Jefferson Lab

The Thomas Jefferson National Accelerator Facility
Theory Group Preprint Series

The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-84ER40150.

JLAB-THY-97-15

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 50 GeV proton machine (JHP) being planned for KEK.

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 issus 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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*Invited talk presented at the 25th INS International Symposium on Nuclear and Particle Physics with High-Intensity Proton Accelerators, Tokyo, Japan, December 1996.

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).

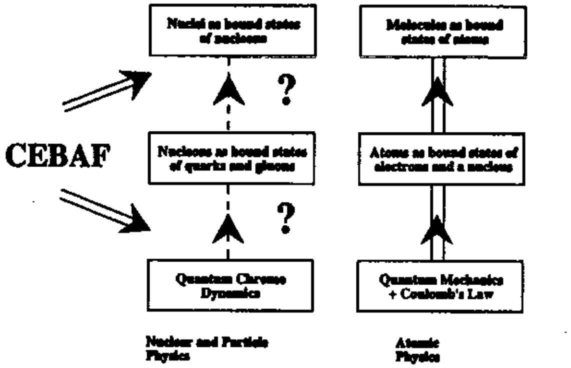

Fig. 1: An analogy between atomic and molecular physics in the 1930's and quark and nuclear physics in the 1990's.

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. 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 those posed above.

2 Finding the Low Energy Effective Degrees of Freedom

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.

I will describe an approach to this issue in two steps. In the first step I will explain why the naive degrees of freedom one might expect to see based on the QCD Lagrangian are irrelevant to the physics of confinement: perturbative QCD fails to even provide an appropriate language for discussing confinement-related physics. Next I will suggest that the appropriate concepts were provided by Nambu in 1973 at the very first of these INS Symposia. In his lecture at that first meeting of which this is the 25^{th}, he introduced three very important ideas. One was that the strong interactions are an $SU(3)$ color theory, the basis of QCD. The other two, which I believe are the key to progress in understanding QCD are:

1) the string (or flux-tube) model for hadrons, and
2) the ideas of "color chemistry".

I will explore these two 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):

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

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

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

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.

2.2 Proposal for the Appropriate Low-Energy Effective Degrees of Freedom

If quarks and gluons are not the correct low energy degrees of freedom, then what are? One possibility, which has support from many different approaches, is that they are constituent quarks and flux tubes (basically, Nambu's strings). The arguments for constituent quark dominance come from the large N_c limit [2], from quenched lattice QCD, and from the Heavy Quark limit of QCD [3].

That confinement is realized in QCD in terms of the development of a confining chromoelectric flux tube is becoming increasingly firmly established. 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.

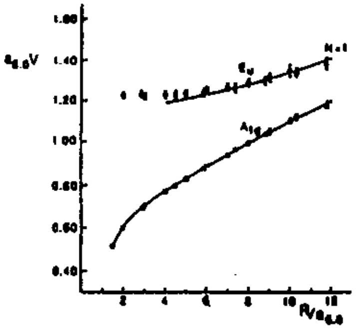

Fig. 2: the ground state and first excited adiabatic potentials from lattice QCD [4]

3 The Origin of Nuclear Forces

Having touched in this overview on a key issue in the "atomic" physics of QCD, namely the active degrees of freedom in the low-lying spectrum, I would now like to turn to a key issue in the "molecular" physics of QCD: the origin of nuclear forces.

I will argue that the conventional wisdom, that these forces arise from meson exchange, is incomplete. My argument begins by showing that, in a world of heavy quarks, meson exchange would be irrelevant, and that the NN force would be dominated by quark exchange forces. I will then argue that in the real world of light quarks *both* meson and quark exchange forces must be taken into account.

3.1 The NN Force in a Heavy Quark World

To maintain flavor parallels with our world, we consider a world with two heavy quarks U and D analogous to u and d but with $m_U = m_D \equiv m_Q \gg \Lambda_{QCD}$. The low-lying mesons and baryons of such a world will live (almost entirely) in the one-gluon-exchange region as nonrelativistic, nearly hydrogenic bound states with radii $r \sim (m_Q\alpha_s)^{-1}$.

The conventional picture of "proton"-"proton" scattering in such a world would be based on the exchange of mesons between two UUD ground states. The underpinning of such a picture is dispersion theory which tells us that the scattering amplitude should be an analytic function of momentum transfer q^2 apart from poles and cuts *determined by the physical spectrum*. We will see by examining the heavy quark limit that this statement is not accurate, and that in fact in the heavy quark limit it is completely misleading.

3.2 A Simpler Problem First

We begin by considering the simpler problem of the elastic form factor of the "proton". The usual argument is that this form factor is an analytic function of q^2 apart from vector meson poles and multiparticle threshold cuts along the real q^2 axis. Since the lowest vector meson will have a mass of approximately $2m_Q$ and since the lowest meson-meson cut will start at about $4m_Q$, one would expect on the basis of meson exchange theory a "proton" charge radius r_{ch} of order m_Q^{-1}. This is, however, clearly the wrong answer: this "proton" will have a charge radius of order $(m_Q\alpha_s)^{-1}$ corresponding the the three particle Bohr radius of the UUD ground state.

This discrepancy is a variant of one resolved long ago by nuclear theorists for the deuteron: it is a consequence of "anomalous thresholds" [6,7]. The discrepancy (and the speculation that anomalous thresholds were its resolution) was noted in the context of heavy quarks in Ref. [8]. The resolution is more subtle in the case of heavy quarks than in the case of the deuteron, however, since with confinement there are no actual anomalous thresholds (the deuteron can be dissociated into its constituents, but a hadron cannot be), but it has now been satisfactorily accomplished [9]. The essential point for us is that one can see explicitly in the dispersion relations for both normal bound states and confined ones that there are contributions to the form factor of a composite system arising from two intrinsically distinct physical mechanisms: structure associated with the spatial extension of the composite system (the anomalous threshold term) and structure associated with the current-constituent vertex function (the normal dispersion relation terms).

I should quickly add that the additional effect being discussed here is not associated with, for example, an NNV vertex arising from form factors for the strong emission of a vector meson V from the nucleon. There will also be such an effect related to compositeness, but it simply modifies the hadronic matrix element of the current-constituent vertex. The main effect is a *direct* one, best illustrated by the canonical example: a system with reduced mass μ and binding energy ϵ has an asymptotic wavefunction

$$\psi \sim \frac{1}{r} exp[-(2\mu\epsilon)^{1/2} r].$$

This leads to a form factor with a cut starting at $q^2 = 32\mu\epsilon$. Note that this anomalous threshold cut is not associated with any physical thresholds; moreover, it dominates the charge radius if ϵ is small. Another example is also useful: a system confined by harmonic forces has $\psi \sim exp[-\frac{1}{2}\alpha^2 r^2]$ and a form factor $F(\vec{q}^{\,2}) \sim exp[-q^2/16\alpha^2]$ which means that in this case the charge radius is being controlled by a singularity at infinity!

3.3 The Nucleon-Nucleon Problem

The extension of these considerations to "nucleon"-"nucleon" scattering in a heavy quark world appears to be straightforward. Conventional meson theory would say that the "nucleon"-"nucleon" cross section would correspond to a low energy effective potential with a range of order m_Q^{-1}. Since the UUD "nucleon" has a size given by its Bohr radius, and since quark exchange will occur via residual color Coulomb interactions with the same range (outside this range they are screened since the "nucleon" is color neutral), the actual effective potential will have a range of order $(m_Q\alpha_s)^{-1}$. Moreover, the strength of quark exchange dominates that of meson exchange by many powers of α_s. Thus in the limiting heavy quark world where $m_Q \to \infty$, the "nucleon"-"nucleon" interaction is controlled entirely by the composite nature of the "nucleons". What is more relevant for the extrapolation to the real world is that by understanding this limit we can see that quark exchange and meson exchange are (as they are in the case of the form factor) physically distinct sources of interactions. Moreover, one can see from the extrapolation of m_Q down to Λ_{QCD} that in the real world there is no reason to expect other than that these two contributions to NN scattering are of comparable importance.

These expectations have been born out over the last few years by many explicit calculations in NN, YN, $N\Delta$, $\Delta\Delta$, $K\bar{K}$, and other hadron-hadron systems. Especially noteworthy have been the calculations using resonating group methods by Oka, Yazaki, and collaborators and by Fujiwara and collaborators.

The heavy quark limit thus shows that meson theory can fail totally, and that as $m_Q \to 0$ so that QCD becomes a one scale theory there is every reason to expect that the two time-ordered graphs of the old string theory become comparable ($V_{meson} \sim V_{quark\ exchange}$). I believe we will eventually appreciate that only Yukawa's *original* meson (whose mass avoids the single scale argument by chiral symmetry) will survive as a distinct contributor to interhadronic forces, while other mesons and quark exchange will be merged into a single comprehensive nuclear theory of the future.

4 Conclusions

The prospects for progress in understnding strong interactions 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 and RHIC at Brookhaven. In the longer term we can look forward to powerful new insights from the JHP project.

I conclude that 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.

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