QCD, jets and gluons

After the introduction of colour, it became crucial to find direct evidence for the existence of quarks. This was obtained from experiments that scattered leptons from protons and others that studied the annihilation of electrons and positrons. Confirmation of the existence of coloured quarks enabled a practical quantum field theory of interacting quarks to be constructed.

Direct evidence for quarks

The success of the quark model in explaining the hadron spectrum was strong indirect evidence for the existence of quarks, but physicists still wanted to see some direct proof, ideally in the form of free quarks. Initially it was thought that if enough energy were brought to bear on hadrons, the strong force could be overcome and free quarks would emerge, something like ionising an atom or splitting a nucleus.

Experimenters tried colliding high-energy projectiles with protons. All that happened was that more particles, such as pions, were produced: no quarks were dislodged. Some physicists argued that perhaps the quarks were very heavy and that accelerators did not have sufficient energy to overcome the strong force. They suggested that in this case free quarks might be present in collisions induced by cosmic rays, some of which were known to have energies far higher than any man-made accelerator had achieved. Since quarks had to have non-integer electric charges, free quarks would necessarily be stable, because there are no lighter particles with non-integer charges to which they could decay. As a result, some bizarre searches were conducted of places where quarks might have come to rest, including deep-sea sludge and crushed oyster shells. Still no free quarks were found. Physicists were puzzled; conferences featured debates about the 'meaning' of quarks. According to his biographer, Gell-Mann tired of such discussions and got a doctor friend to write a fake medical note saying that he could no longer contribute to these talks because philosophy was bad for his health!

The first direct evidence for quarks finally came in 1968 in experiments at the SLAC laboratory in California, which essentially repeated the experiments conducted fifty years earlier that had discovered the existence of the nucleus but used different projectiles with higher energies. Rutherford, Geiger and Marsden had investigated the charge distribution within an atom by firing a beam of alpha particles at gold nuclei and observing the distribution of the scattered particles. Because of the relationship between distance and energy, probing the structure of hadrons requires projectiles with much higher energies – in the GeV region – than those used in that early experiment. SLAC had the ability to reach these higher energies. The team first used electrons scattered from protons, in a type of experiment referred to as *deep inelastic scattering*, because the projectiles, instead of scattering elastically, probe deep into the structure of the proton. The reactions studied are depicted in symbols as $e^- + p \rightarrow e^- + X$, where X stands for the many hadrons that were produced. Later experiments used muons as projectiles.

A study of the distribution of the scattered leptons, again comparable to what Rutherford and his colleagues had done, quickly showed that it was not consistent with the proton having a uniform charge distribution. Instead, the proton contained three much smaller entities. These were initially called *partons*, since the existence of quarks remained controversial. To prove that partons were actually quarks, experimentalists needed to find the values of their quantum numbers and show that they were the same as those predicted for quarks, specifically, spin $\frac{1}{2}$ and non-integer electric charges. To do this it was necessary to use neutrinos, which are uncharged and only interact by the weak interaction, as projectiles. Deep inelastic scattering experiments were carried out at a number of laboratories over the following years using ingeniously produced neutrino beams. Combining data from charged and neutral lepton scattering experiments unambiguously proved that partons did indeed have the same properties as quarks.

Feynman diagrams depicting the reactions studied are shown in Figure 6.1; the left panel depicts the use of electrons as the projectiles and the right panel the use of neutrinos. (The reason for the subscript μ on the neutrino will be explained in the next chapter.) In the former case, the probing particle is the exchanged photon and in the latter case it is a W boson, because neutrino scattering is a weak interaction. The target proton (entering from the left) is shown as consisting of three quarks; the exchanged particle interacts with a single quark, while the other two quarks take no part in the interaction – they are said to be *spectators*. This is similar in process to the beta decay of a nucleus, where one nucleon converts to another nucleon and all the other nucleons remain unchanged. In both cases, the scattered quarks and the

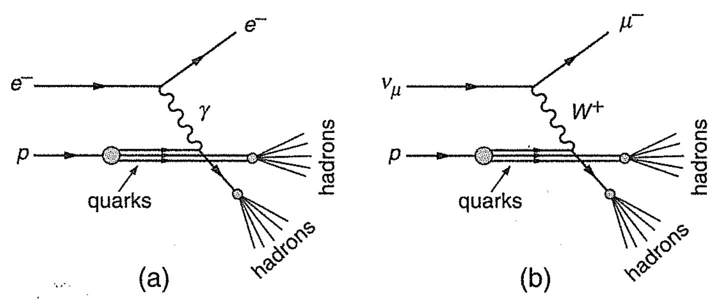

Figure 6.1 Deep inelastic scattering of electrons and neutrinos in the quark-parton model

spectator quarks contribute to the production of hadrons in the overall reaction, a process called *hadronisation*. This way of looking at the reaction, originally called the parton model but now more usually the quark-parton model, explains the data well and is an example of spectator models, where the interaction is with a single quark.

The evidence that there were quarks in nucleons was not totally unexpected. Nevertheless, the experiments provided a number of surprises. First, the quarks, far from being very heavy, were rather light, less than a third of the mass of the proton. At this point you may wonder what is meant by 'mass' when there are no free quarks to 'weigh'. It is worth taking a moment to consider this question. Take, for example, the electron: in QED, an electron constantly emits and reabsorbs virtual photons and these photons constantly create and reabsorb pairs of virtual electrons and positrons, and so on. What is actually measured when scientists 'weigh' an electron is an effective mass that includes the contributions to the total energy from this cloud of particles. These are examples of virtual particles – particles that do not appear in either the initial or final states as seen in the laboratory – that were introduced when I discussed Feynman diagrams previously. The exchanged photon and W boson in Figure 6.1 are also virtual particles. In the case of quarks, the effective mass includes the effects of the cloud of the equivalent force carriers of the strong interaction and the sea of virtual quark–anti-quark pairs they in turn produce. For the quarks in nucleons, the u and d quarks, these contributions are not small. Thus, in quoting masses for quarks we can either give the 'effective' mass as deduced from studies of hadrons, usually called the 'constituent' mass, which is what I have done above, or the theoretical mass without these contributions. The latter is much smaller, just a few MeV.

The deep inelastic scattering experiments also showed that as the energy of the projectiles increased, so that they probed deeper into the structure of the proton, the quarks unexpectedly behaved as if they were free particles trapped within the proton. Presumably the same is true for all hadrons. Finally, if the proton consisted of just three quarks, it would follow that the sum of the momentum of these quarks would have to be equal to that of the proton, and for a fast-moving proton, each quark would have approximately one-third of the proton's momentum. Also, against expectations, this proved not to be the case and an individual quark momentum was found to vary from event to event. Moreover, the sum of the constituent quarks' momenta did not add up to the proton's momentum. Quarks were found to have only about half of the proton's momentum, so a substantial fraction of the momentum was being carried by other particles: these turned out to be gluons.

Direct evidence for colour

Even though direct evidence had been obtained for the existence of quarks in hadrons, there remained the question of colour. The key piece of evidence for colour came from experiments at e^+e^- colliders. When electrons and positrons collide, they annihilate to produce a single virtual photon, which can then produce pairs of real matter and anti-matter particles, including muons and anti-muons and quarks and anti-quarks of any flavour, provided energy is conserved. The quarks and anti-quarks do not appear as free particles but cluster to produce various hadrons depending on the energy of the initial particles. (In symbols, these two reactions are $e^+ + e^- \rightarrow \gamma \rightarrow \mu^+ + \mu^-$ and $e^+ + e^- \rightarrow \gamma \rightarrow q + \bar{q}$.) Both are electromagnetic processes and at high energies the main difference in them is the charge of the particles in the final states. The rates for these reactions depend on the squares of the electric charges involved, so the ratio R of the production rate of $q\bar{q}$ pairs (which, because of hadronisation, is a measure of the production rate of hadrons) to the rate for production of $\mu^+\mu^-$ pairs is equal to the sum of the squares of the electric charges on the quarks. Assuming the initial leptons have only sufficient energy to produce the u, d and s quarks and their anti-particles and using the hypothesised values of their electric charges, this ratio was predicted to be $\frac{2}{3}$. However this prediction completely ignores colour. If colour were a real property of quarks, each quark and anti-quark could be produced in each of the three different colour states with equal probability. This follows because although the photon is exchanged between charged particles (it is said to 'couple' to charged particles) it is 'blind' to colour. So the prediction would need to be multiplied by 3, the number of colours, which would give a ratio of 2.

The first experiment to test the existence of colour was conducted in 1970 and data from later experiments considerably reduced remaining uncertainties. Across the board, the findings ruled out a ratio of $\frac{2}{3}$; they were consistent with a ratio of 2. This unambiguous existence for the colour quantum number convinced the few remaining doubters about the reality of quarks and set the stage for the construction of a quantum field theory of the strong interaction.

Quantum chromodynamics

The quantum field theory of interacting quarks was constructed by analogy with the theory of electromagnetic interactions, QED. It was assumed that quarks interact via the exchange of massless spin-1 particles, which came to be known as gluons. The source of the interaction is the colour charge, just as the source of the electromagnetic interaction is the electric charge. For this reason, the theory is called quantum chromodynamics (QCD), yet another name coined by Gell-Mann.

There are many similarities between QED and QCD. Both are theories of forces being transmitted by spin-1 bosons and both have the property of gauge invariance. Because of the work of t Hooft, QCD is known to be renormalisable, so not plagued by the infinities that defeated earlier attempts to construct quantum field theories. There is also a parallel with the electromagnetic forces seen in certain energy levels in atoms and in the strong forces seen between quark clusters. For example, in atoms, in addition to the interaction between the electric charges of the electrons and the protons, there is also an interaction between the intrinsic magnetic moments of the electrons and those of the protons and neutrons that produces small shifts in the energy levels of atoms.

Why does the electrically neutral neutron even have a magnetic moment? The answer lies in the fact that the sign of a particle's magnetic moment depends on the orientation of its spin. The neutron is a composite object made of three quarks and although the charges on the quarks must cancel exactly to give zero electric charge for the neutron, the magnetic moments of the three quarks do not, because their three spins must combine to give the correct spin of the neutron. The three spins cannot all be in the same direction.

In hydrogen, the simplest atom, the magnetic interaction changes the energy level by a very small amount, which can be positive or negative depending on the orientations of the spins of the electron and the proton: positive for total spin 1, negative for total spin 0. A similar effect is seen in hadrons, due to the magnetic interactions of their constituent quarks. For example, the octet of spin-1 resonances, including the rho meson, is heavier than the octet of spin-0 ground states (shown in Figure 5.3). The effect is much larger in mesons because they are vastly smaller than atoms and this is further enhanced by the fact that the strong interaction between quarks is far stronger than the electromagnetic interaction. Whereas the numerical value of the electromagnetic coupling constant α (also known as the fine structure constant), is approximately $\frac{1}{137}$, the value of the strong interaction equivalent, denoted α_s, is approximately forty times larger.

Although there are many similarities between QCD and QED, there are also profound differences. First, although a photon couples to charged particles, it is not itself electrically charged, so photons do not couple directly to other photons. In QCD, the equivalent particles are gluons and they couple to quarks that carry the colour quantum number. Just as electric charge has to balance in interactions, so does colour charge. If a quark of one colour (for example, red) changes to a quark of a different colour (for example, blue), the exchanged gluon must carry a combination of colours (in this case, red-blue) to balance the colour charges. So gluons carry a colour quantum number and do couple directly to other gluons. By considering all possible transformations of quarks of a definite colour, it is possible to deduce that there are eight possible combinations of colour that can be carried by gluons, that is, there are eight distinct varieties of gluons. QCD is a more complicated theory than QED, which has just two electric charges, positive and negative and only one force carrier, the photon. It is worth emphasising that in the strong interaction, colour determines the strength of the force, not the flavour of the quark that is carrying colour. The strong interaction is flavour-independent, just as the nuclear strong force is independent of electric charge.

The fact that gluons couple directly to other gluons raises the interesting possibility that, provided the forces were strong enough, particles consisting of colourless combinations of gluons that would not violate colour confinement could exist. These have been given the name *glueballs*; several experiments have been conducted to search for them. The obstacle to finding glueballs comes from the difficulty in predicting the masses of particles using QCD. What predictions there are suggest that the forces between gluons could be strong enough to support stable clusters. Unfortunately, the calculations also suggest that if glueballs exist, their masses fall in a region where several standard, electrically-neutral meson resonances – clusters of a quark and an anti-quark – already exist. It has proven problematic to distinguish possible glueballs from these other states experimentally. To date there is no definite evidence for the existence of glueballs but some slight evidence for states that could be clusters of quarks and glueballs – the so-called *hybrid mesons*. If glueballs exist, they would help to expand our understanding of QCD.

The simple fact that gluons couple directly to other gluons creates a crucial difference in the behaviour of QCD compared to QED. In QED, although the electromagnetic coupling α is referred to as a coupling constant, this is not the whole story. Instead, as a consequence of the cloud of virtual particles that always surrounds a charged particle, the coupling constant increases slightly as energies increase or, equivalently, distances decrease. The cloud essentially screens the charge of the particle and so changes its effective charge as seen by a second charged particle. This behaviour is an intrinsic property of QED. In QCD, a similar cloud of virtual particles exists, which consists of gluons and quark-anti-quark pairs. However, because of the gluon-gluon interactions in QCD, it turns out that this produces an 'anti-screening' effect and the coupling for the strong interaction α_s decreases with energy. Because of these energy dependencies, the couplings are often referred to as 'running' coupling constants.

The behaviour of the strong interaction coupling gives a qualitative explanation for why quarks in hadrons appear to behave as free particles when they are probed with high-energy projectiles: the coupling between the quarks decreases as energies increase, that is, as shorter distances are probed. This phenomenon is referred to as *asymptotic freedom*, since quarks would become free particles at infinitely large energies. Conversely, the extra interactions also explain why quarks are permanently confined in hadrons, because as the quarks are separated, the force between them increases. This is something like stretching an elastic string: as the length of the string is increased, a restoring force proportional to the extension comes into play and this force continues to resist the stretching until at some point the string breaks and the two parts of the string are freed (Hooke's Law of classical physics). In the case of QCD, the two quarks are not freed. Instead, as the force between the quarks increases, it resists quark separation until the energy generated by the gluon fields between the quarks becomes sufficiently strong to create new hadrons, yet the quarks remain confined. This property of QCD is referred to, rather dramatically, as *infra-red slavery*.

Experiments support this picture of coloured quarks interacting via the exchange of coloured gluons. One piece of evidence concerns the deep inelastic scattering experiments that gave the first direct evidence for the existence of quarks in hadrons. In the parton model used to interpret these experiments, it was assumed that the confined quarks had no mutual interactions. But in QCD it is necessary to take into account these mutual interactions via the exchange of gluons. There are two effects: first, the leptons not only interact with one of the three quarks comprising the proton but also with the sea of virtual quarks and anti-quarks surrounding it. Second, the energy dependence of the strong interaction coupling has to be taken into account. These QCD modifications produce small changes in the predictions for deep inelastic scattering data, which have been verified by more recent and precise experiments.

Another piece of evidence came from experiments conducted to test whether quarks possessed colour. The early experiments differentiated between two fixed ratios, depending on whether colour existed or not. Later experiments at higher energies revealed a small energy dependence in this ratio. This is illustrated in Figure 6.2, which shows the measured ratio R for experiments in the energy range 10 GeV to 40 GeV. At these energies, quarks that are heavier than the u, d and s quarks can be produced and the value of R is larger. As the quarks and anti-quarks accelerate away from the point where they are produced, they radiate photons (because the quarks are charged) as well as gluons, the

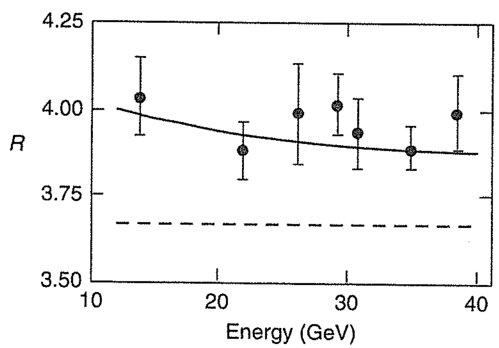

Figure 6.2 The ratio R of the cross-sections for hadron to muon production in e^+e^- annihilations

force carriers of the strong interaction. Radiation of photons can be calculated using the electromagnetic coupling α and radiation of gluons calculated using the strong coupling, α_s. These effects result in the energy dependence of R. In particular, the strong coupling varies significantly in the energy region under investigation. The solid curve in Figure 6.2 depicts the prediction including these corrections, while the dotted line is the prediction of the simple parton model. Both curves assume the existence of colour. Without colour, both predictions would have to be divided by a factor of three and would be in total disagreement with the data.

There are many more examples of coloured quarks interacting via the exchange of coloured gluons. Even in processes that cannot be calculated from first principles using the method of perturbation theory, QCD can be used to provide a detailed framework for experimental analyses. Whenever QCD has been tested, it has passed the test, with predictions that agree with experiment to accuracies better than one part in a thousand. Although this does not match the phenomenal precision of QED, it is still a very impressive vindication. Ideally, physicists would like a mathematical proof of confinement in QCD but just as for the calculations on glueballs, this has not yet been possible.

Jets and the direct evidence for gluons

Although QCD quickly proved to be a successful explanation of a wide range of experimental results, direct evidence for the existence of gluons still needed to be found. Unfortunately, just as for free quarks, it is not possible to detect free gluons; gluons are coloured and free gluons are forbidden to exist by the requirement of colour confinement. However, other evidence for gluons emerged in 1979, from an experiment using an electron-proton collider at the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg, Germany and later in e^+e^- annihilations using electron-positron colliders. Using electrons and positrons is more efficient than using interactions involving protons, since conservation of baryon number means that energy is always 'wasted' in producing baryons from proton targets.

When electrons and positrons annihilate, pairs of quarks and anti-quarks can be produced. As these move apart, the force between them increases in accordance with the predictions of QCD. This process continues until the strong gluon field has enough energy to create further pairs of quarks and their anti-particles, which quickly undergo hadronisation and form clusters that can be observed in the laboratory as hadrons. These annihilations have been studied for a range of energies up to more than 100 GeV. As the energy increases, QCD predicts that there should be an increasing tendency for the hadrons to be contained within a small angular region tied to the direction in which the original quarks were produced. In other words, the hadrons 'remember' the mechanism by which they were produced, as illustrated in Figure 6.3a. At high energies two prominent *jets* of hadrons should appear back-to-back, ensuring momentum conservation. Figure 6.3b shows an electronic reconstruction of the paths of particles in a track chamber from an e^+e^- collider at DESY. The view of the interaction region is taken along the beam pipe. As usual, the curvature of the tracks is due to an applied magnetic field. The two-jet events beautifully confirm the predictions of QCD.

What role do gluons play in this? As the quarks and anti-quarks accelerate away from the point of interaction they radiate gluons

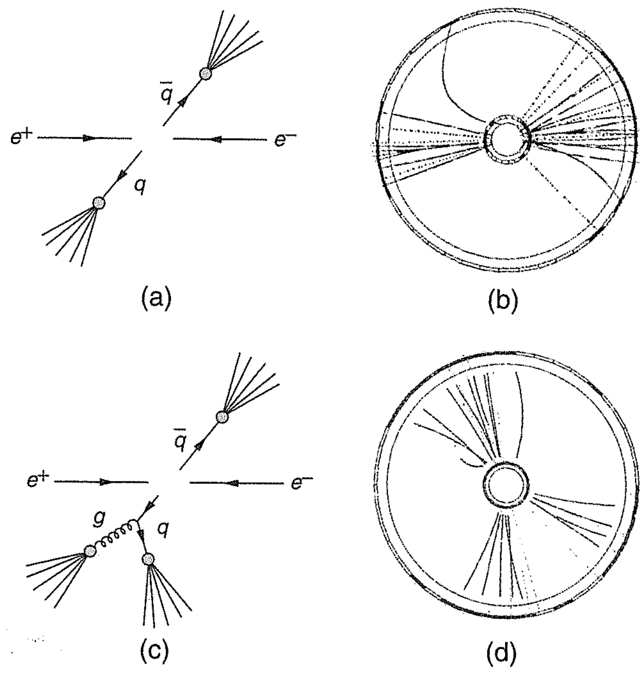

Figure 6.3 Two-jet and three-jet events in an e^+e^- collider experiment

but usually these carry little momentum, so any jets they generate will be subsumed within the quark jets. However, if a gluon is produced with a momentum comparable to that carried by a quark, to conserve momentum the direction of the quark will change and the jets produced by the gluon and quark will have distinct directions. Figure 6.3c illustrates this mechanism, where the gluon, g, is drawn as a coiled line. This effect occasionally happens. A typical 'three-jet' event, recorded at DESY in 1980, is shown in Figure 6.3d. This is probably the closest we will ever get to seeing a gluon.

By analysing their energies and angular distributions, we can show these three-jet events really are evidence for gluons. It is possible to deduce which jet is due to a gluon and moreover, the spin of the particle that produced it. The data are only compatible with spin 1, completing the direct confirmation of the existence of gluons. Further, because the ratio of the rate of production of three-jet events, those involving gluons, to the rate for two-jet events depends on the size of the strong coupling α_s, quantitative tests of QCD are possible. Again, QCD passes the test.