32–9 Quarks

All particles, except the gauge bosons, are either leptons or hadrons. The principal difference between these two groups is that the hadrons interact via the strong interaction, whereas the leptons do not.

The six leptons $(\mathrm{e}^-, \mu^-, \tau, \nu_e, \nu_\mu, \nu_\tau)$ are considered to be truly elementary particles because they do not show any internal structure, and have no measurable size. (Attempts to determine the size of leptons have put an upper limit of about 10^{-18} m.)

Quarks

There are hundreds of hadrons, on the other hand, and experiments indicate they do have an internal structure. In 1963, M. Gell-Mann and G. Zweig proposed that none of the hadrons, not even the proton and neutron, are truly elementary, but instead are made up of combinations of three, more fundamental, pointlike entities called, somewhat whimsically, **quarks**.† Today, the quark theory is well-accepted, and quarks are considered the truly elementary particles, like leptons. The three quarks originally proposed were labeled u, d, s, and have the names *up*, *down*, and *strange*. The theory today has six quarks, just as there are six leptons—based on a presumed symmetry in nature. The other three quarks are called *charmed*, *bottom*, and *top*. The names apply also to new properties of each (quantum numbers c, t, b) that distinguish the new quarks from the old quarks (see Table 32–3), and which (like strangeness) are conserved in strong, but not weak, interactions. All quarks have spin $\frac{1}{2}$ and an electric charge of either $+\frac{2}{3}e$ or $-\frac{1}{3}e$ (that is, a fraction of the previously thought smallest charge e). Antiquarks have opposite sign of electric charge Q, baryon number B, strangeness S, charm c, bottomness b, and topness t. Other properties of quarks are shown in Table 32–3.

FIGURE 32–12 Quark compositions for several particles.

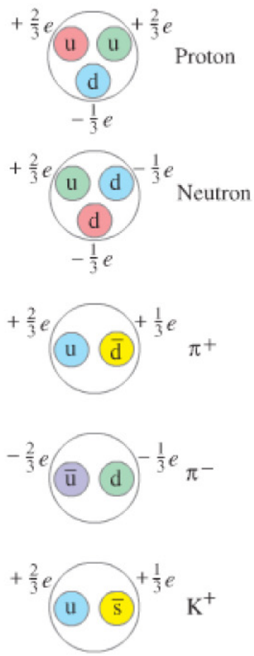

TABLE 32–3 Properties of Quarks (Antiquarks have opposite sign Q, B, S, c, t, b)

		Quarks					
Name	Symbol	Charge Q	Baryon Number B	Strangeness S	Charm c	Bottomness b	Topness t
Up	u	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	0
Down	d	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	0	0
Strange	s	$-\frac{1}{3}e$	$\frac{1}{3}$	−1	0	0	0
Charmed	c	$+\frac{2}{3}e$	$\frac{1}{3}$	0	+1	0	0
Bottom	b	$-\frac{1}{3}e$	$\frac{1}{3}$	0	0	−1	0
Top	t	$+\frac{2}{3}e$	$\frac{1}{3}$	0	0	0	+1

Mesons = quark + an antiquark

Baryons = 3 quarks

All hadrons are considered to be made up of combinations of quarks, and their properties are described by looking at their quark content. Mesons consist of a quark–antiquark pair. For example, a π^+ meson is a $\mathrm{u\bar{d}}$ combination: note that for the $\mathrm{u\bar{d}}$ pair, $Q = \frac{2}{3}e + \frac{1}{3}e = +1e$, $B = \frac{1}{3} - \frac{1}{3} = 0$, $S = 0 + 0 = 0$, as they must for a π^+; and a $\mathrm{K^+ = u\bar{s}}$, with $Q = +1$, $B = 0$, $S = +1$. Baryons, on the other hand, consist of three quarks. For example, a neutron is $\mathrm{n = ddu}$, whereas an antiproton is $\mathrm{\bar{p} = \bar{u}\bar{u}\bar{d}}$. See Fig. 32–12. Strange particles all contain an s or $\bar{\mathrm{s}}$ quark, whereas charmed particles contain a c or $\bar{\mathrm{c}}$ quark. A few of these hadrons are listed in Table 32–4.

After the quark theory was proposed, physicists began looking for these fractionally charged particles, but direct detection has not been successful. Current models suggest that quarks may be so tightly bound together that they may not ever exist singly in the free state. But observations of very high energy electrons scattered off protons suggest that protons are indeed made up of constituents.

†Gell-Mann chose the word from a phrase in James Joyce's *Finnegans Wake*.