20.2: Quantum Chromodynamics

The standard model postulates that all known particles are either fundamental point particles or are composed of fundamental point particles according to a remarkably small set of rules. Just as atoms are bound states of atomic nuclei and electrons, atomic nuclei are bound states of protons and neutrons. Atomic nuclei are discussed in the next section. In this section we delve one step deeper in the heirarchy of the universe. We now believe that all hadrons are actually bound states of fundamental spin 1/2 particles called quarks. Whereas all other known charged particles have an electric charge equal to an integer multiple of $\pm$e where e is the proton charge, quarks have electric charges equal to either -e $/\ 3$ or $+2e/3$. Leptons themselves are considered to be fundamental, so the leptons and the quarks form the basic building blocks of all matter in the universe.

Quarks are subject to electromagnetic forces via their charge, but interact most strongly via the so-called strong force. The strong force is carried by massless, uncharged, spin 1 bosons called gluons.

Type	Charge	Rest energy	s	c	b	t
down (d)	-1⁄3	0.333	0	0	0	0
up (u)	+2⁄3	0.330	0	0	0	0
strange (s)	-1⁄3	0.486	-1	0	0	0
charm (c)	+2⁄3	1.65	0	+1	0	0
bottom (b)	-1⁄3	4.5	0	0	-1	0
top (t)	+2⁄3	176	0	0	0	+1

Table 20.1: Table of quark types, charge (as a fraction of the proton charge), rest energy (in GeV), and the four “exotic” flavor quantum numbers.

When Murray Gell-Mann and George Zweig first proposed the quark model in 1963, they needed to postulate only three types or flavors of quarks: up, down, and strange. These were sufficient to explain the constitution of all hadrons known at the time. We currently know of six different flavors of quarks. Their properties are listed in table 20.1. The properties charm, topness, and bottomness are analogous to strangeness — these properties are conserved in strong interactions. Weak interactions, discussed in the next section, can turn quarks of one flavor into another flavor. However, the strong and electromagnetic forces cannot do this.

Type	Charge	Rest energy	Spin	Composition	Mean life
proton	+1	938.280	1/2	uud	stable
neutron	0	939.573	1/2	udd	898
lambda	0	1116	1/2	uds	3.8×10^{-9}
delta++	+2	1232	3/2	uuu	5.6×10^{-24}
positive pion	+1	140	0	ud	2.6×10^{-8}
negative pion	-1	140	0	ud	2.6×10^{-8}
neutral pion	0	135	0	uu - dd	8.7×10^{-17}
positive rho	+1	770	1	ud	4×10^{-24}
positive kaon	+1	494	0	us	1.24×10^{-8}
neutral kaon	0	498	0	ds	8.6×10^{-11}
J/psi	0	3097	1	cc	1.5×10^{-20}

Table 20.2: Sample hadrons. The charge is specified as a fraction of the proton charge, the rest energy is in MeV, and the mean life (1.44 multiplied by the half life) is in seconds. The composition is presented in terms of the flavors of quarks and antiquarks that make up the particle.

Just as the proton and the neutron have antiparticles, so do quarks. Antiquarks of a particular type have strong and electromagnetic charges of the sign opposite to the corresponding quarks. Quarks have baryon number equal to $1/3$, while antiquarks have $-1/3$. Thus combining three quarks results in a baryon number equal to 1, while together a quark plus an antiquark have baryon number zero. All baryons are thus combinations of three quarks, while all mesons are combinations of a quark and an antiquark. Table 20.2 lists a sampling of hadrons and some of their properties. Notice that the same combination of quarks can make up more than one particle, e. g., the positive pion and the positive rho. The positive rho may be considered as an excited state of the ud system, while the positive pion is the ground state of this system.

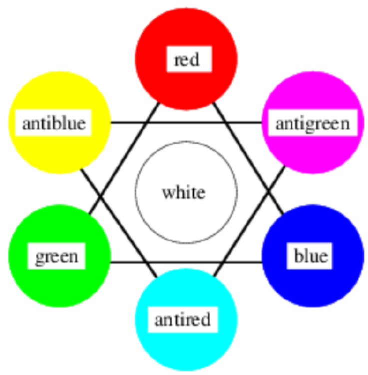

Figure 20.2.1:: The color table of quantum chromodynamics. Quarks have colors red, green, and blue, while antiquarks have colors antired (cyan), antigreen (magenta), and antiblue (yellow). The combination of a quark and its corresponding antiquark is colorless or white, as is the combination of three quarks (or antiquarks) of three different colors.

Yet to be mentioned is the quantum number color, which has nothing to do with real colors, but has analogous properties. Each flavor of quark can take on three possible color values, conventionally called red, green, and blue. This is illustrated in figure 20.1. Antiquarks can be thought of as having the colors antired, antigreen, and antiblue, also known as cyan, magenta, and yellow. Because of this, the theory of quarks and gluons is called quantum chromodynamics. Counting all color and flavor combinations, there are $6 \times 3 = 18$ known varieties of quarks.

As in electromagnetism, the strong force has associated with it a "strong charge", g_s. However, this charge is somewhat more complicated than electromagnetic charge in that there are three kinds of strong charge, one for each of the strong force colors. Each color of charge can take on positive and negative values equal to $\pm g_s$. As with electromagnetism, positive and negative charges (of the same color) cancel each other. However, in quantum chromodynamics there is an additional way in which charges can cancel. A combination of equal amounts of red, green, and blue charges results in zero net strong charge as well.

The delta++ particle (see table 20.2) is good evidence for the existence of the color quantum number. Since all three u-quarks in the delta++ have spin orientation up, the Pauli exclusion principle would only allow one of these quarks to exist in the ground state if color did not exist, resulting in a much larger mass. As it is, each of the quarks in the delta++ takes on a different value of the color quantum number (red, green, or blue), which means that the Pauli exclusion principle does not prevent them from all from residing in the ground state.

Gluons, the intermediary particles of the strong interaction come in eight different varieties, associated with differing color-anti color combinations. Since gluons don't interact via the weak force, there is no flavor quantum number for gluons — quarks of all flavors interact equally with all gluons.

The quark model of matter has led to extensive searches for free quark particles. However, these searches for free quarks have proven unsuccessful. The current interpretation of this result is that quarks cannot exist in a free state, basically because the attractive potential energy between quarks increases linearly with separation. This appears to be related to the fact that gluons, the intermediary particles for the strong force, can interact with each other as well as with quarks. This leads to a series of increasingly complex processes as quarks move farther and farther apart. The result is called *quark confinement* — apparently, individual quarks can never be observed outside of the confines of the observable particles that contain them.

Confinement works not only on single quarks, but on any "colored" combinations of quarks and gluons, e. g., a red up quark combined with a green down quark. It appears that long range inter-quark forces only vanish for interactions between "white" or "color-neutral" combinations of quarks. This is why only color-neutral combinations of quarks — three quarks of three different colors or a quark-antiquark pair of the same color — are actually seen as observable particles.

The strong equivalent of the fine structure constant is the *coupling constant* for the strong force:

$$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \tag{20.2.1}$$

Note that a_s is dimensionless. The binding energy between quarks is comparable to the rest energies of the quarks themselves. In other words, $a_s \approx 1$. Furthermore, as we have noted, the potential energy between two quarks appears to increase indefinitely with separation. Though forces exist between color-neutral particles, they are weak and of short range compared to the forces between quarks or colored combinations of quarks. However, they are still relatively strong compared to, say, electromagnetic forces. As we shall see later, these residual strong forces are responsible for nuclear processes.

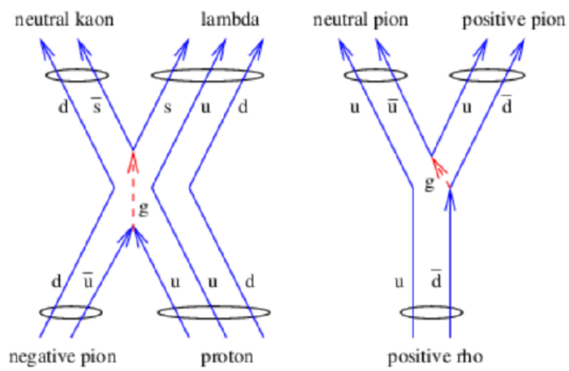

Figure 20.2.2:: Some sample strong interactions illustrated in terms of gluon emission and absorption. The process on the left shows the reaction $\pi + p \rightarrow K^0 + \Lambda^0$, while the one on the right shows the decay $\rho^+ \rightarrow \Pi^+ + \Pi^0$. Quarks are labeled with solid lines while gluons are shown by dashed lines.

Interactions between hadrons can be thought of as resulting from interactions between the individual quarks making up the hadrons. Two sample strong interactions are shown in Figure 20.2.2. Virtual gluons can be emitted and absorbed by quarks much as virtual photons can be emitted and absorbed by electrically charged particles. Particles unstable to strong decay processes (such as the positive rho particle) typically live only about 10^{-23} s, whereas particles stable to strong decay but unstable to weak decay live of order 10^{-10} s or longer, depending strongly on how much energy is liberated in the decay. Particles subject to electromagnetic decay processes, such as the neutral pion, take on mean lifetimes intermediate between strong and weak values, typically of order 10^{-18} s.