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BARYONS AND QCD*

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I present an idiosyncratic view of baryons which calls for a marriage between quark-based and hadronic models of QCD. I advocate a treatment based on valence quark plus glue dominance of hadron structure, with the sea of $q\bar{q}$ pairs (in the form of virtual hadron pairs) as important corrections.

1 Why Baryons?

There are, appropriately enough, three main reasons why I believe that baryons deserve special attention.

The first is that baryons *are* the stuff of which our world is made. As such they must be at center stage in any discussion of the nitty-gritty of why the world we actually experience has the character it does. Thus an understanding of how Quantum Chromodynamics (QCD) makes baryons must form the basis for an eventual understanding of the origin of the forces between nucleons and thence of the origin of the periodic table. I am convinced that completing this chapter in the history of science will be one of the most interesting and fruitful areas of physics for the next twenty years.

My second reason is that they are the simplest system in which the essential nonabelian character of QCD is manifest. There are, after all, N_c quarks in a proton because there are N_c colors, and this fact is in turn a consequence of the remarkable and quintessentially nonabelian property of QCD that three particles can attract each other (in contrast to Quantun Electrodynamics (QED) where the e^-e^- force is repulsive). This fact has many intriguing consequences, *e.g.*, the prediction of color transparency for baryons.

The third reason is historical. It is no accident that baryons have played a much more prominent role in the discovery of QCD than mesons. Gell-Mann and Zweig were forced to the quarks by $3 \times 3 \times 3$ giving the octet and decuplet; Greenberg was led to color by the spin-statistics paradox in the Δ^{++}, and Dalitz's quark model for baryons was one of the earliest indications of the power of the valence quark model.

1.1 What is the Goal?

What is the goal of this research, and indeed of all modern work on QCD? Some of our colleagues argue that since the fundamental Lagrangian is known, strong interaction physics is a dead field. Need I point out that this is as silly as claiming that once we knew Schrodinger's and Maxwell's equations we knew everything worth knowing about condensed matter physics? Others argue that "strong QCD" [1] is so complicated that, while very interesting, it is hopeless to try to understand it. I hold the truth to lie in between: our goal is to understand QCD. This includes being able to compute some quantities exactly, but most importantly acheiving a qualitative explanation of the main features of QCD, including the answers to such questions as:

1) What is the physical origin of color confinement?
2) Why is the low energy spectrum dominated by what appear to be $q\bar{q}$ and qqq systems?

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3) Where, as a corollary, are the gluonic degrees of freedom?
4) Why is a nucleus made of nucleons, instead of a "quark soup"?
5) What is the origin of the well-established empirical nucleon-nucleon force?

On the other hand, I would not advocate attempting to compute everything with precision, nor on insisting that we understand every detail of strong interaction physics.

1.2 Where Should We Start?

I believe that the key to a qualitative understanding of strong QCD is the same as in most other areas of physics: identifying the apprpriate degrees of freedom. For example, atomic physics is based on taking the nuclei and electrons as the low energy effective degrees of freedom, with the underlying effects of nucleons subsumed into static nuclear properties and those of photons into low energy effective potentials; nuclear physics is in turn very well-described by nucleons moving in an empirical nucleon-nucleon potential.

Foremost among the puzzles we face in QCD is a "degree of freedom" problem: the low energy spectrum of QCD behaves as though it is built from the degrees of freedom of spin-$\frac{1}{2}$ fermions confined to a $q\bar{q}$ or qqq system. Thus, for mesons we seem to observe a "quarkonium" spectrum, while for the baryons we seem to observe the spectrum of the two relative coordinates of three spin-$\frac{1}{2}$ degrees of freedom.

These apparent degrees of freedom are to be contrasted with the most naive interpretation of QCD which would lead us to expect a low energy spectrum exhibiting 36 quark and antiquark degrees of freedom (3 flavors $\times$ 2 spins $\times$ 3 colors for particle and antiparticle), *and* 16 gluon degrees of freedom (2 spins $\times$ 8 colors). Less naive pictures exist, but none evade the puzzle of the missing gluonic degrees of freedom in the low energy spectrum.

The second major "degree of freedom problem" has to do with $q\bar{q}$ pair creation. At least naively, one would expect pair creation to be so strong that a valence quark model would fail dramatically. Of course, we know empirically that pair creation is suppressed: the observed hadronic spectrum is dominated by narrow resonances, while the naive picture would predict resonances with widths Γ comparable to their masses m.

There are three main puzzles associated with the nature and importance of such $q\bar{q}$ pairs in low energy hadron structure:

1) the origin of the apparent valence structure of hadrons (since even as $N_c \to \infty$, the "Z-graphs" to be defined below would produce pairs unless the quarks were heavy),

2) the apparent absence of unitarity corrections to naive quark model spectroscopy, despite one's expectation of mass shifts $\Delta m \sim \Gamma$ (where Γ is a typical hadronic width), and

3) the systematic suppression of OZI-violating amplitudes A_{OZI}, relative to one's expectation (from unitarity) that $A_{OZI} \sim \Gamma$.

2 My Biases

I believe that there are strong indications coming from, appropriately enough, three different directions which converge on a simple picture of the structure of strong QCD: valence plus glue dominance with $q\bar{q}$ corrections. I will now discuss the lessons to be learned from each of these three approaches in turn.

2.1 The Large N_c Limit of QCD

It is now widely appreciated that many of the observations mentioned above can be rationalized in QCD within the $1/N_c$ expansion [2]. Moreover, there is growing evidence from lattice QCD that while $N_c = 3$ might not be sufficiently large for the $1/N_c$ expansion to be used quantitatively, the main qualitative features of QCD (including confinement and the spontaneous breakdown of chiral symmetry) are independent of N_c.

We should therefore take seriously the fact that it can be shown in the large-N_c limit that hadron two-point functions are dominated by graphs in which the valence quark lines propagate from their point of creation to their point of annihilation without additional quark loops. Indeed, in the limit $N_c \to \infty$, meson mass shifts and widths are proportional to $1/N_c$ while their masses are independent of N_c. A form of the OZI rule also emerges naturally. Large-N_c QCD thus presents a picture of narrow resonances interacting weakly with hadronic continua. In this picture the resonances themselves are made of valence quarks and glue.

2.2 Quenched QCD

Quenched lattice QCD provides other new insights into QCD. In quenched QCD the lattice sums amplitudes over all time histories in which no $q\bar{q}$ loops are present. It thus gives quantitative results from an approximation with many elements in common with the large N_c limit. One of the most remarkable features of these approximate calculations is that they provide a very good description of low energy phenomenology, and that for various intermediate quantities like the QCD string tension they provide very good approximations to the full QCD results with the true lattice coupling constant replaced by an effective one. (We note in passing the very important new development of "perfect actions" which promise to revolutionize the practical range of applicability of full lattice QCD). In quenched QCD, as in the large N_c limit, two point functions are thus dominated by their valence content (namely pure glue for glueballs, $q\bar{q}$ plus glue for mesons, and qqq plus glue for baryons).

In comparing the large N_c limit and quenched lattice QCD we note that:

1) In both pictures all resonances have only valence quarks, but they have an unlimited number of gluons. Thus they support valence models for mesons and baryons, but not for glueballs or for the gluonic content of mesons and baryons.

2) In both pictures a propagating valence quark has contributions from not only a positive energy quark propagator, but also from "Z-graphs". (A "Z-graph" is a time-ordered graph in which the interactions first produce a pair and then annihilate the antiparticle of the produced pair against the original propagating particle). Cutting through a two-point function at a fixed time therefore would in general reveal not only the valence quarks but also a large $q\bar{q}$ sea. This dominance thus does not seem to correspond to the usual valence approximation. Consider, however, the Dirac equation for a single light quark interacting with a static color source (or a single light quark confined in a bag). This equation represents the sum of a set of Feynman graphs which also include Z-graphs, but the effects of those graphs is captured in the lower components of the single particle Dirac spinor. *I.e.*, such Z-graphs correspond to relativistic corrections to the quark model. That such corrections are important in the quark model has been known for a long time. For us the important point is that while they have quantitative effects on quark model predictions (*e.g.*, they are commonly held to be responsible for much of the required reduction of the nonrelativistic quark model prediction that $g_A = 5/3$ in neutron beta decay), they do not qualitatively

change the single-particle nature of the spectrum of the quark of our example, nor would they qualitatively change the spectrum of $q\bar{q}$ or qqq systems. Note that this interpretation is consistent with the fact that Z-graph-induced $q\bar{q}$ pairs do *not* correspond to the usual partonic definition of the $q\bar{q}$ sea since Z-graphs vanish in the infinite momentum frame. Thus the $q\bar{q}$ sea of the parton model is also associated with the $q\bar{q}$ *loops*.

3) Finally, we note that the large N_c and quenched approximations are *not* identical. For example, the NN interaction is a $1/N_c$ effect, but it is not apparently suppressed in the quenched approximation.

2.3 The Heavy Quark Limit

The third perspective from which there is support for the same picture is the Heavy Quark Limit [3]. While this limit has the weakest theoretical connections to the light quark world, it has powerful phenomenological connections: see Fig. 1(a). We see from this picture that in mesons containing a single heavy quark, $\Delta E_{orbital}$ (the gap between, for example, the $J^{PC} = 1^{--}$ and 2^{++} states), is approximately independent of m_Q, as predicted in the Heavy Quark Limit, while $\Delta E_{hyperfine}$ decreases like m_Q^{-1} as expected.

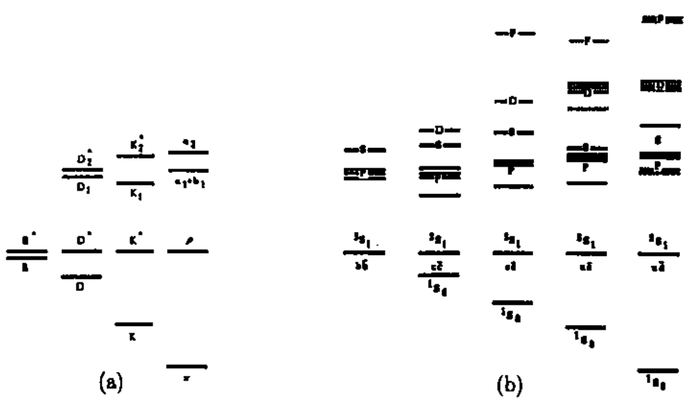

Fig. 1: (a) $Q\bar{q}$ and (b) $Q\bar{Q}$ meson spectra as a function of the "heavy" quark mass

Recall that in the Heavy Quark Limit a hadronic two-point function is dominated by a single valence Q plus its associated "brown muck", with neither $Q\bar{Q}$ loops nor Q Z-graphs. The fact that heavy-quark-like behaviour persists all the way down to light quark masses suggests that light quarks, like heavy quarks, behave like single valence quarks and thus by extension that the "brown muck" behaves like a single valence antiquark.

Fig. 1(b) shows that heavy quark behaviour also apparently persists in a stronger form: the light meson spectrum appears to mimic the $Q\bar{Q}$ quarkonium spectrum. This is surprising since this spectrum depends on the decoupling of gluonic excitations (as opposed to glue) from the spectrum *via* an adiabatic approximation.

While the adiabatic approximation is more general, it is becoming increasingly firmly established that this approximation is realized in QCD in terms of the development of a confining chromoelectric flux tube. These flux tubes are the analog of the Abrikosov vortex lines that can develop in a superconductor subjected to a magnetic field, with the vacuum acting as a dual (*i.e.*, electric) superconductor creating a chromoelectric Meissner effect. A $Q\bar{Q}$ system held at fixed separation $r >> \Lambda_{QCD}$ is known to have as its ground state a flux tube which leads to an effective low energy (adiabatic) potential corresponding to the standard "quarkonium" potential. However, this system also has excited states, corresponding to excited gluonic adiabatic surfaces on which spectra of "hybrid states" are built. In this picture, the ordinary $c\bar{c}$ and $b\bar{b}$ spectra are built on the lowest adiabatic surface in an adiabatic approximation in which the gluonic flux tube adjusts instantly to the positions of the Q and $\bar{Q}$ sources.

Lattice results allow us to check many aspects of the flux tube picture. For example, the lattice confirms the flux tube model prediction that sources with triality are confined with a string tension proportional to the square of their color Casimir. The predicted strongly collimated chromoelectric flux lines have also been seen on the lattice. I have found it particularly encouraging that the first excited adiabatic surfaces have been seen [4] with an energy gap $\delta V(r) = \pi/r$ above the quarkonium potential as predicted [5], and with the expected doubly-degenerate phonon quantum numbers. See Fig. 2. This strongly suggests that the J^{PC} exotic hybrid mesons predicted ten years ago [5] exist.

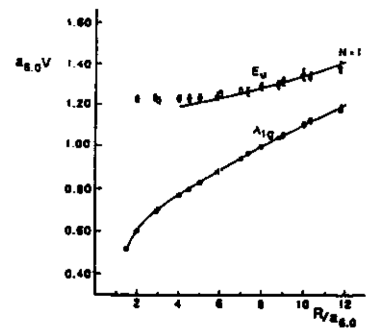

Fig. 2: the ground state and first excited adiabatic potentials from lattice QCD [4]

3 The Next Steps

The preceeding discussion strongly suggests that we treat the phenomenology of strong QCD in two steps in which the zeroth order approximation is the (relativistic) constituent quark model with flux tube gluodynamics [5], and in which $q\bar{q}$ physics and other formally $1/N_c$ effects are treated as perturbations. In this picture one would first treat the resonances as narrow non-interacting states, and then couple these states to continua and other $1/N_c$ effects.

3.1 The Small Effect Pitfall

In making this call for consensus in how to approach understanding strong QCD, I will begin with a warning and a confession. The warning is

"Beware of valence plus glue predictions that are not leading order in N_c."

and the confession is that I have myself been guilty of ignoring this warning.

There are many examples of predictions which heed this warning, including

- resonance spectra,
- magnetic moments,
- most electromagnetic amplitudes, and
- valence parton distributions.

There are also many which do not, including

- some electromagnetic amplitudes (including $E2/M1$ in $N \to \Delta$),
- scattering amplitudes,
- "accidentally small effects" (e.g., the photocouplings of the Roper resonance), and
- the $\Delta - N$ splitting.

While in all of these latter cases making a valence plus glue prediction without taking into account the effects of the $q\bar{q}$ sea *is* a serious violation of the spirit of the above warning, I will explain below that in many cases sea quark effects are suppressed by an additional factor which makes them much smaller than other $1/N_c$ effects. This important suppression factor thus makes some violations more of a technical infraction than a serious crime.

3.2 Some Comments on the Proposed Marriage

The program I am advocating may be viewed as one of "unquenching the quark model". My colleagues and I have been working in this direction for a while now, and as a result I have some "lessons learned" to convey on the character of this program. The central element of this message is that in some circumstances low energy hadronic effective theories can be very misleading as tools for calculating the effects of $q\bar{q}$ pairs. A corollary is that, while formally of order $1/N_c$, there are critical cases where meson corrections are additionally suppressed.

3.2.1 Thresholds, Mass Shifts, and the Unquenched Quarkonium Potential

Consider two resonances which are separated by a mass gap δm in the narrow resonance approximation. In general we would expect that departures from the narrow resonance approximation, which produce resonance widths Γ, ought also to produce shifts Δm of order Γ. Yet even though a typical hadronic mass spectrum is characterized by mass gaps δm of order 500 MeV, and typical hadronic widths are of order 250 MeV, this does not seem to happen.

We have proposed a simple resolution of this puzzle [6]. As mentioned above, in the flux tube model of Ref. [5] the quark potential model arises from an adiabatic approximation to the gluonic degrees of freedom embodied in the flux tube. For example, the standard heavy $Q\bar{Q}$ quarkonium potential $V_{Q\bar{Q}}(r)$ is the ground state energy $E_0(r)$ of the gluonic degrees of freedom in the presence of the $Q\bar{Q}$ sources at separation r. At short distances where perturbation theory applies, the effect of N_f types of light $q\bar{q}$ pairs is (in lowest

order) to shift the coefficient of the Coulombic potential from $\alpha_s^{(0)}(Q^2) = \frac{12\pi}{33 ln(Q^2/\Lambda_0^2)}$ to $\alpha_s^{(N_f)}(Q^2) = \frac{12\pi}{(33-2N_f) ln(Q^2/\Lambda_{N_f}^2)}$. The net effect of such pairs is to produce a *new* effective short distance $Q\bar{Q}$ potential.

Similarly, when pairs bubble up in the flux tube (*i.e.*, when the flux tube breaks to create a $Q\bar{q}$ plus $q\bar{Q}$ system and then "heals" back to $Q\bar{Q}$), their net effect is to cause a shift $\Delta E_{N_f}(r)$ in the ground state gluonic energy which in turn produces a new long-range effective $Q\bar{Q}$ potential.

In Ref. [6] we showed that the net long-distance effect of the bubbles is to create a new string tension b_{N_f} (*i.e.*, that the long distance potential remains linear). Since this string tension is to be associated with the observed string tension, after renormalization *pair creation has no effect on the long-distance structure of the quark model in the adiabatic approximation*. Thus the net effect of mass shifts from pair creation is much smaller than one would naively expect from the typical width Γ: such shifts can only arise from nonadiabatic effects. For heavy quarkonium, these shifts can in turn be associated with states which are strongly coupled to nearby thresholds. For example, it is now clear that the Υ_{4S} is displaced from its potential model position by about 50 MeV as a result of its couplings to the very nearby $B\bar{B}$ threshold.

We should emphasize that it was necessary to sum over very large towers of $Q\bar{q}$ plus $q\bar{Q}$ intermediate states to see that the spectrum was only weakly perturbed (after unquenching and renormalization). In particular, we found that no simple truncation of the set of meson loops can reproduce such results.

3.2.2 The Chiral Threshold of QCD

The threshold of QCD is, of course, a special case. In the chiral limit the very low energy strongly interacting world consists of massless pions with thresholds m_π, $2m_\pi$, $3m_\pi$, $... << \Lambda_{QCD}$ plus these continua interacting with the heavy, nearly static baryonic degrees of freedom N and Δ. The last several years have seen progress in understanding both the theory and phenomenology of this limit. On one front, there has been continuous progress in experiment, with important new tests of improved predictions of chiral perturbation theory. This progress has been focussed by not only more reliable higher-loop-order calculations, but also by QCD-based calculations of the chiral coefficients (which are strictly speaking unknown parameters of the chiral expansion). It is consistent with the program outlined here that the coefficients seem to be resonance-dominated: this is what one would expect in a weakly-coupled narrow resonance world.

There has also been great theoretical progress in the last several years on another front. While the chiral expansion for processes involving only the mesons is very well-defined, the expansion for processes including baryons had always been sick. A technique borrowed from the Heavy Quark Limit [7] has recently fixed this problem: one simply needed to expand simultaneously in the momentum of the pions and in the velocities of the baryons.

While chiral perturbation theory is now well-defined in the chiral limit, it remains a challenge to understand its range of applicability in a world in which the symmetry is explicitly broken by quark mass terms and also to explore its radius of convergence in the expansion in momentum and baryon velocity.

3.2.3 Molecules

We see from both of the previous examples that QCD can get interesting around thresholds. There is, appropriately enough, a third example of such effects: weakly bound hadron-hadron states, or molecules.

It should be emphasized that we still lack a clear understanding of why the low energy world appears to be dominated by $q\bar{q}$ and qqq "atoms" along with some very important but, on the scale of the interquark forces, very weakly bound "molecules", namely nuclei. In principle QCD might create other color-singlet "atoms" from $qq\bar{q}\bar{q}$, $qqqq\bar{q}$, or from $qqqqqq$.

The first system (originally called "baryonium" because such resonances would have appeared in baryon-antibaryon scattering) has been extensively studied both theoretically and experimentally. Current opinion favors there being no "atomic" states in this system, but identifies several potential "molecules", including the $f_0(980)$, the $a_0(975)$, the $f_1(1420)$, and the $f_2(1520)$.

The latter system (ususally called "dibaryons") also has a long history. Of particular interest over the last ten years has been the $uuddss$ system, where a stable state was predicted in the bag model [8]. Searches for such a state are reaching good levels of sensitivity, and we may expect a verdict on their existence soon. It may be that the $qqqqqq$ system also has no "atoms", only "molecules". This does not diminish the importance of understanding the structure of such systems since they are our best way of gaining new experimental perspectives on the most important such system: the NN system. Indeed, one might argue that if $uuddss$ were deeply bound, we would learn less from it about the origin of the NN force. I would also suggest that in any case predictions [9] for relatively weakly bound $qqqqqq$ states in, e.g., the $\Delta\Delta$ channel should be taken very seriously.

While the juries are still out on the $qq\bar{q}\bar{q}$ and $qqqqqq$ systems, there is some very new and important information on the $qqqq\bar{q}$ system. While this system has not been studied in quark models as extensively as the other two (see, however, the work of Lipkin on the "pentaquark" [?]), 25 years ago Dalitz speculated that the $J^P = \frac{1}{2}^-$ $\Lambda(1405)$ strange baryon resonance is a $\bar{K}N$ bound state. This speculation was fueled by a failure of quark models: in the simplest such models [10], the $\Lambda(1405)$ is predicted to be degenerate with the $\Lambda(1520)$. While quark modelers often insisted that the $\Lambda(1405)$ must be a uds state in order that quark model spectroscopy not have a low-lying missing state, such a large error in their mass predictions weakened their arguments. This weakness was exacerbated by cloudy bag model and other calculations which explicitly found that the $\Lambda(1405)$ was dominantly a $\bar{K}N$ state.

Recent data from the Λ_c system now strongly indicates that the $\Lambda(1405)$ is in fact a uds system. Let me recap the argument. Fig. 3 shows a comparison of the lowest-lying states of the Λ_c and Λ (hereafter called Λ_s for the sake of clarity) systems. It is difficult to escape the conclusion from Fig.1 that not only the character, but also the quantitative properties of the spectra of heavy quark systems persist as the mass of the heavy quark drops, and that in particular for many purposes the s quark may be treated as a heavy quark. In the case at hand we note that, as expected in the Heavy Quark Limit [3], $\Delta E_{orbital}$ is approximately constant (the relevant splittings to the center of gravities of the excited states are 362 MeV and 328 MeV, respectively) and $\Delta E_{spin} \sim m_Q^{-1}$ (with the same ratio as the $K^* - K$ and $D^* - D$ splittings). It thus appears that the $\Lambda_s(1405)$ and $\Lambda_s(1520)$ are analogues of the $\Lambda_c(2595)$ and $\Lambda_c(2625)$. Since in the Heavy Quark Limit the spin structure of the $\Lambda_s(1405)$ is totally prescribed, and is incompatible with the $\bar{K}N$ picture, this interpretation is ruled

out, and a 25 year old controversy settled.

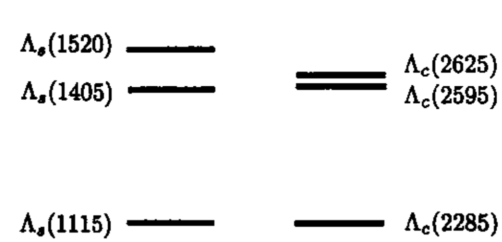

Fig. 3: a comparison of the low-lying Λ_s and Λ_c systems

It is a little too early to finalize the lessons we should take away from this example, but I believe that one is once again the special properties of thresholds in making the effects of continua stick out and, more to the point, the dangers of artificially accentuating a nearby threshold by neglecting the tower of other thresholds which tend to strongly cancel out the effect of any particular channel. This message is even more strongly driven home in the last example below.

3.2.4 The OZI Rule and the Spin Crisis

There is another puzzle of hadronic dynamics which is reminiscent of the near immunity of the quark potential model to unquenching : the success of the OZI rule. A generic OZI-violating amplitude A_{OZI} can, like hadronic mass shifts from $q\bar{q}$ loops, be shown to vanish like $1/N_c$. However, there is something unsatisfactory about this "solution" of the OZI mixing problem [11]. Consider ω-ϕ mixing as an example. This mixing receives a contribution from the virtual hadronic loop process $\omega \to K\bar{K} \to \phi$, both steps of which are OZI-allowed, and each of which scales with N_c like $\Gamma^{1/2} \sim N_c^{-1/2}$. The large N_c result that this OZI-violating amplitude behaves like $1/N_c$ is thus not peculiar to large N_c: it just arises from "unitarity" in the sense that the real and imaginary parts of a generic hadronic loop diagram will have the same dependence on N_c. In this case the deficiency of the large N_c argument is that $A_{OZI} \sim \Gamma << m$ is *not* a good representation of the OZI rule. Since (continuing to use ω-ϕ mixing as an example) $m_\omega - m_\phi$ is numerically comparable to a typical hadronic width, the large N_c result would predict an ω-ϕ mixing angle of order unity in contrast to the observed pattern of very weak mixing which implies that $A_{OZI} << \Gamma << m$.

In Refs. [12] we showed how this disaster is naturally averted in the flux tube model through a "miraculous" set of cancellations between mesonic loop diagrams consisting of apparently unrelated sets of mesons (*e.g.*, the $K\bar{K}$, $K\bar{K}^* + K^*\bar{K}$, and $K^*\bar{K}^*$ loops tend to strongly cancel against loops containing a K or K^* plus one of the four strange mesons of the $L = 1$ meson nonets).

Of course the "miracle" occurs for a good reason. In the flux tube model, where pair creation occurs in the $^3P_0$ state, the overlapping double hairpin graphs which correspond to OZI-violating loop diagrams (see Fig. 4), cannot contribute in a closure-plus-spectator approximation since the 0^{++} quantum numbers of the produced (or annihilated) pair do not match those of the initial and final state for any established nonet. Refs. [12] demonstrate that this approximation gives zero OZI violation in all but the (unobserved) 0^{++} nonet, and shows that corrections to the closure-plus-spectator approximation are small, so that the observed hierarchy $A_{OZI} << \Gamma$ is reproduced.

We emphasize once again that such cancellations require the summation of a very large set of meson loop diagrams with cancellations between apparently unrelated sets of intermediate states.

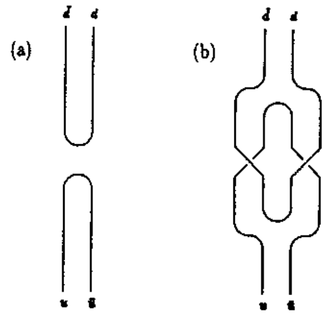

Fig. 4: (a) OZI-violation in a meson propagator by "pure annihilation". (b) A different time ordering of the same Feynman graph gives an OZI-violating loop diagram via two OZI-allowed amplitudes.

Note that this example has direct implications for baryons via such OZI-violating processes as $p \to p\phi$ which can, in analogy to $\omega - \phi$ mixing, proceed *via* the OZI-allowed steps $p \to \Lambda K \to pK\bar{K} \to \phi$. Such processes, if uncancelled by other loop diagrams, would in turn contribute to the strange quark currents of the proton.

With this background in mind, let me close with some comments on the spin crisis. In the spirit of "valence quark plus glue with $q\bar{q}$ corrections", let us write

$$\Delta q = \Delta q_{valence} + \Delta q_{sea}$$

and note that:

1) Given the earlier discussion, we do not expect the nonrelativistic result $\Delta q_{valence} = 1$ since the lower components of the relativistic valence quarks developed *via* Z-graphs typically reduce their contributions to $\Delta q_{valence} \simeq 0.75$.

2) Since $\Delta q_{sea} = \sum_f \Delta q_{sea}^{(f)}$, where $\Delta q_{sea}^{(f)}$ is the spin sum contribution of the quark-antiquark sea of flavor f, if there are N_f approximately flavor-symmetric light quark flavors then $\Delta q_{sea} \simeq N_f \Delta q_{sea}^{(f_1)}$, where f_1 is the first of these light flavors. Note that no matter how suppressed $\Delta q_{sea}^{(f_1)}$ might be, if $N_f >> N_c$, $\Delta q - \Delta q_{valence}$ will be large. In other words, the relevant point in the spin crisis is that $\Delta q_{sea}^{(s)} << \Delta q_{valence}$ is indeed what is observed experimentally.

3) A possible scenario for the spin crisis is that $\Delta q_{valence} \simeq 0.75$, $\Delta q_{sea}^{(s)} \simeq -0.12$, $\Delta q_{sea}^{(u)} \simeq -0.16$, and $\Delta q_{sea}^{(d)} \simeq -0.16$ (where we have speculatively included a small $SU(3)$-breaking effect) leading to $\Delta q \simeq 0.3$. If this scenario is correct, then the spin crisis will have shown us that the valence quarks behave just as they were supposed to do!

Future measurements of νp elastic scattering from LSND, of $G_M^{(s)}$ at low Q^2 from Bates, of $G_M^{(s)}$ and $G_E^{(s)}$ in the GeV^2-range from CEBAF at Jefferson Lab, and of Δg from RHIC

at Brookhaven National Lab will allow us to separate Δq into its components and establish the importance of the sea in the proton.

4 Conclusions

The prospects for the study of baryons seems to me exceptionally bright.

There are first of all many new theoretical tools at hand: the large N_c expansion, the lattice, heavy quark expansions, and heavy baryon chiral perturbation theory.

It is especially significant for this field that new data is *at last* starting to appear. We are now seeing data from Bonn, Mainz, CLEO, SLAC, BNL, LEAR, and others. We will soon be seeing results from Hermes and a flood of new data from CEBAF at Jefferson Lab. In the longer term, we can expect RHIC and a CEBAF energy upgrade to open up other qualitatively new windows on the structure of the proton.

In summary, there is every reason to believe that we are on the threshold of a twenty year journey to complete our understanding of strongly interacting matter.

References

[1] "Strong QCD" is a term proposed by F. Close (private communication) to replace the cumbersome phrase "nonperturbative QCD".

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