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To Reveal the Quark Structure of Matter*

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I present a overview of some central issues facing strong interaction physics today, with an emphasis on questions that will be addressed in concert by CEBAF at Jefferson Lab and by the new DAPHNE machine at Frascati Lab.

1. WHY SHOULD WE CARE?

There are compelling reasons why we should study and understand the quark structure of matter. Before stating them, however, it seems to me critical to first clear away some mistaken reasons that are sometimes given for the pursuit of this knowledge.

First, we should *not* pursue an understanding of the quark structure of matter in order to improve our understanding of ordinary nuclear structure and dynamics. Just as the vast panorama of atomic physics can proceed perfectly well without understanding the structure of the atomic nucleus (apart from a few arcane or very high precision issues), the "nuclear physics approximation" that the nucleus is made of nucleons interacting *via* an effective potential should and will remain the basis for the study of ordinary nuclear structure and dynamics. This approximation is not as accurate as the corresponding "atomic physics approximation", but there is today overwhelming evidence that it correctly captures the essentials of nuclear physics (apart from a few arcane or very high precision issues).

As a corollary to this first point, it follows that it is in general not interesting to try to create a "quark wavefunction" for the nucleus. A description in terms of $3A$ quarks instead of A nucleons would be strictly speaking more fundamental, but given the range of validity of the "nuclear physics approximation", it would also be foolish.

Why then should we care? I will list just three good reasons:

1) Quantum Chromodynamics (QCD) tells us that quarks and gluons are the fundamental basis of the "nuclear physics approximation". We therefore need to use QCD to understand why this successful empirical approximation exists, and where its limits of validity actually lie. *I.e.*, we need to understand the quark structure of matter if we are to succeed, as we must, in deriving the "nuclear physics approximation" from first principles.

2) The quark structure of matter is very poorly understood today, and as such a poorly understood field with such obvious importance to the way the world works, it stands as one of the major intellectual challenges of the end of the 20th century.

3) Finally, we should pursue these studies because it is clear that no matter what future more all-encompassing theories may eventually be discovered, QCD will always survive as the theory of the strong interactions, just as QED will always survive as the theory of electromagnetism. Our current ignorance of how this very beautiful and fundamental law of nature works simply cannot be allowed to continue.

To make the preceeding somewhat abstract discussion more concrete, and to introduce several topics on which I'd like to focus, let me be a little more specific about what I see as some of the key scientific issues facing us in the study of the quark structure of matter. By analogy with atomic physics, I divide them into two broad areas: the "atomic" physics of quarks (corresponding to the simplest quark-gluon systems like the proton and

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its excitations, meson spectroscopy, glueballs, *etc.*) and the "molecular" physics of quarks, corresponding to issues related to the origin of relatively weakly bound strongly interacting matter like nuclei themselves and other possible related structures (*e.g.*, $K\bar{K}$ molecules).

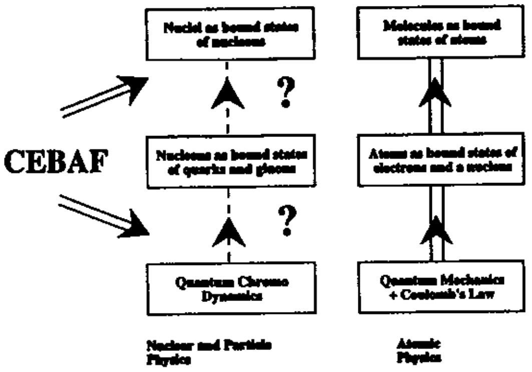

Fig. 1: An analogy between atomic and molecular physics in the 1930's and quark and nuclear physics in the 1990's.

In the "atomic" physics of quarks I would list as three key issues:

- what is the origin of quark confinement?,
- where are the missing gluonic degree of freeedom in low energy spectroscopy?, and
- why do we seem to observe only $q\bar{q}$ and qqq "atoms" in QCD, when other color singlet structures (like $qq\bar{q}\bar{q}$) could certainly exist?

In the "molecular" physics of quarks I would list as three key issues:

- why can the nucleus be described in the "nuclear physics approximation" as being made of A nucleons instead of a soup of $3A$ quarks?,
- what is the origin of the residual forces between these nucleonic clusters?, and
- what is the nature of nuclear matter in the short-distance regime where these clusters necessarily overlap and lose their identity as low energy effective degrees of freedom?

Let me then summarize the spirit of this introduction by asking: 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 in any detail. I hold the truth to lie in between: our goal is to provide a "physicist's understanding" of 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 those posed above.

2. WHERE DO WE START?: A PROPOSAL FOR A GENERAL FRAMEWORK

I believe that the key to a qualitative understanding of strong QCD is the same as in most other areas of physics: identifying the appropriate 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 established 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 × 2 spins × 3 colors for particle and antiparticle), *and* 16 gluon degrees of freedom (2 spins × 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 in the large N_c limit to be described in the next section, "Z-graphs" 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 $A_{OZI} \sim \Gamma$.

I believe that there are strong indications coming from several 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. 2(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. 2: (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. 2(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 3. This strongly suggests that the J^{PC} exotic hybrid mesons predicted ten years ago [5] exist.

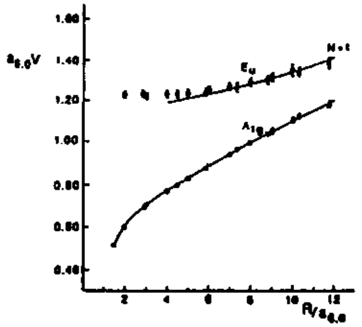

Fig. 3: the ground state and first excited adiabatic potentials from lattice QCD [4]

I will explore these ideas at some length below. First we need to understand why the apparent degrees of freedom in the QCD Lagrangian are not useful for describing strong interactions.

2.1 The Breakdown of Perturbative QCD

We all know that asymptotic freedom guarantees that at sufficiently small distances Quantum Chromodynamics (QCD) becomes a weakly coupled quark-gluon theory which is amenable to a perturbative expansion in the running coupling constant α_s. However, the other side of this coin is that at large distances α_s becomes large so that quark-gluon perturbation theory may break down.

In fact, we now know from numerical studies that QCD predicts confinement: the potential energy between two static quarks grows linearly with their separation r with a constant of proportionality b, called the string tension, that is about 1 GeV/fm. Let me show you

that such a result rigorously implies the breakdown of perturbative QCD. Given that confinement is the central feature of strong interaction physics, we are therefore forced to seek new methods for the study of most strong interaction phenomena.

In the pure gluon sector of QCD in which the static potential problem is posed (*i.e.*, QCD with static sources and *no* dynamical quarks), the equation for the string tension must take the form

$$b = f_b(g^2)$$

where f_b is some function of the dimensionless coupling constant g^2 since this is the only parameter of pure QCD. This equation is impossible, however, since b has dimensions of $[mass]^2$! The resolution of this paradox lies in the fact that g^2 is not a coupling "constant": according to asymptotic freedom

$$\frac{1}{g^2(Q^2)} = \frac{1}{g_0^2(Q_0^2)} + \frac{11}{16\pi^2}\ln\frac{Q^2}{Q_0^2}$$

where $g(g_0)$ is the effective coupling at momentum transfer $Q^2(Q_0^2)$. Thus QCD is defined by a universal "coupling constant curve" $g^2(Q^2)$ on which g^2 takes all values from zero to infinity, and not a single number. In a given universe with scales external to QCD (like the electroweak electron mass or the masses of the current quarks) this universal curve can be "pegged" to a given normalization at some external scale μ^2, but in pure QCD this is irrelevant: for us the key point is that a particular curve can be defined by choosing a value for $g^2(\mu^2)$ at any normalization point μ^2. This choice then simultaneously gives us a coupling constant $g^2(\mu^2)$ and a scale to give dimension to equation (1):

$$b = \mu^2 f_b(g^2(\mu^2)) \quad .$$

Thus in a pure QCD world, the string tension b and all other dimensionful quantities would have a scale set by the dummy variable μ^2, and all observables would be dimensionless ratios in which this variable cancels out.

Alternatively, we can note that any point μ^2 could have been chosen to define the curve $g^2(Q^2)$ and so

$$\frac{db}{d\mu^2} = 0$$

or, *i.e.*,

$$0 = f_b - \frac{11}{16\pi^2} g^4 \frac{df_b}{dg^2}$$

implying that

$$f_b \propto exp\left[-\frac{16\pi^2}{11g^2}\right] \quad .$$

The essential singularity in g^2 means that the "Feymman diagrammar" is useless for this problem, and that *plane wave quarks and gluons are not a useful starting point for low-energy, confinement-dominated physics.* To make progress in understanding the main phenomena of strong interaction physics, we must therefore either resort to purely numerical methods (*e.g.*, lattice QCD), or we must replace the Feymman diagrammar by new conceptual elements. I have proposed that these might be valence quarks and flux tubes.

3. WHAT ARE SOME KEY ISSUES AND EXPERIMENTS?

It is impossible in a brief overview to do justice to the range and depth of the scientific program of CEBAF at Jefferson Lab (and of complementary programs at other labs including here at DAPHNE) which will be carried out over the next decades to accomplish the goal of understanding the quark structure of matter. In this section, as a result, I will only be able to highlight a very few key examples of this program as concrete illustrations of the kinds of issues and experiments which will constitute the body of the effort that will be required.

3.1. Excited States of the Nucleon

The proton and neutron are the fundamental quark atoms in several senses: they are the stable atoms of which our world is made, and they are also the quintessential manifestations of QCD in that three quarks form a color singlet only because QCD is a three-color nonabelian theory.

The spectrum of excited states of the nucleons (the N^*s) and their internal structure are thus very basic to understanding the active low energy degrees of freedom of QCD. Current evidence favors the view that this spectrum is dominated by that of three spin-$\frac{1}{2}$ valence quarks (*i.e.*, that it is the spectrum of three spin-$\frac{1}{2}$ quarks and their two relative spatial coordinates), but the evidence remains fragmentary and controversial.

Jefferson Lab's CLAS spectrometer was designed specifically to study the spectrum and structure of the N^*s by their electromagnetic excitation with photon and electron beams. Taking data at a terabyte per day, it should revolutionize our understanding of this system. In concert with parallel efforts in hadroproduction at the AGS at Brookhaven and the newly planned 50 GeV proton machine JHP at KEK in Japan, one can expect that our knowledge of such states will eventually be rather complete.

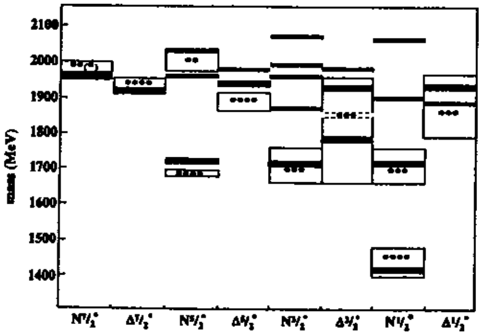

Fig. 4: Current evidence on the N^* spectrum is fragmentary with 10 of 21 positive parity states expected in the valence quark model missing (boxes with stars are observed states)

3.2. Gluonic States

One of the most glaring discrepancies between naive expectations from the QCD Lagrangian and observation is the apparent absence in the low energy spectra of QCD of the gluonic states discussed in Section 2.

Recall that while the gluonic degrees of freedom are missing from the low energy spectrum, we know from deep inelastic scattering and from various theoretical approaches to QCD that the mass of the proton is dominantly gluonic! Given this, it is somehow inconceivable that sufficiently energetic probing of the proton would not eventually excite this glue.

While it would be ideal to discover the gluonic excitations of the proton, phenomenological studies indicate that for technical reasons it will be much easier experimentally (and theoretically) to study the analogous states of mesons. The key reason for this preference for mesons is that their gluonic excitations, unlike those of the nucleons, will in many cases display J^{PC} exotic quantum numbers, thereby greatly facilitating their separation from ordinary $q\bar{q}$ states via partial wave analysis.

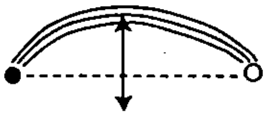

Fig. 5: A sketch of a gluonic excitation of a meson in the flux tube model.

As with any spectroscopy, the spectrum of gluonic excitations is important in revealing the character of the underlying associated gluonic degree of freedom being excited. In particular, if confinement does indeed arise from the formation of chromoelectric flux tubes, then the excitation of these flux tubes (see illustration) will display the spectrum and quantum numbers characteristic of such a collective (string-like) degree of freedom.

3.3. The Role of the Quark-Antiquark Sea

Next to the gluonic degree of freedom issue, the next most puzzling aspect of the observed structure of hadrons, in my opinion, is the seeming unimportance of $q\bar{q}$ pairs. Naively, given that the light quarks of the QCD Lagrangian are essentially massless, one would expect all hadrons to be full of a bubbling sea of pairs. Yet for the most part, until very recently at least, there was little evidence that $q\bar{q}$ pairs were playing much of a role in hadron structure.

The program I have advocated above of valence quark plus flux-tube dominance has as its first correction the addition of $q\bar{q}$ pairs as a perturbation: this may be viewed as a program 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.

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 such 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 (*not* 500 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.

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 $\omega \rightarrow K\bar{K} \rightarrow \phi$, 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. 6(b)), 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; no low-energy hadronic effective theory of which I am aware could reproduce this physics.

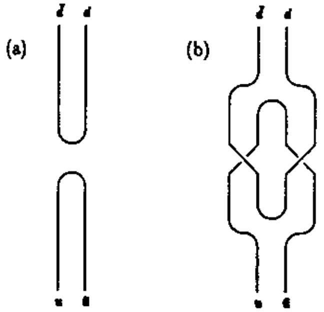

Fig. 6: (a) OZI-violation in a meson propagator by "pure annihilation". (b) A different time ordering of the same Feynman graph gives an OZI-violating loop diagram via two OZI-allowed amplitudes.

Note that this example has direct implications for baryons via such OZI-violating processes as $p \rightarrow p\phi$ 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!

We can expect that, within the intrinsic systematic errors, Δu, Δd,and Δs will be known in another year or two. Then, the next logical step will be to determine the contribution of sea quarks, and the strange quarks in particular, to the static properties of the nucleons. Using parity violation as a probe, the SAMPLE experiment at MIT's Bates Lab and then an extensive program of measurements planned for CEBAF at Jefferson Lab (including measurements utilizing the existing Hall A spectrometers as well as a new special purpose detector called G^0 funded for construction in Hall C) will allow us to decompose the nucleon form factors into their quark-level components: G_E^u, G_E^d, G_E^S, and G_M^u, G_M^d, G_M^S each as a function of Q^2. See Figures 7, 8, and 9 for illustrations of the power of the planned CEBAF experiments.

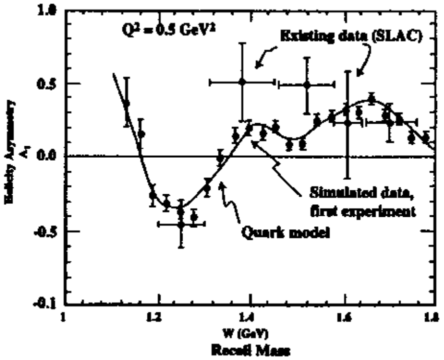

Fig. 7: Hall B will contribute to the measurements of $\Delta q's$ at low Q^2 via precise measurements of the helicity asymmetry in the resonance region.

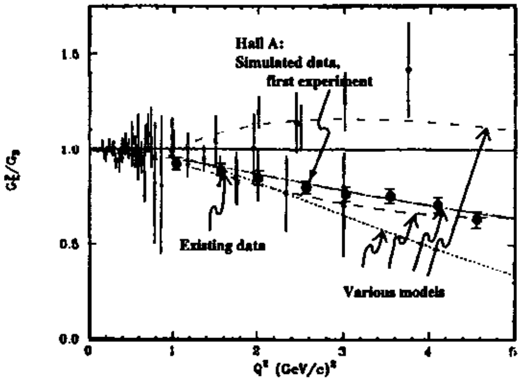

Fig. 8: The projected Hall A measurement of G_E^P used as precision input to the quark-level decomposition of the effect of the sea in the form factors.

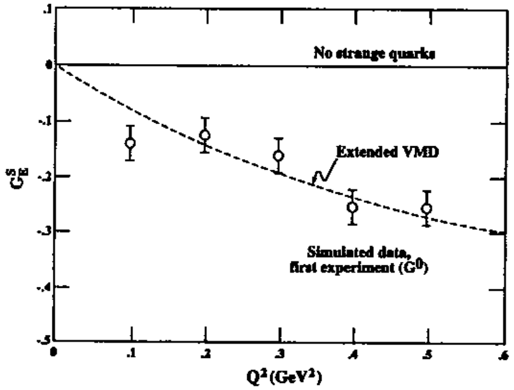

Fig. 9: Projected measurement of G_E^S using the G^0 spectrometer

3.4 Properties of Heavy Quark Systems

The earlier discussions show that Heavy Quark systems can potentially teach us much about the light quark world. Here I want to focus on a recent example which is very relevant to hyperon spectroscopy and the issue of the existence of multiquark systems.

Twenty five years ago Dalitz speculated that the $J^P = \frac{1}{2}^-$ $\Lambda(1405)$ strange baryon resonance might be a $\bar{K}N$ bound state. This speculation was fueled later by a failure of quark models: in the simplest such model [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. 10 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.2(a) 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 centers of gravity 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 early interpretation is ruled out, and a 25 year old controversy settled.

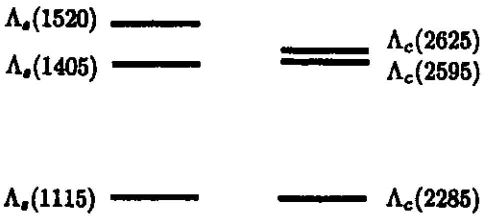

Fig. 10: a comparison of the low-lying Λ_s and Λ_c systems

3.5. Color Transparency

One of the most spectacular predictions of QCD arises directly from its nonabelian character: that three quarks in a color singlet will lose their strong interactions when in a spatially small cluster. The physics is basically identical to that of an e^+e^- pair in QED: if in a small configuration, this state will interact only through its dipole moment $\vec{d}$, and this interaction can be made arbitrarily weak by arranging for $\vec{d}$ to be arbitrarily small. Of course while the analogy for $q\bar{q}$ systems is direct, the twist in QCD is that three quarks, each of which is charged, can have a cancelling monopole moment since their charges are nonabelian and have left over only a dipole interaction which can once again be made arbitrarily weak by arranging that the three quarks be arbitrarily close together.

Needless to say, arranging experimentally to observe the interaction of such small systems is not at all easy, but a number of proposals to carry out such measurements are now approved for CEBAF at Jefferson Lab. Initial efforts at other labs are also continuing, and it is reasonable to expect that this very interesting phenomenon will be established in the coming few years.

3.6. Medium Modification

Just as the properties of an atom are modified if it is dissolved in a liquid or embedded as an impurity in a solid, the properties of hadrons (both baryons and mesons) are expected to be modified when they are buried in a nucleus. The experimental program approved for CEBAF includes a number of high precision experiments designed to see shifts in the masses and static properties of hadrons in nuclei.

Such "medium modifications" are probably an intrinisic element of ordinary nuclear binding (as are induced dipole moments in chemical binding). In addition, such modifications at ordinary nuclear densities must somehow foreshadow the deconfinement phase transition to a quark-gluon plasma at high density.

3.7. Short Distance Structure in Nuclei

Processes with rates which depend on two nucleons being in very close proximity are especially interesting for probing the range of validity of the "nuclear physics appreciation". Since a nucleon has a diameter approaching 2 fermis, when two nucleons are close together their quark wavefunctions will be strongly overlapped, and one expects the quarks to lose their association with an individual nucleon. Thus, *e.g.*, the short distance behavior of the deuteron should in some way be determined by the properties of a six quark cluster.

While it remains very controversial how to describe this six quark cluster (or even whether it exists at all), CEBAF's very first experiment seems to indicate that there is a transition at short distances between nucleonic and quark degrees of freedom: as one can see from Figure 11, there is now established a clear break in the slope of the $\gamma d \rightarrow pn$ cross section at high energy.

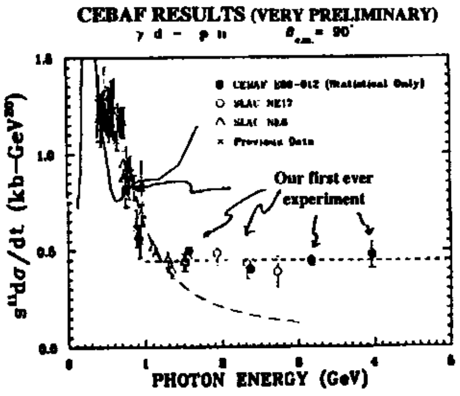

Fig. 11: Preliminary results from the first CEBAF experiment ($E89-012$) showing a break in the slope of the $\gamma d \rightarrow pn$ cross section at $E_\gamma \simeq 2GeV$.

3.8. Beyond the NN Interaction

Identifying the basic origin of the NN force in the "nuclear physics approximation" is one of the fundamental tasks confronting us in our struggle to understand the role of QCD in making the world the way it is.

If we had only the forces in the NN system to guide us, this task would be made much more difficult. The reason is that there is a "confusion theorem" between the two leading contenders for the source of interhadronic potentials: meson exchange and quark exchange. The "theorem" is simple to understand: $q\bar{q}$ exchange leads to exactly the same t-channel quantum numbers as the exchange of a quark and "quark hole". Thus, while physically distinct (when two nucleons exchange a meson, at some intermediate time there are in addition to the original six quarks the extra $q\bar{q}$ pair; when two nucleons exchange quarks between themselves, there are never more than six quarks present), both mechanisms will lead one to an indentical parameterization of the effective NN potential. Without a quantitative understanding of how to calculate the strength of a given t-channel contribution, such parameterizations cannot disentangle the two mechanisms.

For this reason, studies of other interhadronic forces will probably be essential in unravelling the true origin of the NN force. The ΛN and ΣN systems are good places to start extending our knowledge of such forces and CEBAF at Jefferson Lab and FINUDA at DAPHNE have important roles to play. I believe it will also be vital to reach some understanding of the nature of the forces in other baryon-baryon channels like ΔN and $\Delta\Delta$, and also in mesonic channels. In this latter area, once again both CEBAF and KLOE at DAPHNE expect to make major contributions to our understanding of the $K\bar{K}$ system by defining the properties of the $f_0(980)$ and $a_0(980)$ as potential $K\bar{K}$ molecules (*i.e.*, mesonic analogues of the deuteron).

4. CONCLUSIONS

These examples of some key issues and experiments, which we will be part of writing into the history books how QCD leads to the phenomenon that make up the world around us, are necessarily superficial. However, I hope they will have provided a sense of the excitement that some of us feel as we begin this new era of strong interaction physics.

My optimism about the future is partly based on the existence of many new theoretical tools at hand: the large N_c expansion, the lattice, heavy quark expansions, and heavy baryon chiral perturbation theory.

However, 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, RHIC at Brookhaven, and DAPHNE at Frascati Lab. In the longer term we can look forward to powerful new insights from the 50 GeV JHP project.

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

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