8. THE STANDARD MODEL

Thanks to the work of theoretical and experimental physicists, all known features of the subatomic world can be explained in terms of what is called the Standard Model. A grand achievement of modern physics, this model incorporates all the major advances of the past three decades. With the discovery of a third family of quarks and leptons in the late 1970's, the Standard Model was nearly complete. But a few more elements were needed to fill out the picture—like a way to lash quarks together inside hadrons.

From scattering experiments physicists knew that quarks inside a hadron acted like individual particles—like pairs or trios of colorful marbles rattling around in a bag. But some unfamiliar force was confining these quarks so that they never emerged individually. As subatomic forces are conveyed by particles, there had to be a particle (or a group of them), which physicists called the *gluon* (g), carrying the force that imprisoned them inside hadrons. Quarks would attract one another by swapping gluons.

Describing this interquark force in detail, however, was not a simple feat. Physicists still cannot isolate a single quark and study its interaction with known forces—as can be done, for example, with an electron in electric or magnetic fields. They must always work with ensembles of two or three quarks, which complicates matters enormously.

An important theoretical breakthrough occurred in the spring of 1973. Three Americans—David Politzer of Harvard, and David Gross and Frank Wilczek at Princeton—independently showed that Yang-Mills gauge theories predicted that the force between two particles *decreases* as they approach one another. It is somewhat like the force exerted on two marbles by a rubber band connecting them, which slackens as they come closer together. Such behavior is contrary to normal expectations based on forces like gravity and electromagnetism, which increase at close quarters, but it is vary much how quarks behave. Politzer, Gross and Wilczek had discovered the correct theoretical framework needed to describe such a force.

The force between quarks becomes feeble at short distances, like those separating quarks inside a proton. When one of them is struck by a high-energy probe, such as an electron, the quark behaves like a relatively free, unbound particle—as does one marble when hit by another. As the struck quark begins to fly away from its siblings, however, the force between them gets stronger: the "rubber band" becomes more taut. One of two things now happens. Either the force yanks the truant quark back into the fold, or the quark has sufficient energy to break free. In the latter case, however, it does so only after acquiring enough energy to create a new quark to take its place and a corresponding antiquark bound to itself. We are still left with hadrons: a baryon made of three quarks and a meson composed of a quark-antiquark pair.

In gauge theories, forces are due to some kind of "charge." During the summer of 1973 several physicists suggested that the new property of color—originally proposed to distinguish one quark from

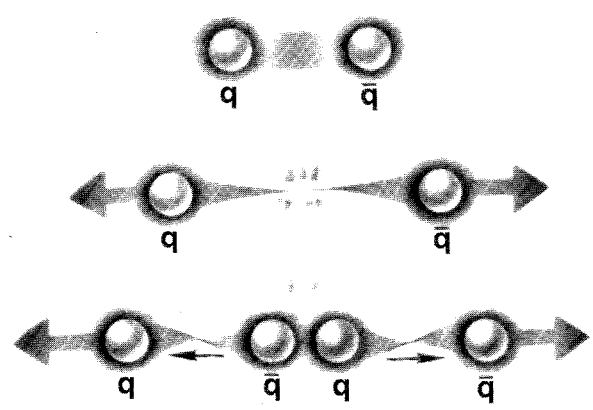

Figure 19. The force between two quarks grows stronger as they separate. They can break free of one another only by creating a quark-antiquark pair.