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PARTICLE PROLIFERATION

More than 100 new particles have been discovered since the 30 of 1957, which has made necessary a new classification system. Particles are classified into groups according to the types of forces that they "feel" or interactions they undergo. There are four known forces or interactions in nature: gravitational, electromagnetic, strong, and weak. These forces and interactions will be discussed in the next section. Of these forces, the weak and strong are used to classify all particles except the photon. Those that feel the strong force are called hadrons and are divided into two groups: baryons and mesons. Those that do not feel the strong force are called leptons. The photon is in a completely different category since it has no mass and no charge and does not participate in either of these interactions.

The proliferation of particles has occurred almost exclusively in the strongly interacting particles. The number of hadrons has increased by more than 100, while the number of leptons has increased only by two. Strongly interacting particles known as of 1964 are shown in Fig. 13.5. These are only those with rest mass below 2000 MeV.

Classification of the particles is made easier by the assignment of quantum numbers that refer to individual properties of the particle. Quantum numbers assume only certain discrete values and a complete quantum number list uniquely identifies the particle and will define its characteristics. Some quantum numbers have already been discussed — for example, those of electric charge, spin, strangeness, etc.

A scheme that has been valuable not only for classifying particles but also for predicting the existence of previously undiscovered particles is a system called the "eightfold way." In 1961, this system was developed independently by Murray Gell-Mann and Y. Neemann. It has been referred to as the eightfold way because it involves eight quantum numbers associated with each particle. The choice of name may be partly due to a statement attributed to Buddha: "Now this, O monks, is noble truth that leads to the cessation of pain: this is the noble Eightfold way: namely, right views, right intention, right speech, right action, right living, right effort, right mindfulness, right concentration." One significant accomplishment for the eightfold way was the prediction of a new particle, the omega minus (Ω^-), with a mass of between 1676 and 1680 MeV. In January 1964, scientists at Brookhaven using the alternating gradient synchrotron that we discussed in Chapter 11 first detected this particle, thus confirming the prediction of its existence.

A more recent development of the eightfold way has been the prediction of quarks.† Gell-Mann and Zweig independently proposed that there were three particles that could be combined to form all of the hadrons. This quark model uses

†Gell-Mann took the word "quark" from James Joyce's novel, *Finnegan's Wake*. In that work, a barkeeper, H. C. Earwicker, says at intervals: "Three quarks for Muster Mark."

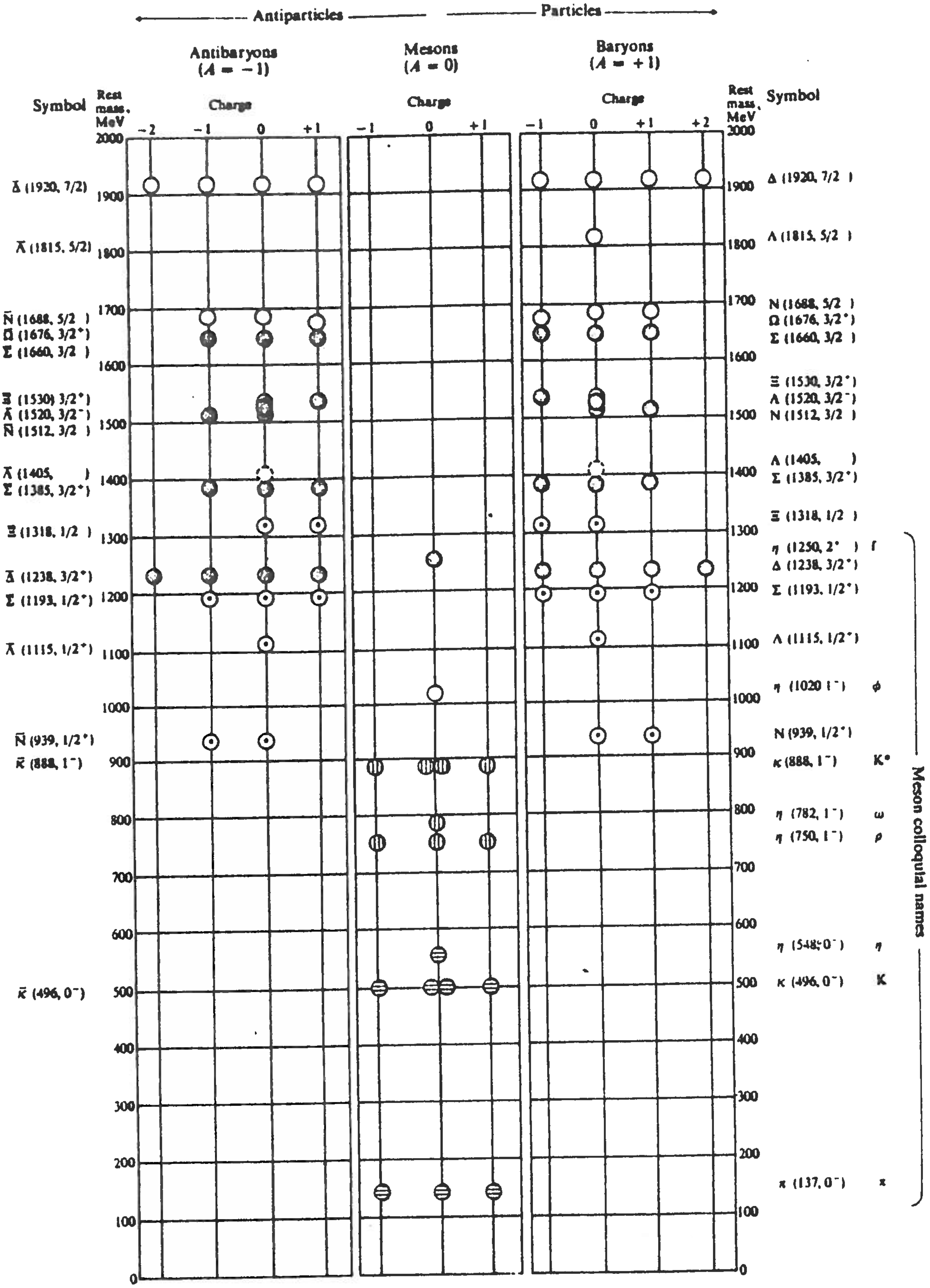

Figure 13.5 Strongly interacting particles as of 1964.

From "Strongly Interacting Particles," by Geoffrey F. Chew, Murray Gell-Mann, and Arthur H. Rosei three quarks: one with the electronic charge $-\frac{1}{3}e$ and strangeness 0 (d quark), a second with electric charge $+\frac{2}{3}e$ and strangeness 0 (u quark), and a third with electronic charge $-\frac{1}{3}e$ and strangeness -1 (s quark). Each quark has an antiquark associated with it ($\bar{u}$, $\bar{d}$, and $\bar{s}$). The magnitude of each of the quantum numbers for the antiquarks has the same magnitude as those for the quarks, but the sign is changed. All baryons are formed of three quarks. For example, the proton is made up of two u quarks and a d quark (uud). For these quarks, the electric charges are $+\frac{2}{3}$, $+\frac{2}{3}$, and $-\frac{1}{3}$ for a total value of $+1$. The baryon numbers are $+\frac{1}{3}$, $+\frac{1}{3}$, and $+\frac{1}{3}$, for a total of $+1$. The strangeness numbers are 0, 0, and 0 for a total strangeness of 0. All are in agreement with the quantum numbers for the proton. The mesons are formed of a quark and an antiquark. For example, the positively charged pi-meson is the combination of a u quark and a d antiquark ($u\bar{d}$). Electric charges of these quarks are $+\frac{2}{3}$ and $+\frac{1}{3}$ for a total of $+1$. The baryon numbers are $+\frac{1}{3}$ and $-\frac{1}{3}$ for a total baryon number of 0. The strangeness numbers are 0 and 0 for a total of 0. All of these are in agreement with the quantum numbers for the pi-meson.

In recent years, a fourth quark has been added to the list; it has electric charge $+\frac{2}{3}e$ and strangeness 0. This quark differs from the u quark by a new quantum number given the arbitrary name "charm." The charmed quark was suggested to explain the suppression of certain decay processes that are not observed. With only three quarks, the processes would proceed at measurable rates and should have been observed. Until recently, there had been no physical evidence for the existence of this fourth quark. All of the hadrons known could be made by combining the original three quarks with no need for the fourth one. However, by using the fourth quark with the other three, the hadrons can be arranged in families as shown in Fig. 13.6. The planes of the figures indicate the values of charm. Positions within the planes are determined by isotropic spin and strangeness. Each point on these diagrams represents a particle formed by the combination of the quarks indicated in parentheses. All hadrons discussed thus far are found on the planes designated charm = 0 in the diagram. For example, in diagram (b) we see the kaons. In diagram (d) we see the nucleons [neutron (udd) and proton (uud)]. In diagram (e) the sigma particles, the cascade particles, and the omega minus particle are found.

The first evidence for charm did not come from the discovery of a charmed particle but from a study of the mesons ρ ($u\bar{u}$), ω ($d\bar{d}$), and ϕ (ss), which are shown in the middle of Fig. 13.6(b). The ρ, ω, and ϕ were believed to be particles made up of a quark bound to its antiquark. A particle with mass of 3.1 GeV was discovered in late 1974 by a group at Brookhaven National Laboratory led by S. C. C. Ting and simultaneously by a group at the Stanford Linear Accelerator Center led by Burton Richter. The new particle was named the "J" particle by Ting and the "Psi" particle by Richter. The evidence was strong that this particle was the fourth particle shown in the center of Fig. 13.6(b) and was the combination of a charmed quark and its antiquark ($c\bar{c}$). If this were the case, then other states of the new particle were expected to exist and one such state was to be at about 3.7 GeV. This 3.7 GeV state should decay into an intermediate state with the emission of a photon and then the

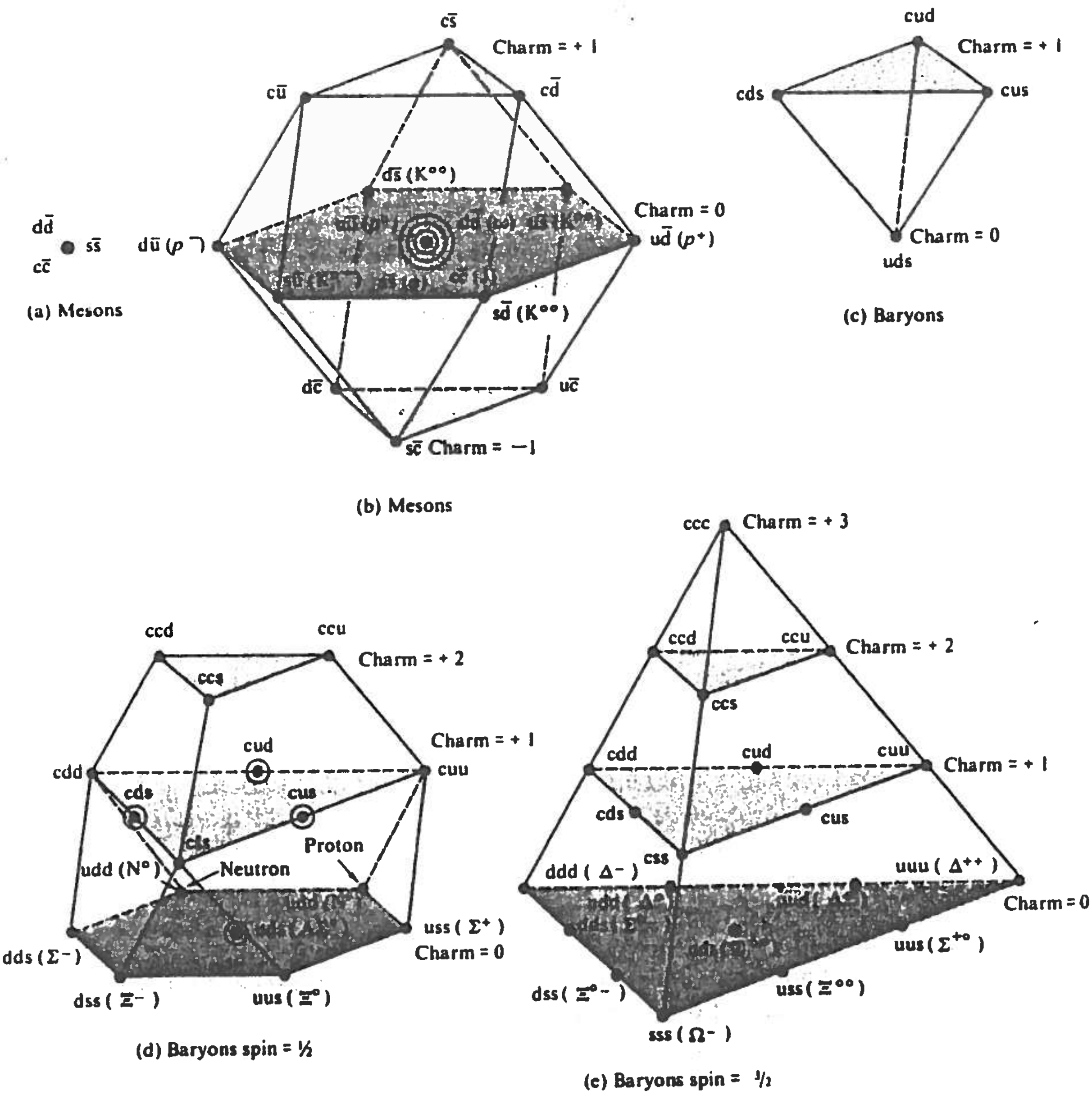

Figure 13.6 The hadrons can be arranged as polyhedrons. Each supermultiplet consists of particles with the same value of spin angular momentum. Within each supermultiplet the particles are assigned positions according to three quantum numbers: Positions on the shaded planes are determined by isotopic spin and strangeness; the planes themselves indicate values of charm. The mesons are represented by a point (a) and by an Archimedean solid called a cuboctahedron (b), which comprises 15 particles, including six charmed ones. The mesons shown are those with a spin of 1, but all mesons fit the same point and cuboctahedron representations. The baryons form a small regular tetrahedron (c) of four particles, a truncated tetrahedron (d) of 20 particles, and a larger regular tetrahedron (e) also made up of 20 particles. Both mesons and baryons are identified by their quark constitution, and for those particles that have been observed the established symbol is also given. Each figure contains one plane of uncharmed particles that are identical with earlier representations of the "eightfold way."

intermediate state should decay into the 3.1 GeV state with the emission of another photon. The 3.7 GeV state was discovered at SPEAR and the cascade process was recently observed at the DORIS storage ring facility in Hamburg, Germany, as well as at SPEAR. The J/ψ particle appears to be the particle formed by the combining of the charmed quark and its antiquark ($c\bar{c}$). However, the particle has charm equal to zero because the charmed quark has charm +1 and the charmed antiquark has charm −1.

A necessary test of the charm theory was, of course, the discovery of a particle with nonzero charm quantum number. As can be seen in Fig. 13.6, there are many mesons with charm of +1 and −1 and many baryons with charm of +1, +2, or +3. The first observation of a meson with charm was made in the summer of 1976. It was composed of a charmed quark and the antiparticle of a normal quark; thus the charm quantum number was +1. The first observation of a charmed baryon was made at the Fermi National Laboratory at Batavia, and is believed to be the (cud) baryon with charm +1, indicated in Fig. 13.6(c).

In 1977, a new particle was discovered at Fermi Lab that provided evidence for yet another quark. This particle, called the upsilon-meson, was thought to be made up of the new quark along with the associated antiquark. The fifth quark has been named the bottom quark (sometimes called beauty). As in the case of the J/psi meson, consisting of a charm-anticharm pair, this upsilon particle can be considered as a system of two quarks, bottom-antibottom, that orbit each other. Another particle has been discovered that is believed to be a member of this family and exhibiting naked beauty just as the D particles exhibited naked charm (see Fig. 13.6). This new particle formed by the decay of one of the upsilon particles is called a B-meson.

Things seem to be getting out of hand again. A few years ago everything seemed to be in a high state of disorder. There were a few leptons and many many hadrons. Then it was observed that three quarks could be put together in such a way to form all of the known hadrons. At that time, it seemed that leptons and three quarks could be the basic building blocks of nature. The need was then seen for the charmed quark. And now evidence for a fifth quark has occurred. So the question is how many quarks are there?

There were problems with the quark model, one of them being the omega-minus hyperon. It was believed to contain three identical s-quarks (see Fig. 13.6e). If this were true, it would violate the Pauli exclusion principle that prohibits two or more fermions from occupying identical quantum states.† The solution was the assignment of individual characteristics called "color" to quarks. The colors are red, blue, and yellow.

It appears to be developing that we have two separate families of particles, leptons and quarks. There are six known leptons and appear to be five known quarks, each with three different colors. For consistency a sixth quark has been

†The proton, neutron, and others with two identical quarks would violate this principle also.

Table 13.1

	Leptons		Quarks					
			Red		Blue		Yellow	
Third generation	ν_τ	0	t	+2/3	t	+2/3	t	+2/3
	τ^-	−1	b	−1/3	b	−1/3	b	−1/3
Second generation	ν_μ	0	c	+2/3	c	+2/3	c	+2/3
	μ^-	−1	s	−1/3	s	−1/3	s	−1/3
First generation	ν_e	0	u	+2/3	u	+2/3	u	+2/3
	e^-	−1	d	−1/3	d	−1/3	d	−1/3

predicted but not observed in any way. The families of particles are broken down by generation and there appear to be three generations. Table 13.1 shows how these basic particles are presently classified.

We see that the first generation contains two leptons, the electron and the electron neutrino, and two quarks, up and down. The second generation includes the muon and muon-neutrino and the strange and charmed quarks. And the third generation includes the tau and the tau-neutrino and the bottom and perhaps the top quarks. Note that in ordinary matter, made up of atoms, only the first generation particles are necessary. The other basic particles are only observed in extremely high-energy collisions. One puzzle in nature is why the second and third generation particles appear in nature at all.

There are basic differences in the families of particles shown in Table 13.1. The first is that the leptons have charges of absolute value zero or one, while the quarks have charges of absolute value one third or two thirds. Combinations of quarks to form particles observed in nature yield charges that are integral. The second significant difference is that the leptons appear as free particles in nature but quarks are only observed as constituents of observed mesons or hadrons.

The fact that no free quarks have been observed is predicted by the accepted theory of the strong interactions. However, many searches have been carried out to try to observe one of these particles. Searches have been conducted in large accelerator facilities throughout the world. In at least ten countries, many groups using cosmic-ray techniques have contributed to the search for quarks. Other searches have been carried out in material samples, using several different methods including mass spectroscopy, improved versions of the Millikan oil-drop experiment, and optical spectroscopy. All have been negative with the possible exception of the Millikan oil-drop technique. William M. Fairbank and co-workers using niobium spheres in a magnetic field at extremely low temperatures believe they have observed a particle with fractional charge. If these data are indeed due to free quarks, it will be an exciting new experimental discovery. However, it will have serious effects on the standing of the theory for these interactions.

Our recipe for forming particles by combining quarks is now modified a small amount. Quarks can be combined in two ways to form hadrons. Three quarks bound together yield a baryon. One quark bound with an antiquark yields a meson. However, the rule now is that the combination of quark colors must result in white in analogy to the mixing of the three primary colors to obtain white. A particle is made white (or colorless†) by combining a red quark, a blue quark, and a yellow quark (baryon) or a colored quark and its antiquark (meson). Combining three different colored quarks or a quark and its antiquark gives rise to a color neutral state, much as combining an electron and a proton creates a charge neutral state (hydrogen atom).

13.8

BASIC INTERACTIONS

As was pointed out in the last section, there are four basic interactions or forces in nature — gravitational, electromagnetic, strong, and weak. These four interactions vary in strength and range over wide margins, as can be seen in Table 13.2, which summarizes the characteristics.

The theory that describes the electromagnetic interaction is quantum electrodynamics, QED. This theory, which is one of the most accurate theories ever devised, was finalized in the 1950s after some 25 years of work. The electromagnetic interaction between two charged particles is understood on the basis of this theory as the exchange of a third particle. The third particle is identified as a photon, the quantum of electromagnetic radiation. As we have pointed out, the photon is a massless particle that has no electric charge. QED theory dictates that the range of interaction is inversely proportional to the mass of the particle exchanged. Thus the theory is consistent with the mass of the photon being zero and the range of the electromagnetic interaction being infinite.

The theory for the strong interaction is modeled after quantum electrodynamics. Whereas in the electromagnetic interaction the forces are between particles that have a charge, in the strong interaction the forces are between particles that have color. Particles that have no color are not subject to the force. This theory is referred to as quantum chromodynamics, QCD. If we arbitrarily take the strength of the electromagnetic interaction to be one, then the relative strength of the strong interaction is 100. The strong interaction is 100 times as strong as the electromagnetic.

As you might guess, this theory is a much more complicated theory because there are three colors involved, whereas in the electromagnetic theory there is only

† Basic colors combine to give white, which is referred to as "colorless' in some cases.

Table 13.2 Characteristics of the Four Fundamental Forces in Nature

	Gravitational	Electromagnetic	Strong	Weak
Range of action	∞	∞	10^{-13} cm	$< 10^{-15}$ cm
Relative strength	10^{-37}	1	100	10^{-11}
Particles acted upon	All particles and energy	All charged particles	Hadrons	Hadrons and leptons
Carrier (or mediator) of force	Graviton	Photon	Eight gluons	Three intermediate vector bosons

one charge. In this theory, the force is also transmitted by the exchange of a third particle. However, in this case more than one exchange particle is needed and, in fact, eight are necessary. These particles, called gluons, are massless and some carry color charge. The significance of this characteristic is that some quarks can emit a gluon carrying color and change to another type quark.

The weak interaction has a special charge associated with it and is 10^{-11} times as strong as the electromagnetic. Three particles are associated with the transmission of the weak interaction. They are the W^+, which also has a positive electric charge, the W^-, which has a negative electric charge, and the W^0, which is electrically neutral.

The remaining interaction is gravitational, the weakest of them all. This interaction is 10^{-37} times as strong as the electromagnetic and has a range of infinity. It is speculated that the carrier of this force is a particle called a graviton.

For many years physicists have been working on the unification of interactions in nature.† The first major success in this work occurred in 1967 when Sheldon Glashow and Stephen Weinberg formulated a theory that combined the weak and the electromagnetic interactions, and a year later, when Abdus Salam independently formulated the same theory. This theory combined these two interactions into an electro-weak force mediated by a family of four particles — the photon, two charged W mesons, and a new neutral meson Z^0. In 1978, a group of experimenters at SLACK conducted an elegant experiment that precisely tested and confirmed predictions of the combined theory. Since that time, many other experiments have supported the theory. For this work, Glashow, Weinberg, and Salam were awarded the 1979 Nobel Prize in physics.

† Einstein spent his last 30 years working to unify gravity and electromagnetism and published his negative results every time "to save another fool from wasting time on the same idea." Wolfgang Pauli, who was skeptical that these different forces could stem from a single source, once stated that "what God hath put asunder no man shall ever join."

Now physicists are trying to incorporate the strong interaction with the successful theory for the electro-weak interaction. Several theories have been proposed. One called the grand unified theory combines the electromagnetic, weak, and strong forces within a framework using the following particles to carry the force: the photon, the weak bosons, the eight gluons, and twelve other very heavy bosons with masses of approximately 10^{15} GeV. In this theory it would be possible for a quark to change into a lepton. One consequence of this change would be the decay of a proton with a predicted lifetime of the order of 10^{33} years. The success of this grand unified theory will have to wait the results of experiments presently being performed.

Finally, the successful unification of the four interactions, the ultimate goal of physicists, would be a tremendous triumph of the great intellectual adventure we call science. It would establish a single set of uniform rules for all phenomena everywhere in the universe on scales from inconceivably small to the inconceivably large. When it occurs it will stand with the other great steps taken in science — Copernicus's helioconcentric universe, Newton's law of gravity, Einstein's general theory of relativity and quantum mechanics.

13.9

CONSERVATION OF PARITY

We mentioned various conservation laws, for example, those of conservation of mass, conservation of momentum, conservation of strangeness, etc. Some of these laws are good for all interactions. However, some do not hold for one or more of the four types. For instance, the total strangeness value remains constant for the strong and electromagnetic interactions, but for the weak interaction this law is violated. Another limited conservation law is conservation of parity. Parity is conserved in the strong and electromagnetic interactions and was thought to be conserved in all interactions until a few years ago. It is now known that parity is not conserved in the weak interactions.

In the mathematical description of particles and their interactions, it is possible to describe particles so that if all of the coordinates (x, y, and z) are reversed and made negative, the resulting description will either be identical to or have exactly the negative value of the previous description. This property, called parity, is even or odd depending on whether the description remains positive or turns negative. The algebraic function $y = \cos x$ is symmetrical and has the same form when reversed right to left, that is $f(x) = +f(-x)$. Its parity is even (+) (see Fig. 13.7). The function $y = \sin x$ is antisymmetrical. When it is reversed right to left, $f(x) = -f(-x)$ and its parity is odd (−). The quantum-mechanical wave functions that represent particles or systems of particles can be described in the same way. They are either symmetric (even parity +) or antisymmetric (odd parity −). Thus the