, there will also be an excess of protons and neutrons over antiprotons and antineutrons.

### 5. *From $10^{-3}$ s to 30 min*

The universe has now expanded and cooled to the point where protons and neutrons can combine to form the nucleus of deuterium. The deuterium nuclei combine to form helium as described in section 5.9 on fusion. There are about 77% hydrogen nuclei, and 23% helium nuclei present at this time and this ratio will continue about the same to the present day. There are no atoms formed yet because the temperature is still too high. What is present is called a *plasma*.



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### 6. *From 30 min to 1 Billion Years*

Further expansion and cooling now allows the hydrogen and helium nuclei to capture electrons and the first chemical elements are born. Large clouds of hydrogen and helium are formed.

### 7. *From 1 Billion Years to 10 Billion Years*

The large rotating clouds of hydrogen and helium matter begin to concentrate due to the gravitational force. As the radius of the cloud decreases, the angular velocity of the cloud increases in order to conserve angular momentum. (Similar to the spinning ice skater) These condensing, rotating masses are the beginning of galaxies.

Within the galaxies, gravitation causes more and more matter to be compressed into spherical objects, the beginning of stars. More and more matter gets compressed until the increased pressure of that matter causes a high enough temperature to initiate the fusion process of converting hydrogen to helium and the first stars are formed. Through the fusion process, more and more chemical elements are formed. The higher chemical elements are formed by neutron absorption until all the chemical elements are formed.

These first massive stars did not live very long and died in an explosion — a supernova — spewing the matter of all these heavier elements out into space. The fragments of these early stars would become the nuclei of new stars and planets.

### 8. *From 10 Billion Years to the Present*

The remnants of dead stars along with hydrogen and helium gases again formed new clouds, which were again compressed by gravity until our own star, the sun, and the planets were formed. All the matter on earth is the left over ashes of those early stars. Thus, even we ourselves are made up of the ashes of these early stars. As somebody once said, there is a little bit of star dust in each of us.

## The Language of Physics

### **Leptons**

Particles that are not affected by the strong nuclear force (p. ).

### **Hadrons**

Particles that are affected by the strong nuclear force (p. ).

### **Baryons**

A group of hadrons that have half-integral spin and are composed of three quarks (p. ).

### **Mesons**

A group of hadrons that have integral spin, that are composed of quark-antiquark pairs (p. ).

### **Antiparticles**

To each elementary particle in nature there corresponds another particle that has the characteristics of the original particle but opposite charge. Some neutral particles have antiparticles that have opposite spin, whereas the photon is its own antiparticle. The antiparticle of the proton is the antiproton. The antiparticle of the electron is the antielectron or positron. If a particle collides with its antiparticle both are annihilated with the emission of radiation or other particles. Conversely, photons can be converted to particles and antiparticles (p. ).

### **Antimatter**

Matter consists of protons, neutrons, and electrons, whereas antimatter consists of antiprotons, antineutrons, and antielectrons (p. ).

### **Quarks**

Elementary particles that are the building blocks of matter. There are six quarks and six antiquarks. The six quarks are: up, down, strange, charmed, bottom, and top. Each quark and antiquark also comes in three colors, red, green, and blue. Each color quark also has an anticolor quark. Baryons are composed of red, green, and blue quarks and mesons are made up of a linear combination of colored quark-antiquark pairs (p. ).

### **Quantum electrodynamics (QED)**

The merger of electromagnetic theory with quantum mechanics. In QED, the electric force is transmitted by the exchange of a virtual photon (p. ).

### **Weak nuclear force**

The weak nuclear force does not exert the traditional push or pull type of force known in classical physics. Rather, it is responsible for the transmutation of the subatomic particles. The weak force is independent of electric charge and acts between leptons and hadrons and also between hadrons and hadrons. The weak force is the weakest force after gravity (p. ).

### **Electroweak force**

A unification of the electromagnetic force with the weak nuclear force. The force is mediated by four particles: the photon and three intermediate vector bosons called  $W^+$ ,  $W^-$ , and  $Z^0$  (p. ).

### **The strong nuclear force**

The force that holds the nucleons together in the nucleus. The force is the result of the color forces between the quarks within the nucleons. At relatively large

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separation distances within the nucleus, the quark-antiquark pair (meson), which is created by the gluons, is exchanged between the nucleons. At shorter distances within the nucleus, the strong force can be explained either as an exchange between the quarks of one proton and the quarks of another proton, or perhaps as a direct exchange of the gluons themselves, which give rise to the quark-quark force within the nucleon (p. ).

### **Quantum chromodynamics (QCD)**

In QCD, the force holding quarks together is caused by the exchange of a new particle, called a gluon. A gluon interacting with a quark changes the color of a quark (p. ).

### **Grand unified theory**

A theory that merges the electroweak force with the strong nuclear force. This force should be able to transform quarks into leptons and vice versa. The theory predicts the existence of 12 new particles, called X particles that are capable of converting hadrons into leptons by changing quarks to leptons. This theory also predicts that an isolated proton should decay. However, no such decays have ever been found, so the theory may have to be modified (p. ).

### **Gravitons**

The quanta of the gravitational field. Since gravitation is a warping of spacetime, the graviton must be a quantum of spacetime (p. ).

### **Superforce**

An attempt to unify all the forces under a single force. The theories go under the names of supersymmetry, super gravity, and superstrings (p. ).

### **The Big Bang theory**

The theory of the creation of the universe that says that the universe began as a great bundle of energy that exploded outward about 15 billion years ago. It was not an explosion of matter into an already existing space and time, rather it was the very creation of spacetime and matter (p. ).

## **Questions for Chapter 6**

\*1. Discuss the statement, “A graviton is a quantum of gravity. But gravity is a result of the warping of spacetime. Therefore, the graviton should be a quantum of spacetime. But just as a quantum of the electromagnetic field, the photon, has energy, the graviton should also have energy. In fact, we can estimate the energy of a graviton. Therefore, is spacetime another aspect of energy? Is there only one fundamental quantity, energy?”

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\*2. Does antimatter occur naturally in the universe? How could you detect it? Where might it be located?

3. When an electron and positron annihilate, why are there two photons formed instead of just one?

4. Murray Gell-Mann first introduced three quarks to simplify the number of truly elementary particles present in nature. Now there are six quarks and six antiquarks, and each can come in three colors and three anticolors. Are we losing some of the simplicity? Discuss.

5. Discuss the experimental evidence for the existence of structure within the proton and the neutron.

6. How did the Pauli exclusion principle necessitate the introduction of colors into the quark model?

\*7. If the universe is expanding from the Big Bang, will the gravitational force of attraction of all the masses in the universe eventually cause a slowing of the expansion, a complete stop to the expansion, and finally a contraction of the entire universe?

\*8. Just as there are electromagnetic waves associated with a disturbance in the electromagnetic field, should there be gravitational waves associated with a disturbance in a gravitational field? How might such gravitational waves be detected?

\*9. Einstein's picture of gravitational attraction is a warping of spacetime by matter. This has been pictured as the rubber sheet analogy. What might antimatter do to spacetime? Would it warp spacetime in the same way or might it warp spacetime to cause a gravitational repulsion? Would this be antigravity? Would the antiparticle of the graviton then be an antigraviton? Instead of a black hole, would there be a white hill?

10. Discuss the similarities and differences between the photon and the neutrino.

## Problems for Chapter 6

### Section 6.2 Particles and Antiparticles

1. How much energy is released when an electron and a positron annihilate? What is the frequency and wavelength of the two photons that are created?

2. How much energy is released when a proton and antiproton annihilate?

3. How much energy is released if 1.00 kg of matter annihilates with 1.00 kg of antimatter? Find the wavelength and frequency of the resulting two photons.

4. A photon "disintegrates," creating an electron-positron pair. If the frequency of the photon is  $5.00 \times 10^{24}$  Hz, determine the linear momentum and the energy of each product particle.

### Section 6.4 Quarks

5. If the three quarks shown in the diagram combine to form a baryon, find the charge and spin of the resulting particle.

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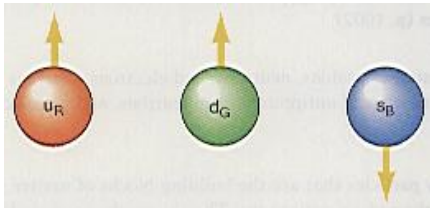


Diagram for problem 5.

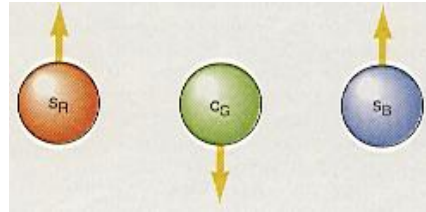


Diagram for problem 6.

6. If the three quarks shown in the diagram combine to form a baryon, find the charge and spin of the resulting particle.

7. If the three quarks shown in the diagram combine to form a baryon, find the charge and spin of the resulting particle.

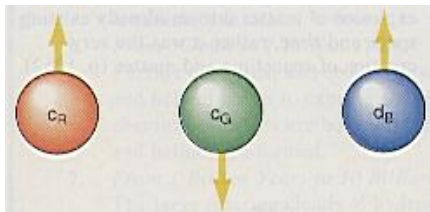


Diagram for problem 7.

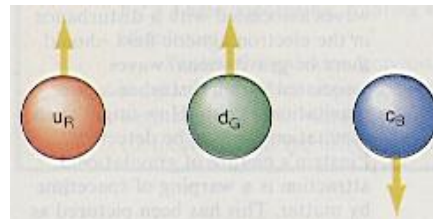


Diagram for problem 8.

8. Find the charge and spin of the baryon that consists of the three quarks shown in the diagram.

9. If the two quarks shown in the diagram combine to form a meson, find the charge and spin of the resulting particle.

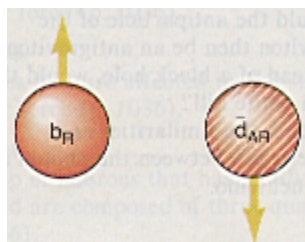


Diagram for problem 9.

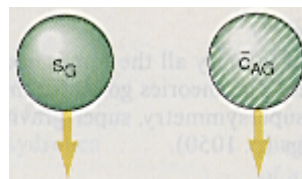


Diagram for problem 10.

10. If the two quarks shown in the diagram combine to form a meson, find the charge and spin of the resulting particle.

11. Find the charge and spin of the meson that consists of the two quarks shown in the diagram.



Diagram for problem 11.

12. Which of the combinations of particles in the diagram are possible and which are not. If the combination is not possible, state the reason.

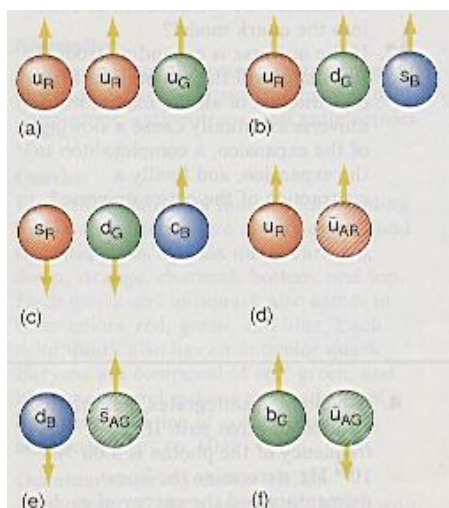


Diagram for problem 12.

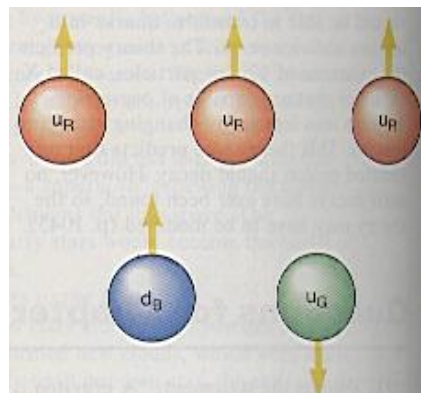


Diagram for problem 13.

13. Why are the two particles in the diagram impossible?

14. A baryon is composed of three quarks. It can be made from a total of six possible quarks, each in three possible colors, and each with either a spin-up or spin-down. From this information, how many possible baryons can be made?

15. A meson is composed of a quark-antiquark pair. It can be made from a total of six possible quarks, each in three possible colors, and each with either a spin-up or spin-down, and six possible antiquarks each in three possible colors, and each with either a spin-up or spin-down. Neglecting linear combinations of these quarks, how many possible mesons can be made?

16. From problems 14 and 15 determine the total number of possible hadrons, ignoring possible mesons made from linear combinations of quarks and antiquarks. Could you make a “periodic table” from this number? Discuss the attempt to attain simplicity in nature.

17. Determine all possible quark combinations that could form a baryon of charge +1 and spin  $\frac{1}{2}$ .

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