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Quarks and gluons

Our prime candidate for a fundamental theory of strong hadronic forces is a model of quarks interacting through the exchange of non-Abelian gauge fields. The quark model represents a new level of substructure within hadronic particles such as the proton. We have several compelling reasons to believe in this next layer of matter.

First, the large cross sections observed in deeply inelastic lepton–hadron scattering indicate important structure at distance scales of less than 10^{-16} centimeters, whereas the overall proton electromagnetic radius is of order 10^{-13} centimeters. The angular dependences observed in these experiments suggest that the underlying charged constituents carry half-integer spin. These studies have raised the question of whether it is theoretically possible to have pointlike objects in a strongly interacting theory. Asymptotically free non-Abelian gauge interactions offer this hope (Perkins, 1977).

A second impetus for a theory of quarks lies in low energy hadronic spectroscopy. Indeed, it was the successes of the eightfold way (Gell-Mann and Ne'eman, 1964) which originally motivated the quark model. We now believe that the existence of two 'flavors' of low mass quarks lies at the heart of the isospin symmetry in nuclear physics. Adding a somewhat heavier 'strange' quark to the theory gives rise to the celebrated multiplet structure in terms of representations of the group $SU(3)$.

Third, we have further evidence for compositeness in the excitations of the low-lying hadrons. Particles differing in angular momentum fall neatly into place on the famous 'Regge trajectories' (Collins and Squires, 1968). In this way families of states group together as orbital excitations of some underlying system. The sustained rising of these trajectories with increasing angular momentum points toward strong long-range forces. This originally motivated the stringlike models of hadrons.

Finally, the idea of quarks became incontrovertible with the discovery of the 'hydrogen atoms' of elementary particle physics. The intricate spectroscopy of the charmonium and upsilon families is admirably explained in potential models for non-relativistic bound states of heavy quarks (Eichten *et al.*, 1980).

Despite these successes of the quark model, an isolated quark has never been observed. (Some hints of fractionally charged macroscopic pieces of matter may eventually prove to contain unbound quarks, or might be a sign of some new and even more exciting type of matter (LaRue, Phillips and Fairbank, 1981).) These basic constituents of matter do not copiously appear as free particles emerging from present laboratory experiments. This is in marked contrast to the empirical observation in hadronic physics that anything which can be created will be. The difficulty in producing quarks has led to the speculation of an exact confinement. Indeed, it may be simpler to imagine a constituent which can never be produced than an approximate imprisonment relying on some unnaturally effective suppression factor in a theory seemingly devoid of any large dimensionless parameters.

But how can we ascribe any reality to an object which cannot be produced? Are we just dealing with some sort of mathematical trick? We will now argue that gauge theories potentially possess a simple mechanism for giving constituents infinite energy when in isolation. In this picture a quark–antiquark pair will experience an attractive force which remains non-vanishing even for asymptotically large separations. This linearly rising long-distance potential energy forms the basis of essentially all models of quark confinement.

We begin by coupling the quarks to a conserved 'gluo-electric' flux. In usual electromagnetism the electric field lines thus produced spread and give rise to the inverse square law Coulombic field. If in our theory we can now somehow eliminate massless fields, then a Coulombic spreading will no longer be a solution to the equations. If in removing the massless fields we do not destroy the Gauss law constraint that the quarks are the sources of electric flux, the electric lines must form into tubes of conserved flux, schematically illustrated in figure 1.1. These tubes will only end on the quarks and their antiparticles. A flux tube is a real physical object carrying a finite energy per unit length. This is the storage medium for the linearly rising interquark potential (Kogut and Susskind, 1974).

A simple model for this phenomenon is a type II superconductor containing magnetic monopole impurities. Because of the Meissner effect (Meissner and Ochsenfeld, 1933), a superconductor does not admit magnetic fields. However, if we force a hypothetical magnetic monopole into the system, its lines of magnetic flux must go somewhere. Here the role of the 'gluo-electric' flux is played by the magnetic field, which will bore a tube of normal material through the superconductor until it ends on an antimonopole or it leaves the boundary of the system. Such flux tubes have been experimentally observed in applied magnetic fields (Huebner and Clem, 1974).

Another example of this mechanism occurs in the bag model (Chodos *et al.*, 1975). Here the gluonic fields are unrestricted in the baglike interior of a hadron but forbidden by ad hoc boundary conditions from extending outside. In attempting to extract a single quark from a proton, one would draw out a long skinny bag carrying the gluo-electric flux of the quark back to the remaining constituents.

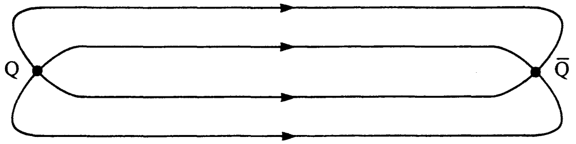

Fig. 1.1. A flux tube from a quark to an antiquark.

The above models may be interesting phenomenologically, but they are too arbitrary to be considered as the basis for fundamental theories. In their search for a more elegant model, theorists have been drawn to non-Abelian gauge fields. This dynamical system of coupled gluons begins like electrodynamics with a set of massless gauge fields interacting with the quarks. Using the freedom of an internal symmetry, the action includes self-couplings of the gluons. The bare massless fields are all charged with respect to each other. The confinement conjecture is that this input theory of massless charged particles is unstable to a condensation of the vacuum to a state in which only massive excitations can propagate. In such a state the gluonic flux around quarks should form into the tubes needed for linear confinement. Much of the recent effort in elementary particle theory has gone into attempts to show that this indeed takes place.

The confinement phenomenon makes the theory of the strong interactions qualitatively different from theories of the electromagnetic and weak forces. The fundamental fields of the Lagrangian do not manifest themselves in free hadronic spectrum. In not observing free quarks and gluons, we are led to the conjecture that all observable strongly interacting particles are gauge singlet bound states of these fundamental constituents.

In the usual quark model baryons are bound states of three quarks. Thus the gauge group should permit singlets to be formed from three objects in the fundamental representation. This motivates the use of $SU(3)$ as the underlying group of the strong interactions. This internal symmetry must not be confused with the broken $SU(3)$ represented in spectroscopic multiplets. Ironically, one of the original motivations for quarks has now become an accidental symmetry. The symmetry considered here is hidden behind the confinement mechanism, which only permits us to observe singlet states.

For the presentation in this book we assume, perhaps too naively, that the nuclear interactions can be considered in isolation from the much weaker effects of electromagnetism, weak interactions, and gravitation. This does not preclude the possible application of the techniques presented here to the other interactions. Indeed, grand unification may be crucial for a consistent theory of the world. To describe physics at normal laboratory energies, however, only for the strong interaction must we go beyond well-established perturbative methods. Thus we frame our discussion around quarks and gluons.