## 32–10 The “Standard Model”: Quantum Chromodynamics (QCD) and the Electroweak Theory

Not long after the quark theory was proposed, it was suggested that quarks have another property (or quality) called **color**, or “color charge” (analogous to electric charge). The distinction between the six quarks (u, d, s, c, b, t) was referred to as **flavor**. According to theory, each of the flavors of quark can have three colors, usually designated red, green, and blue. (These are the three primary colors which, when added together in equal amounts, as on a TV screen, produce white.) Note that the names “color” and “flavor” have nothing to do with our senses, but are purely whimsical—as are other names, such as charm, in this new field. (We did, however, “color” the quarks in Fig. 32–12.) The antiquarks are colored antired, antigreen, and antiblue. Baryons are made up of three quarks, one of each color. Mesons consist of a quark–antiquark pair of a particular color and its anticolor. Both baryons and mesons are thus colorless or white.

*Fermions*
*Bosons*

Originally, the idea of quark color was proposed to preserve the Pauli exclusion principle (Section 28–7). Not all particles obey the exclusion principle. Those that do, such as electrons, protons, and neutrons, are called **fermions**. Those that don’t are called **bosons**. These two categories are distinguished also in their spin (Section 28–6): bosons have integer spin (0, 1, 2, etc.) whereas fermions have half-integer spin, usually $\frac{1}{2}$ as for electrons and nucleons, but other fermions have spin $\frac{3}{2}, \frac{5}{2}$, etc. Matter is made up mainly of fermions, but the carriers of the forces ($\gamma$, W, Z, and gluons) are all bosons. Quarks are fermions (they have spin $\frac{1}{2}$) and therefore should obey the exclusion principle. Yet for three particular baryons (uuu, ddd, and sss), all three quarks would have the same quantum numbers, and at least two quarks have their spin in the same direction (since there are only two choices, spin up $\left[m_s = +\frac{1}{2}\right]$ or spin down $\left[m_s = -\frac{1}{2}\right]$). This would seem to violate the exclusion principle; but if quarks have an additional quantum number (color), which is different for each quark, it would serve to distinguish them and allow the exclusion principle to hold. Although quark color, and the resulting threefold increase in the number of quarks, was originally an *ad hoc* idea, it also served to bring the theory into better agreement with experiment, such as predicting the correct lifetime of the $\pi^0$ meson. The idea of color soon became a central feature of the theory as determining the force binding quarks together in a hadron.

*QCD*
*Gluons*

Each quark is assumed to carry a *color charge*, analogous to electric charge, and the strong force between quarks is referred to as the **color force**. This theory of the strong force is called **quantum chromodynamics** (*chroma* = color in Greek), or **QCD**, to indicate that the force acts between color charges (and not between, say, electric charges). The strong force between two hadrons is considered to be a force between the quarks that make them up, as suggested in Fig. 32–13. The particles that transmit the color force (analogous to photons for the EM force) are called **gluons** (a play on “glue”). They are included in Table 32–5. There are eight gluons, according to the theory, all massless and all have color charge.[†] Thus gluons have replaced mesons (Table 32–1) as the particles responsible for the strong (color) force.

*Confinement*

You might ask what would happen if we try to see a single quark with color by reaching deep inside a hadron and extracting a single quark. Quarks are so tightly bound to other quarks that extracting one would require a tremendous amount of energy, so much that it would be sufficient to create more quarks $(E = mc^2)$. Indeed, such experiments are done at modern particle colliders and all we get is more hadrons (quark–antiquark pairs, or triplets), not an isolated quark. This property of quarks, that they are always bound in groups that are colorless, is called **confinement**.

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[†] Compare to the EM interaction, where the photon has no electric charge. Because gluons have color charge, they could attract each other and form composite particles (photons cannot). Such “glueballs” are being searched for.