Example 11.3

Strangeness Conservation

(a) Based on the conservation of strangeness, can the following reaction occur?

$$\pi^- + p \rightarrow K^+ + K^- + n.$$

(b) The following decay is mediated by the weak nuclear force:

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

Does the decay conserve strangeness? If not, can the decay occur?

Strategy

Determine the strangeness of the reactants and products and require that this value does not change in the reaction.

Solution

a. The net strangeness of the reactants is $0 + 0 = 0,$ and the net strangeness of the products is $1 + (-1) + 0 = 0.$ Thus, the strong nuclear interaction between a pion and a proton is not forbidden by the law of conservation of strangeness. Notice that baryon number is also conserved in the reaction.

b. The net strangeness before and after this decay is 1 and 0, so the decay does not conserve strangeness. However, the decay may still be possible, because the law of conservation of strangeness does not apply to weak decays.

Significance

Strangeness is conserved in the first reaction, but not in the second. Strangeness conservation constrains what reactions can and cannot occur in nature.

11.3 Check Your Understanding What is the strangeness number of a muon?

11.3 | Quarks

Learning Objectives

By the end of this section, you will be able to:

- Compare and contrast the six known quarks
- Use quark composition of hadrons to determine the total charge of these particles
- Explain the primary evidence for the existence of quarks

In the 1960s, particle physicists began to realize that hadrons are not elementary particles but are made of particles called *quarks*. (The name 'quark' was coined by the physicist Murray Gell-Mann, from a phrase in the James Joyce novel *Finnegans Wake*.) Initially, it was believed there were only three types of quarks, called *up* (u), *down* (d), and *strange* (s). However, this number soon grew to six—interestingly, the same as the number of leptons—to include *charmed* (c), *bottom* (b), and *top* (t).

All quarks are spin-half fermions $(s = 1/2)$, have a fractional charge $(1/3 \text{ or } 2/3e)$, and have baryon number $B = 1/3$. Each quark has an antiquark with the same mass but opposite charge and baryon number. The names and properties of the six quarks are listed in Table 11.3.

Quark	Charge (units of *e*)	Spin (*s*)	Baryon number	Strangeness number
Down (*d*)	$-1/3$	1/2	1/3	0
Up (*u*)	$+2/3$	1/2	1/3	0
Strange (*s*)	$-1/3$	1/2	1/3	-1
Charm (*c*)	$+2/3$	1/2	1/3	0
Bottom (*b*)	$-1/3$	1/2	1/3	0
Top (*t*)	$+2/3$	1/2	1/3	0

Table 11.3 Quarks

Quark Combinations

As mentioned earlier, quarks bind together in groups of two or three to form hadrons. Baryons are formed from three quarks. Sample baryons, including quark content and properties, are given in **Table 11.4**. Interestingly, the delta plus (Δ^+) baryon is formed from the same three quarks as the proton, but the total spin of the particle is 3/2 rather than 1/2. Similarly, the mass of Δ^+ with spin 3/2 is 1.3 times the mass of the proton, and the delta zero (Δ^0) baryon with a spin 3/2 is 1.3 times the neutron mass. Evidently, the energy associated with the spin (or angular momentum) of the particle contributes to its mass energy. It is also interesting that no baryons are believed to exist with top quarks, because top quarks decay too quickly to bind to the other quarks in their production.

Name	Symbol	Quarks	Charge (unit of *e*)	Spin (*s*)	Mass (GeV/c^2)
Proton	p	*u u d*	1	1/2	0.938
Neutron	n	*u d d*	0	1/2	0.940
Delta plus plus	Δ^{++}	*u u u*	2	3/2	1.232
Delta plus	Δ^+	*u u d*	1	3/2	1.232
Delta zero	Δ^0	*u d d*	0	3/2	1.232
Delta minus	Δ^-	*d d d*	-1	3/2	1.232
Lambda zero	Λ^0	*u d s*	0	1/2	1.116
Positive sigma	Σ^+	*u u s*	1	1/2	1.189
Neutral sigma	Σ^0	*u d s*	0	1/2	1.192
Negative xi	Ξ^-	*s d s*	-1	1/2	1.321
Neutral xi	Ξ^0	*s u s*	0	1/2	1.315
Omega minus	Ω^-	*s s s*	-1	3/2	1.672
Charmed lambda	Λ_{C+}	*u d c*	1	1/2	2.281
Charmed bottom	Λ_{b0}	*u d b*	0	1/2	5.619

Table 11.4 Baryon Quarks

Mesons are formed by two quarks—a quark-antiquark pair. Sample mesons, including quark content and properties, are given in **Table 11.5**. Consider the formation of the pion ($\pi^+ = u\bar{d}$). Based on its quark content, the charge of the pion is

$$\frac{2}{3}e + \frac{1}{3}e = e.$$

Both quarks are spin-half ($s = ½$), so the resultant spin is either 0 or 1. The spin of the π^+ meson is 0. The same quark-antiquark combination gives the rho (ρ) meson with spin 1. This meson has a mass approximately 5.5 times that of the π^+ meson.

Example 11.4

Quark Structure

Show that the quark composition given in **Table 11.5** for Ξ^0 is consistent with the known charge, spin, and strangeness of this baryon.

Strategy

Ξ^0 is composed of two strange quarks and an up quark (*s u s*). We can add together the properties of quarks to predict the resulting properties of the Ξ^0 baryon.

Solution

The charge of the *s* quark is $-e/3$ and the charge of the *u* quark is 2*e*/3. Thus, the combination (*s u s*) has no net charge, in agreement with the known charge of Ξ^0. Since three spin $-1/2$ quarks can combine to produce a particle with spin of either 1/2 or 3/2, the quark composition is consistent with the known spin ($s = 1/2$) of Ξ^0. Finally, the net strangeness of the (*s u s*) combination is $(-1) + 0 + (-1) = -2,$ which also agrees with experiment.

Significance

The charge, spin, and strangeness of the Ξ^0 particle can be determined from the properties of its constituent quarks. The great diversity of baryons and mesons can be traced to the properties of just six quarks: up, down, charge, strange, top, and bottom.

11.4 Check Your Understanding What is the baryon number of a pion?

Name	Symbol	Quarks	Charge (*e*)	Spin	Mass (GeV/c^2)
Positive pion	π^+	$u\bar{d}$	1	0	0.140
Positive rho	ρ^+	$u\bar{d}$	1	1	0.768
Negative pion	π^-	$\bar{u}d$	-1	0	0.140
Negative rho	ρ^-	$\bar{u}d$	-1	1	0.768
Neutral Pion	π^0	$\bar{u}u$ or $\bar{d}d$	0	0	0.135
Neutral eta	η^0	$\bar{u}u$, $\bar{d}d$ or $\bar{s}s$	0	0	0.547
Positive kaon	K^+	$u\bar{s}$	1	0	0.494
Neutral kaon	K^0	$d\bar{s}$	0	0	0.498
Negative kaon	K^-	$\bar{u}s$	-1	0	0.494
J/Psi	J/ψ	$\bar{c}c$	0	1	3.10

Table 11.5 Meson Quarks

Name	Symbol	Quarks	Charge (*e*)	Spin	Mass (GeV/c^2)
Charmed eta	$\eta 0$	$c\bar{c}$	0	0	2.98
Neutral D	D^0	$\bar{u}c$	0	0	1.86
Neutral D	D^{*0}	$\bar{u}c$	0	1	2.01
Positive D	D^+	$\bar{d}c$	1	0	1.87
Neutral B	B^0	$\bar{d}b$	0	0	5.26
Upsilon	Υ	$b\bar{b}$	0	1	9.46

Table 11.5 Meson Quarks

Color

Quarks are fermions that obey Pauli's exclusion principle, so it might be surprising to learn that three quarks can bind together within a nucleus. For example, how can two up quarks exist in the same small region of space within a proton? The solution is to invent a third new property to distinguish them. This property is called **color**, and it plays the same role in the strong nuclear interaction as charge does in electromagnetic interactions. For this reason, quark color is sometimes called "strong charge."

Quarks come in three colors: red, green, and blue. (These are just labels—quarks are not actually colored.) Each type of quark (u, d, c, s, b, t) can possess any other colors. For example, three strange quarks exist: a red strange quark, a green strange quark, and a blue strange quark. Antiquarks have anticolor. Quarks that bind together to form hadrons (baryons and mesons) must be color neutral, colorless, or "white." Thus, a baryon must contain a red, blue, and green quark. Likewise, a meson contains either a red-antired, blue-antiblue, or green-antigreen quark pair. Thus, two quarks can be found in the same spin state in a hadron, without violating Pauli's exclusion principle, because their colors are different.

Quark Confinement

The first strong evidence for the existence of quarks came from a series of experiments performed at the Stanford Linear Accelerator Center (SLAC) and at CERN around 1970. This experiment was designed to probe the structure of the proton, much like Rutherford studied structure inside the atom with his α-particle scattering experiments. Electrons were collided with protons with energy in excess of 20 GeV. At this energy, $E \approx pc$, so the de Broglie wavelength of an electron is

$$\lambda = \frac{h}{p} = \frac{hc}{E} \approx 6 \times 10^{-17} \text{ m}. \tag{11.1}$$

The wavelength of the electron is much smaller than the diameter of the proton (about 10^{-15} m). Thus, like an automobile traveling through a rocky mountain range, electrons can be used to probe the structure of the nucleus.

The SLAC experiments found that some electrons were deflected at very large angles, indicating small scattering centers within the proton. The scattering distribution was consistent with electrons being scattered from sites with spin 1/2, the spin of quarks. The experiments at CERN used neutrinos instead of electrons. This experiment also found evidence for the tiny scattering centers. In both experiments, the results suggested that the charges of the scattering particles were either $+2/3e$ or $-1/3e$, in agreement with the quark model.

Watch this **video (https://openstaxcollege.org/l/21quarks)** to learn more about quarks.

The quark model has been extremely successful in organizing the complex world of subatomic particles. Interestingly, however, no experiment has ever produced an isolated quark. All quarks have fractional charge and should therefore be easily distinguishable from the known elementary particles, whose charges are all an integer multiple of *e*. Why are isolated quarks not observed? In current models of particle interactions, the answer is expressed in terms of quark confinement. Quark confinement refers to the confinement of quarks in groups of two or three in a small region of space. The quarks are completely free to move about in this space, and send and receive gluons (the carriers of the strong force). However, if these quarks stray too far from one another, the strong force pulls them back it. This action is likened to a bola, a weapon used for hunting (**Figure 11.5**). The stones are tied to a central point by a string, so none of the rocks can move too far from the others. The bola corresponds to a baryon, the stones correspond to quarks, and the string corresponds to the gluons that hold the system together.

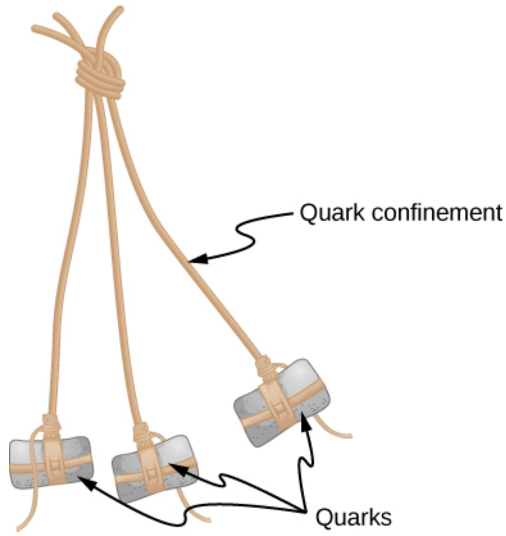

Figure 11.5 A baryon is analogous to a bola, a weapon used for hunting. The rocks in this image correspond to the baryon quarks. The quarks are free to move about but must remain close to the other quarks.

11.4 | Particle Accelerators and Detectors

Learning Objectives

By the end of this section, you will be able to:

- Compare and contrast different types of particle accelerators
- Describe the purpose, components, and function of a typical colliding beam machine
- Explain the role of each type of subdetector of a typical multipurpose particle detector
- Use the curvature of a charge track to determine the momentum of a particle

The goal of experimental particle physics is to accurately measure elementary particles. The primary method used to achieve this end is to produce these particles in high-energy collisions and then measure the products of using highly sensitive particle detectors. These experiments are used to test and revise scientific models of particle interactions. The purpose of this section is to describe particle accelerators and detectors. Modern machines are based on earlier ones, so it is helpful to present a brief history of accelerators and detectors.

Early Particle Accelerators

A **particle accelerator** is a machine designed to accelerate charged particles. This acceleration is usually achieved with strong electric fields, magnetic fields, or both. A simple example of a particle accelerator is the Van de Graaff accelerator (see **Electric Potential (http://cnx.org/content/m58427/latest/)**). This type of accelerator collects charges on a hollow metal sphere using a moving belt. When the electrostatic potential difference of the sphere is sufficiently large, the field is used to accelerate particles through an evacuated tube. Energies produced by a Van de Graaff accelerator are not large enough to create new particles, but the machine was important for early exploration of the atomic nucleus.

Larger energies can be produced by a linear accelerator (called a "linac"). Charged particles produced at the beginning of the linac are accelerated by a continuous line of charged hollow tubes. The voltage between a given pair of tubes is set to draw the charged particle in, and once the particle arrives, the voltage between the next pair of tubes is set to push the charged particle out. In other words, voltages are applied in such a way that the tubes deliver a series of carefully synchronized electric kicks (**Figure 11.6**). Modern linacs employ radio frequency (RF) cavities that set up oscillating electromagnetic