Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/sv119/sv119-close.pdf

TQUARKS: AS CONSTITUENTS AND IN QCD

FRANK CLOSE

Dept of Theoretical Physics, University of Oxford
Oxford OX1 3NP; England

In the 19th century, the first clues that there is a deeper layer of structure within atoms came from the discovery of patterns among the atomic elements: Mendeleev's periodic table. This was accompanied by spectra and followed by Rutherford's direct observation of the atomic nucleus and Thomson's discovery of the electron. In the middle of the 20th century an analogous set of circumstances led to the revelation of the quark layer of reality. Strongly interacting particles – hadrons – were found to be built from quarks, the inter-quark forces being transmitted by gluons.

The analogue of Mendeleev's table was the recognition of patterns – known as the Eightfold Way - among families of hadrons(Gell-Mann,1962). These arise from the various ways that the underlying quarks, which form those hadrons, combine (Gell-Mann 1964; Zweig 1964). In the late 1960s the presence of quarks within hadrons was directly confirmed by experiments scattering high energy beams of electrons and neutrinos from targets of protons and neutrons (Panofsky 1968). Discovery of a spectroscopy of hadrons, analogous to the spectra of atomic elements, completed the parallel.

Today the quark layer of reality is established. However, the quarks revealed by spectroscopy are not easily identified with those that are manifested by the high energy "deep inelastic scattering" experiments. The latter have almost no mass, and as such have the attributes of the basic entities in the fundamental Lagrangian of QCD, the relativistic quantum field theory of the strong force. The

Dalitz, Morpurgo and others initially to have large masses and deep binding (Dalitz 1965; Morpurgo 1965; Morpurgo 1974).

Non-relativistic constituent quarks

The non-relativistic consitutent quark model worked empirically even though there was no well-defined rationale for the approach. The most dramatic success was with photoproduction, where over 100 amplitudes were well described, both in relative magnitudes and phases, a feat which no other approach then or since has matched (Copley 1969; Feynman 1971).

The success of this unfounded non relativistic model was, in many cases at least, revealed to be due to its underlying structure rather than detailed dynamics(Close 1979). A hadron has total spin J, made up of quarks with total spin S and the left over defined by L. In a specific non relativistic model, L was identified with the orbital angular momentum. However, as far as the mathematical algebra was concerned it was not necessary to make this further assumption. This reduced the amount of predictions, but made the survivors stronger. In particular relations among amplitudes survived, and proved empirically successful. Therefore it was possible that the success of the model was due to more general features, driven by the couplings of spins, rather than detailed and ill-founded, dynamics.

One of these successes concerned the photoproduction amplitudes of the prominent resonance D(13) mass 1520 MeV. From proton targets a specific amplitude – when the combined helicity of photon and proton are anti-aligned to total ½ rather than aligned to 3/2 - vanishes. This was described in the model as a cancellation between electric and magnetic multipoles for this transition (Copley 1969, Feynman 1971). Fred Gilman and I then realized that, while this could be accounted for by the general mathematical algebra, without specific recourse to non-relativistic models, a change from photo to electroproduction would provide a sensitive dynamic test (Close 1972). Real quarks would respond more strongly to the magnetic rather than to the electric multipoles as the photon became more virtual; in an algebraic approach there was no reason for such an effect.

Empirically this was verified, and remarkably so (Close 1979). The change to magnetic dominance took place almost immediately as the photon became virtual. The speed of this change was in line with the non-relativistic model. Why the model worked so well was, and remains, a mystery. However, this result proved that constituent quarks are real dynamical degrees of freedom within hadrons and are more than simply book-keeping devices for the mathematical algebra.

Bag models: relativistic quarks; glueballs and hybrids

A resolution to the dichotomy came with the Bag models, notably that of MIT (Jaffe 1978). Quarks with the characteristics of QCD, possibly even massless, were confined in a simple model where, in effect, an infinitely high potential imprisoned them within a femto-universe of about 1 fm. Quantum mechanics implies that a massless fermion confined in such a length scale gains an energy of around 350MeV. This could be identified with the effective mass of the constituent quark.

The model was never developed enough to deal with the excited states that Gilman and I had investigated. However, it had another implication: massless gluons, similarly confined, would themselves gain an energy. This enabled a tentative spectroscopy of glueballs – containing two or more gluons – and hybrids – where a gluon accompanies quarks and/or antiquarks inside the confinement bag.

This simple picture seems remarkably robust in comparison with modern understanding of the spectrum. The equations of QCD, when studied in computer simulations, which assume space-time to consist of a discrete lattice rather than a continuum (so called Lattice QCD), reveal a spectrum of states with remarkable parallels to those of the simple bag model of massless quarks and gluons.

In 1983 Barnes and I computed the spectrum of the lightest hybrid mesons and baryons, including the perturbations of energy levels (hadron masses) arising from single gluon exchanges among the constituents (Barnes 1983a,1983b). For the lightest hybrid mesons this implied that the lightest such state would be $J^{PC} = 0^{-+}$, the next being the exotic 1^{-+}, with $1^{--}$and 2^{-+} heavier and completing the group. This is what modern lattice QCD finds.

We also studied the spectrum of hybrid baryons. There is a rich set of N^* and Delta excitations with positive parity and spins ranging from ½ to 5/2. The pattern here too seems to be confirmed in recent studies of lattice QCD by a group at Jefferson Lab(Dudek 2012).

The message seems to be that the simple bag picture agrees with the pattern of the real world (lattice QCD being the nearest to this that we can simulate at present.) The fact that quarks and gluons act as quasi-free particles until they hit the wall of confinement is a remarkably simple, and empirically successful, description of hadrons. Nature has turned out to be simple enough for us to decode its patterns. Obtaining a robust theoretical description though remains a challenge.

Gluonic Hadrons: a new picture

One thing is missing from all of the above: the structure of a hadron depends on the resolving power of the microscope with which it is examined. In a nutshell: the larger the resolution, or in effect, the shorter the wavelength of the probe, so the more structure is revealed. What appears as a quark at low resolution is revealed as a seed surrounded by virtual quarks and antiquarks, and gluons, at high resolution. This poses a challenge: what would a glueball look like as you power up the microscope?

Scattering electrons from a state of pure glue would not occur, as the electron needs a source of electric charge to couple to. However, as the momentum transferred grows, the resolution improves and the target is increasingly perceived to contain quarks and antiquarks, from which the electron can scatter. The probability of scattering thereby grows.

The quantitative measure is the amount of momentum carried by electrically charged constituents – technically this is given by the integral of the inelastic structure function, $F_2(x, q^2)$, where x is the Bjorken variable and q^2 is the square of the four-momentum transfer (Close 1979). The integral will grow with q^2. As q^2 tends to infinity, the integral tends to an asymptotic value, whose value depends on the number of flavours. Physically, this extreme is where the hadron is perceived as a plasma of quarks, antiquarks and gluons in equilibrium.

This behaviour contrasts what occurs for a hadron such as a proton, where there is electric charge available even as q^2 is small. In this case the integral of $F_2(x, q^2)$ falls to its asymptotic value.

Thus we have a well-defined way of classifying hadrons as gluonic or flavoured: the two classes correspond to the said integral rising or falling to the asymptotic limit. In other words, at small q^2 the hadron's momentum is dominantly carried by gluons or flavoured fermions.

This applies to hadrons made of the constituents as defined by the Lagrangian of QCD and revealed in deep inelastic experiments: lightweight fermions and gluons. There is an interesting question of counting of states relative to classification in the old constituent picture. In the latter, mesons can be glueball, hybrid or conventional. This involves three classes, whereas the novel approach only admits two: gluonic or fermionic. This is a question that I am currently investigating, together with that of decays, and how the concept of multiquark hadrons fits in with this scheme.

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