Fundamental Interactions

3) Strong Interactions

The strong interaction binds the constituents of nucleons and other hadrons. Its properties can be summarised as follows:

It acts only on quarks.

It is strong, overcoming the Coulomb repulsion in the nucleus

It binds quarks in only two configurations: qqq for baryons ($\overline{q}\overline{q}\overline{q}$ for antibaryons)

$q\overline{q}$ for mesons.

never as qq or $qq\overline{q}$ etc[1].

The quarks in baryons can be described by a wavefunction with a spin and a spatial part. However, it appears that the quarks violate the Pauli exclusion principle, in that there are cases where the total wave function is symmetric under the interchange of two identical quarks – indeed, in some cases three identical quarks have identical spin and orbital quantum numbers!

Example: the Δ^{++}. The Δ exists as Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-}. (It has an isospin of $\frac{3}{2}$). It consists of 3 quarks, each with spin $\frac{1}{2}$, with no orbital angular momentum, and has a total (spin) angular momentum of $\frac{3}{2}$.

If we consider the Δ^{++}, it must have 3 identical u quarks, all with $j = \frac{1}{2}, j_z = \frac{1}{2}, l = 0$.

i.e. 3 identical fermions in the same state – same wave function, same quantum numbers.

This violates the Pauli exclusion principle!

The explanation of this is that the quarks also carry an additional quantum number, which is different for all three quarks in a baryon. This quantum number also corresponds to the source or "charge" of the strong interaction. The fact that the sum of three equivalent but different "strong charges" are required to produce a neutral state has led to this charge being known as colour, in analogy with the addition of three primary colours, red, green and blue, making white light. Each quark is labelled as red, green or blue, while antiquarks carry the equivalent "anticolours". All hadrons, whether qqq or $q\overline{q}$, are therefore seen to be colour-neutral states.

The strong interaction is a gauge interaction mediated by a massless, spin 1 gluon, g, which is electrically neutral but carries a composite colour such as red-$\overline{blue}$. The coupling constant is known as α_s (alpha-strong) and the theory is known as Quantum Chromodynamics or QCD in analogy with QED. Note that, unlike in QED, the exchange quantum is also a source, so processes such as the branching of one gluon into two can occur. (The theory is said to be non-Abelian.)

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[1] Recent evidence suggests that states known as "pentaquarks" and "tetraquarks" may exist. These are **not** composed of 5 or 4 quarks, as their names suggest, but (if confirmed) of 4 quarks plus an antiquark in the case of pentaquarks and 2 quarks and 2 antiquarks in the case of tetraquarks. They can therefore be seen as "hadron molecules", formed by a baryon and a meson or two mesons (respectively) loosely bound together. They do not affect the conclusion that free states always consist of either 3 quarks or a quark plus an antiquark.
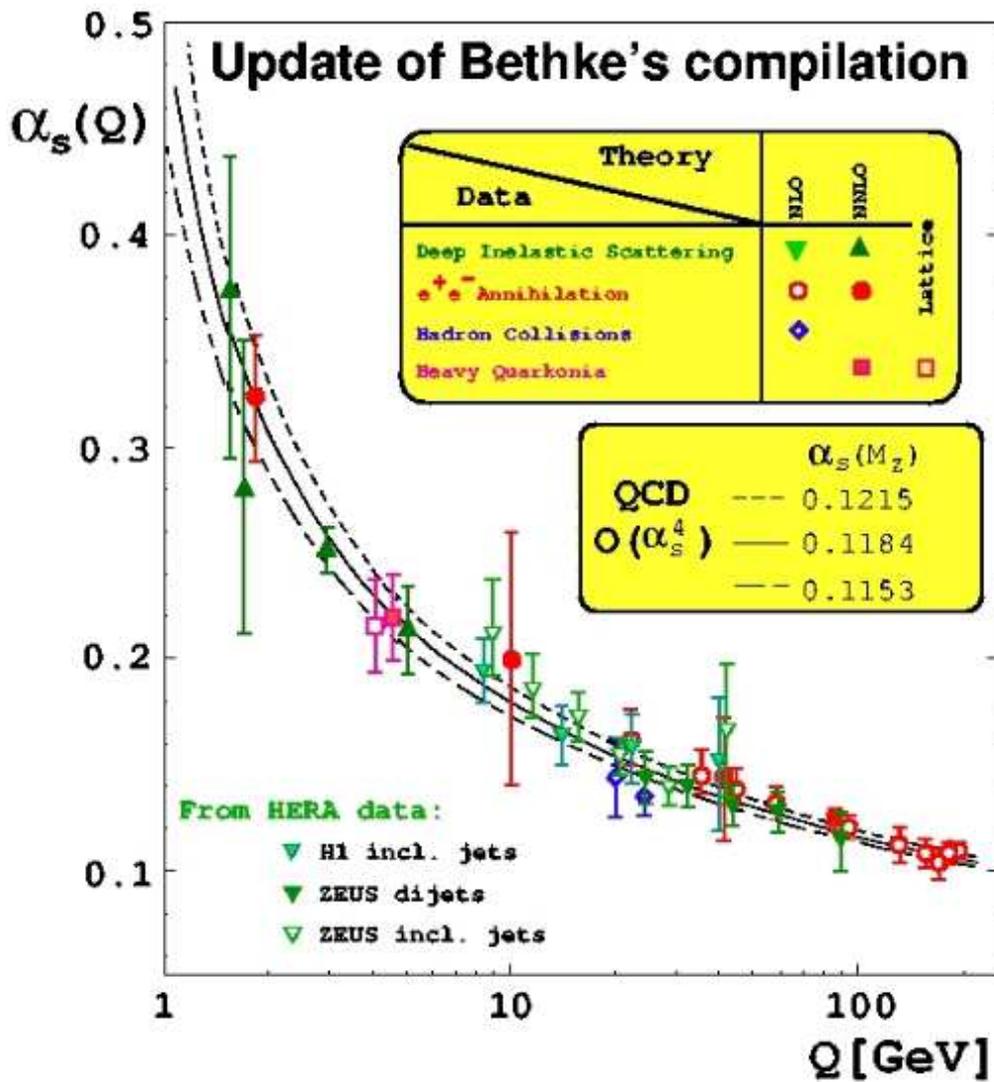
Fig. 8 The change in α_S as a function of momentum transfer. (Note the log scale.)

The final point to note about the strong interaction is its strength! At small momentum transfer (or large distance) $\alpha_s \approx 1$. At shorter distances, or large q, the value of $\alpha_s(q)$ decreases as is seen in figure 8, (enabling perturbation calculations to be done). The origin of this variation with distance is the non-Abelian nature of the interaction. At short distances, the gluon appears dissociated into a colour cloud, and the strength of the colour charge is diluted. This property explains why free quarks are never observed. At large distances, the force becomes extremely strong and the quarks are said to be confined. If a quark is ejected from a hadron, the colour field builds up until it becomes energetically favourable to create a quark-antiquark pair and reduce the field. The new q and $\bar{q}$ are attracted to the original particles, and produce a colourless meson and baryon. When many pairs are produced, this results in a jet of particles following the original quark direction. These can be observed both in inelastic scattering of a lepton from a hadron (where the struck quark in the hadron is ejected) and in e^+e^- annihilation, where a rapidly separating q$\bar{q}$ pair is produced.

(The strong interaction is sometimes described as being a short-range force. Being mediated by massless bosons, the strong force between quarks is **not** short-ranged. However, the strong force between hadrons which are colourless overall – e.g. the force between nucleons in the nucleus – does appear to be short-ranged, in exactly the same way that the electromagnetic force between electrically neutral molecules in a crystal appears short-ranged.)