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QUARK MODELS OF THE NUCLEAR FORCE*

C. E. DeTar
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94305, USA

and

Department of Physics
University of Utah
Salt Lake City, UT 84112, USA

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ABSTRACT

Quark models of the two-nucleon interaction are reviewed with particular emphasis on calculations in the MIT bag model.

1. Present Status of Quantum Chromodynamics

High energy physicists have grown increasingly optimistic in recent years that the gauge theory of colored quarks and gluons, quantum chromodynamics (QCD), will prove to be the underlying theory of hadronic interactions. Although there is still no general agreement about the mechanism which leads to the apparent long-range confinement of quarks and gluons, the short-distance properties of the theory are surprisingly satisfactory. There are many excellent reviews of the successes of the model.[1] I shall simply list a few of these successes:

(i) Spectrum of the light hadrons

The color theory solves the old statistics problem of how to construct sensible three quark states for baryons; and the colored vector gluon exchange gives the correct ordering of mass levels.[2]

(ii) Charmonium

The spectrum of newly discovered hadrons related to the J/ψ meson is manifestly that of a two fermion system (i.e. charmed quark and anti-quark).[3]

(iii) Asymptotic freedom

Perturbation theory is legitimate at short distances. Scaling of the structure functions in deep inelastic electron scattering from nuclei (i.e. the apparent point-like nature of the quarks) is accounted for.[4] Scaling is also explained in the production of $\mu^+\mu^-$ pairs and in production cross sections at high transverse momentum in hadronic collisions.[5]

(iv) Jets in $e^+e^- \rightarrow$ hadrons

The jet structure in the momentum distribution of hadrons produced in e^+e^- collisions

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could be initiated by the formation of a rapidly separating quark-antiquark pair. The angular distribution of the jet axis is consistent with the assignment of spin 1/2 to the quark in this process.[6]

(v) The ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

This ratio depends on the numbers and charges of the quarks and is typical of a theory with three colors.[7]

Of these successes, (i) and (ii) are shared with non-relativistic quark models, which were, incidentally, devised for specifically this purpose.[8] The scaling results (iii) are also predicted by the less specific parton model[5,11], and (iv) and (v) do not characterize gluons in any way. Recent measurements, particularly in the past year, of the departure from Bjorken scaling in deep inelastic electron, muon, and neutrino scattering from hadrons, have provided the most impressive test of QCD to date. Neutrino scattering experiments carried out at the BEBC (bubble chamber) facility at CERN measured this departure from exact scaling and found excellent agreement with the peculiar predictions of QCD.[1,9] Thus we may add

(vi) Departure from Bjorken scaling in deep inelastic leptoproduction

Another peculiar prediction of QCD is the subject of current research. The newly discovered upsilon particle, thought to be a $^3S_1$ bound state of a heavy (~ 5 GeV) quark and antiquark pair should decay in analogy with triplet positronium into three gluons, which would generate three jets.[10] We await results from experiments currently in progress at the e^+e^- facility at DESY and future experiments planned at PETRA and PEP.

2. Relevance to Nuclear Physics

Although none of the above listed tests constitutes by itself a direct confirmation of QCD, the circumstantial evidence is mounting. And it raises the tantalizing prospect of soon actually being able to <u>calculate</u> hadronic interactions from what are more or less first principles. Where do we expect these developments to be of interest in nuclear physics? Even if the nucleon is to be regarded as a three quark object to first approximation we clearly don't want to turn N-body nuclear problems into 3N-body quark problems unless we are forced to do so. Consider the two-nucleon interaction. The meson-exchange models regard the nucleons as point-like objects with clouds of various mesons which mediate the nuclear force. The quark-gluon model regards them as basically tightly bound three-quark objects with internal gluon fields. They interact by exchanging quarks and gluons. Each model has its proper domain of applicability which depends on the internuclear separation. At short range—i.e. distances smaller than or comparable to the charge radius of the proton ($\lesssim$ 1 fm)—the meson exchange picture becomes uneconomical. Too many combinations of exchanges are important. At long range the description of meson exchange in the quark language becomes uneconomical because the details of the binding of the quarks which form the exchanged mesons must be carefully taken into account. One hopes that the two pictures are complementary at some intermediate range.

In the deuteron the nuclei are on average quite far apart and so presumably have only a few percent probability of being found in a region in which a six-quark description is important. However in larger nuclei the average separation is approximately 1.5 fm; here it is more likely that clusters of six quarks occur. One therefore expects the six-quark character to manifest itself in processes that are sensitive to the short distance interaction of nucleons.

(i) Deep inelastic electron scattering from nuclei

The differential cross section for scattering electrons inelastically from a nucleus depends on the invariant momentum transfer $Q^2 > 0$ to the electron, the beam energy E and the energy loss of the electron $\nu = E-E'$ in the laboratory. It is written in terms of the conventional structure functions for the nucleon as

$$\frac{d^2\sigma}{d\Omega d\nu} = \frac{d\sigma_M}{d\Omega}\left[W_2(\nu, Q^2) + 2\tan^2\frac{\theta}{2}\, W_1(\nu, Q^2)\right]$$

where

$$\frac{d\sigma_M}{d\Omega} = \frac{\alpha^2\cos^2\frac{\theta}{2}}{4E^2\sin^2\frac{\theta}{2}}, \quad Q^2 = 4EE'\sin^2\frac{\theta}{2} \ .$$

According to the quark-parton model[11] and experimental observation[12] at large Q^2 the structure functions W_1 and νW_2 become functions of the scaling variable

$$x = \frac{Q^2}{2M_A\nu}$$

where M_A is mass of the nucleus. The fundamental process at large Q^2 ($\gtrsim 1$ GeV^2/c^2) (in the parton model) is the scattering of the electron from a single quark. If the process is viewed in a frame in which the target nucleus moves at a high momentum P, the scaling variable is tied to the momentum of the struck quark, according to the kinematical criteria of the parton model, namely

$$P_{quark} = xP \, .$$

For scattering from a hydrogen target the dimensional counting rules of the parton model[5,13] based on three quarks give a distribution

$$\nu W_2 \underset{x\to 1}{\sim} (1-x)^3$$

near the kinematical boundary $x = 1$. For scattering from a deuterium target, the same counting rules give

$$\nu W_2 \underset{x\to 1}{\sim} (1-x)^9 \ .$$

The power law behavior at large x is typical of a six-quark model, and is not expected to be produced by a two-nucleon model which fails to take into account the three-quark composition of the nucleons. Because a single nucleon moving slowly in a deuteron would contain quarks traveling at $x \leq 1/2$ the region $x \geq 1/2$ is sensitive to the high momentum, small separation component of the deuteron wave function. For a phenomenological analysis of the deuteron structure function see Ref. 14. For larger nuclei it is likewise to be expected that the region $x \gtrsim 1/A$ probes aggregates of six or more quarks.

(ii) Fast fragments in nuclear collisions

Experiments on fast nuclear collisions can measure the momentum spectrum of leading hadrons in the final state. The cross section for producing protons with a C^{12} beam, for example, where the protons have a fraction x of the beam's momentum is predicted to have the behavior

$$\frac{1}{\sigma}\frac{d\sigma}{dx}(C_{12} + A \rightarrow \pi + \text{anything}) \underset{x \rightarrow 1}{\simeq} (1-x)^{65}$$

according to a model based on 36 quark constituents in C_{12}! This behavior is observed (see references in Blankenbecler, Ref. 15). The distribution of protons for $x \gtrsim 1/12$ is expected to be sensitive to clusters of six or more quarks.

(iii) Electromagnetic form factors

According to the counting rules of the parton model[14, 15] the large t dependence of the deuteron's form factors follows a power law

$$F_d(t) \sim 1/t^5$$

typical of a six-quark object. This power law is indeed observed.[14, 15]

(iv) Neutron stars

At sufficiently high densities neutron stars are thought to collapse into quark stars.[16] The nature of this transition is of course sensitive to the short range component of the two-nucleon interaction.

(v) New nuclear excitations

Chapline and Kerman[17] have made the intriguing suggestion that multiquark clusters may be sufficiently long-lived that they could be produced as resonances in collisions of nuclei. Their possible existence and stability can also be investigated theoretically.

3. The MIT Bag Model

The MIT bag model provides a practical scheme in which confinement is achieved in a natural, if not phenomenological, Lorentz covariant manner.[18] The conventional QCD Lagrangian for interacting quarks and gluons is supplemented with a constant term B and then integrated only over the volume of the hadron to define the action

$$I = \int_{t_1}^{t_2} dt \int_V (\mathscr{L}_{QCD} - B)\, d^3V \ . \qquad (3.1)$$

The geometrical degrees of freedom are coupled to the internal field degrees of freedom in a manner which makes the action stationary.[18] The resulting classical equations of motion are Lorentz covariant; and color confinement arises naturally from the boundary conditions for the gluon fields. Many of the features of the model can be understood by resorting to the static cavity approximation.[18, 19] The hamiltonian then takes the form

$$H = \int_V \psi^\dagger (-i\alpha\cdot\nabla)\psi \, dV + \frac{1}{2} \int_V (\vec{E}^a\cdot\vec{E}^a + \vec{B}^a\cdot\vec{B}^a) dV - g_c \int_V \vec{J}^a\cdot\vec{A}^a dV + BV . \tag{3.2}$$

The fermion field ψ carries suppressed color and flavor indices, and the color electric and magnetic fields $\vec{E}^a$ and $\vec{B}^a$, the color vector potential $\vec{A}^a$ and color current $\vec{J}^a$ all transform as octets $(a=1,\ldots,8)$ under color rotations. The color charge strength is g_c. The volume of integration V is inside a static surface S. The BV term, the hallmark of the MIT bag model, may be regarded as a postulated energy required to populate a volume V of the vacuum with the hadronic fields. The shape and size of the hadron in the static cavity approximation is found by minimizing the energy with respect to the orientation of the surface.

To lowest order in the gluon coupling the fermion field ψ satisfies the free Dirac equation inside the cavity and a linear boundary condition on the surface.

$$\begin{aligned} -i\alpha\cdot\nabla\psi &= \omega\,\psi \quad \text{in } V \\ -i\alpha\cdot\hat{n}\,\psi &= \gamma_0\psi \quad \text{on } S \end{aligned} \tag{3.3}$$

where $\hat{n}$ is the unit outward normal to the surface. The boundary condition implies that

$$\hat{n}\cdot\bar{\psi}\vec{\gamma}\psi = 0 , \tag{3.4}$$

i.e. no baryonic current flows across the surface. The cavity eigenmodes of Eqs. (3.3) serve as a basis for the quantization of the quark fields. The color electric and magnetic fields are found to lowest order in the gluon coupling by solving Maxwell's equations with the current density

$$J^{a\mu} = g_c : \bar{\psi}\lambda^a\gamma^\mu\psi$$

where λ^a are the 3×3 matrix generators of color SU(3). The linear boundary conditions satisfied by the fields are these:

$$\hat{n}\cdot\vec{E}^a = 0; \quad \hat{n}\times\vec{B}^a = 0 .$$

The former guarantees that the total color charge generators Q^a vanish so that the hadron is a color singlet.

The energy for the hadrons to second order in g_c thus consists of several contributions:

(1) Energy due to the quark motion

(2) Energy due to the quark interaction

(3) Volume energy

(4) "Zero-point energy" (see below)

For spherical hadrons of radius R with massless quarks, the above listed terms appear respectively as

$$E = c_Q/R + c_{EB}/R + \frac{4}{3}\pi R^3 B - Z_0/R . \tag{3.5}$$

The constants c_Q and c_{EB} depend on quark number and the internal symmetry configuration, but Z_0 is a constant independent of quark number. The zero-point energy term $-Z_0/R$ represents the finite contribution to the energy due to the normal ordering of the fields in the hamiltonian. It also includes the correction due to the motion of the center of mass of the quarks in the static cavity and so it is basically negative.[20] In practice it is determined phenomenologically. The radius R is found by minimizing E(R) in Eq. (3.5).

Masses and other static parameters of the various light hadrons have been calculated with reasonable success using the above model with four adjustable parameters: g_c^2, B, Z_0 and a mass for the strange quark m_s.[19] Two masses which are of particular interest to the two-nucleon interaction are those of the nucleon and Δ. Without the color interaction these states would be degenerate. The color interaction breaks the degeneracy. Since these states are formed as a color singlet with all quarks in the same orbital the color charge density is locally zero and the color electrostatic contribution to the energy vanishes (apart from quantum fluctuations). It is the color magnetic interaction, proportional to the product of spinors of the interacting quarks given by $-\sum_{a,i} \lambda_1^a \sigma_1^i \lambda_2^a \sigma_2^i$, which is responsible for the mass difference.

4. The Two-Nucleon Interaction in the MIT Bag Model

(i) Limitations of the classical cavity approximation

At short range two interacting nucleons occupy a common volume V and their quarks intermingle. At long range the six-quark volume fissions into two three-quark regions. At the point of fission all interaction ceases. Long-range meson exchange effects are not seen in this picture but might be found if quantum fluctuations of the surface were considered. The magnitude of these effects are only of the order of tens of MeVs and certainly within the error of other approximations of the model, such as the neglect of higher order terms in the color coupling constant. But it is certainly more economical to use the meson exchange picture at long range. Therefore, the present calculation is restricted to the short range interaction ($r \lesssim 1$ fm).

(ii) Collective motion in the bag model

If the static cavity approximation is followed strictly, the deuteron turns out to be a nearly spherical rigid six-quark bag with a binding energy of ~ -300 MeV. However, the classical treatment of the surface has excluded important degrees of freedom, which if properly included, would contribute a kinetic energy due to quantum fluctuations. We are, of course, interested in adiabatic collective motions of the system which cause fluctuations in some measure of the internucleon separation. As a first step in studying this collective motion we compute the deformation energy due to distortions of the system from its point of static classical equilibrium. This is done by introducing a variable δ which gives a measure of the gross distortion of the system and then by fixing the variable through a constraint term in the hamiltonian:

$$H(c_\delta, \delta_0) = H_0 + c_\delta (\delta - \delta_0)$$

where δ is to have the value δ_0 and c_δ is a Lagrange multiplier. A deformation energy curve $E(\delta_0)$ is obtained.

To complete the dynamical description of the collective motion a momentum p conjugate to δ must be found. The calculation should be repeated, constraining both δ to δ_0 and p to p_0, yielding $E(\delta_0, p_0)$. This is the effective classical hamiltonian for the collective motion and in the low momentum approximation the hamiltonian

$$E(\delta_0, p_0) \approx E(\delta_0) + p_0^2/2m(\delta_0)$$

may be quantized following standard methods. Motion in more than one collective variable can also be considered. Any arbitrariness in the choice of collective variables should be compensated in the dynamical description by the form of the inertial quantities such as $m(\delta_0)$. Only the computation of a deformation energy is reported here.

5. Deformation Energy of the Six-Quark System

(i) Shape

Although the computational program admits a variety of axially symmetric shapes leading to fission[21], maintaining a spherical shape has only a small effect upon the calculation at short distances and gives an adequate qualitative description of the deformation energy at short and intermediate range.

(ii) Configuration

To describe the separation of the three-quark clusters with quantum numbers of the neutron and proton, two hybrid orbitals were constructed from the single particle cavity eigenmodes—a left and right orbital as follows:

$$q_L = q_S - \sqrt{\mu}\, q_A$$

$$q_R = q_S + \sqrt{\mu}\, q_A .$$

The orbital q_S is the lowest state which is symmetric under reflections through the equatorial (x-y) plane and q_A is the lowest antisymmetric state. These are respectively, the $S_{1/2}$ and $P_{3/2}$ orbitals in the sphere. The variational parameter μ ranges from 0 to 1 for maximal to minimal overlap between the orbitals. Creation operators for quarks in these orbitals are assembled so as to produce the proper quantum numbers of the neutron and proton; and the two-nucleon state is then formed from the (fully antisymmetrized) combination

$$(p_L^\dagger n_R^\dagger \pm p_R^\dagger n_L^\dagger) \mid 0 \rangle$$

for even and odd parity states.

(iii) Constraint

In the present study the parameter δ is

$$\delta = \frac{2\sqrt{\mu}(1+\mu)}{1+\mu^2} \int q_S^\dagger(\vec{x})\, q_A(\vec{x})\, z\, dV ,$$

which turns into the internuclear separation at large distances. At small distances the definition of internuclear separation is somewhat arbitrary, but is made unambiguous in a dynamical calculation when the expression for the associated inertia is given.

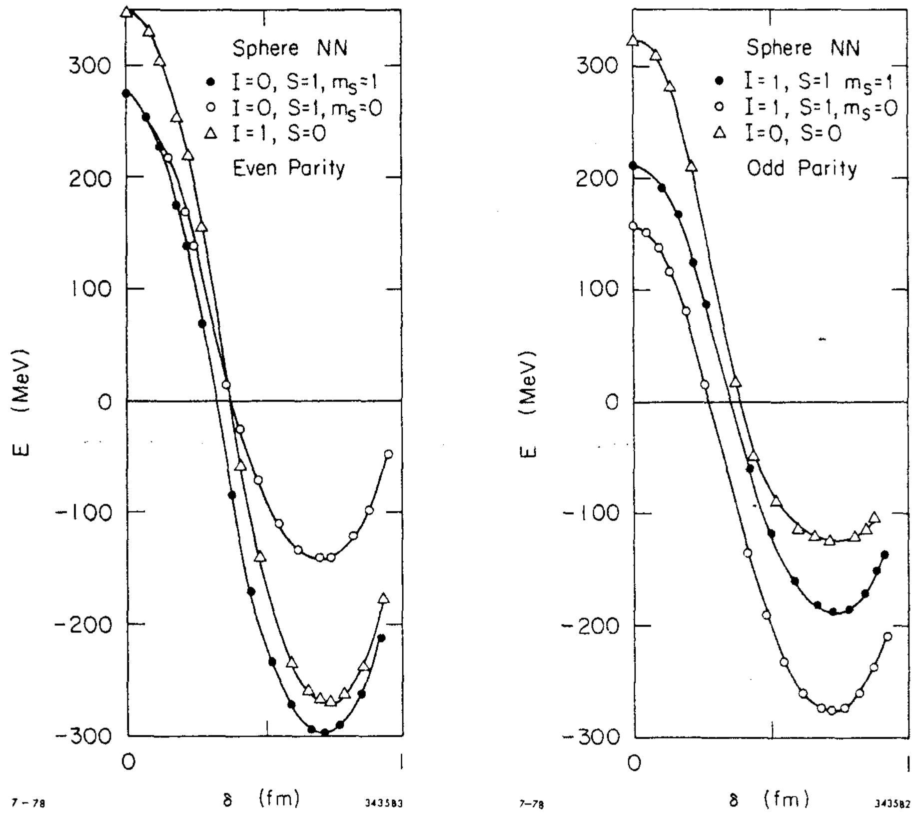


Fig. 1 — Interaction energy for a spherical bag of six quarks as a function of the constrained separation parameter δ (a) for even parity two-nucleon configurations, and (b) for odd parity configurations with rotational kinetic energy included.

6. Results and Discussion

In Fig. 1a results for three even parity states are shown. The spin projection m_S is taken with respect to the separation axis. We note a soft repulsive core and a rather deep region of attraction around $\delta = 0.7 - 0.8$ fm.

The soft repulsive core may be understood as arising from the effect of the color-magnetic interaction—the same one which splits the Δ from the nucleon. Repulsion occurs when all quarks are placed in the same spatial orbital. The repulsion is color-magnetic in origin and is due to the fact that in this state the sum of the values of $-\lambda_i\sigma_i\cdot\lambda_j\sigma_j$ for all pairs in the six quark configuration is positive, whereas it is negative in the three quark nucleons.

The intermediate range attraction corresponds to values of μ around 1/2. The left-right separation of the color singlet combinations is pronounced though by no means complete. The correlation of the color singlet combinations lowers the energy dramatically because of the strong color electrostatic attraction. In effect, two bound states within the larger bag are formed.

When the bag is permitted to assume non-spherical shapes a slightly prolate ellispoid results at minimum energy in the state $I=0$, $S=1$, $m_s=1$, lowering the energy in the process by about 20 MeV.[21] In Fig. 2 contours of equal baryon number density are drawn for a longitudinal cross section of the bag at the energy minimum. Two non-interacting nucleons are also shown for the sake of comparison. The minimum energy configuration shows an enhanced density on left and right corresponding to the emergence of the two nucleons.

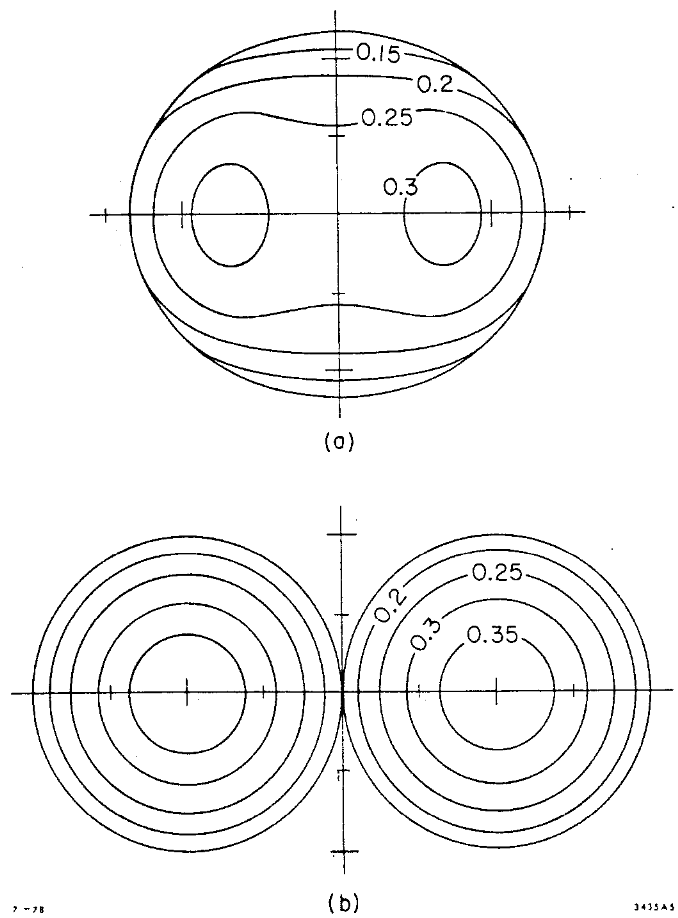


Fig. 2 — (a) Longitudinal section of six-quark bag at minimum deformation energy in the state $I=0$, $S=1$, $m_S=1$ (Ref. 21). Scale is in fermis. Contours show surfaces of equal baryon number density (fm^{-3}). (b) Two spherical non-interacting nucleons in the bag model.

It is interesting that the energy of a single bag containing, so to speak, two nucleons is lower than that of two separate nucleons. The fields due to each nucleon perceive a larger volume than in a single nucleon and so have a lower energy. Introducing a partition (fissioning) requires the fields to satisfy boundary conditions on a larger surface and so raises the energy.

In Fig. 1b the corresponding calculation for the odd parity channel is shown. Zero separation here means five quarks in the $S_{1/2}$ orbital and one in the $P_{3/2}$ orbital. In the conventional decomposition of the two-nucleon potential

$$V = V_C^I + \sigma_1\cdot\sigma_2 V_{SS}^I + S_{12} V_T^I + S\cdot L\, V_{SO}^I$$

The tensor term is responsible for the difference between the potentials for $m_s=1$ and $m_s=0$ in the $S=1$ channels. Both isosinglet and isotriplet tensor contributions are shown

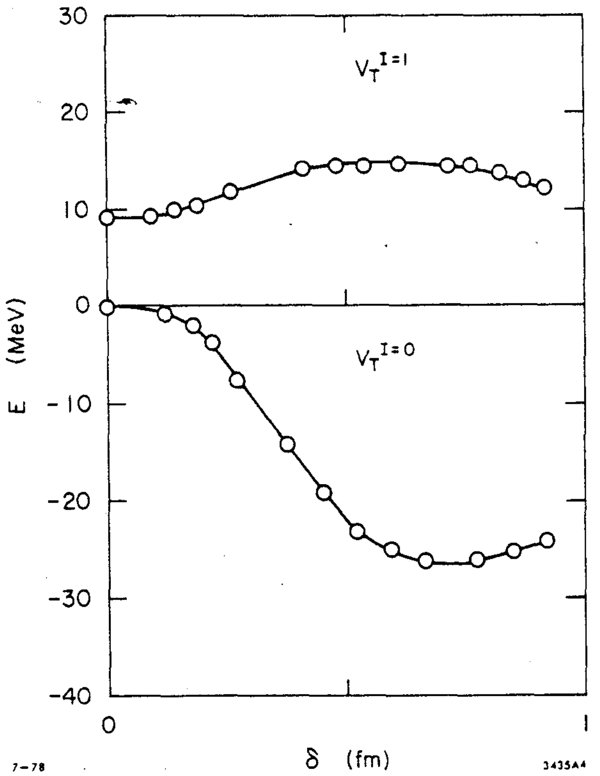


Fig. 3 — Isotriplet and isosinglet tensor contribution to interaction energy in six-quark spherical bag.

in Fig. 3. They agree in sign with that of the Yale and Hamada-Johnston potentials.[22] The sign of the isosinglet tensor potential is directly related to the sign of the quadrupole moment of the deuteron. Since the even parity isosinglet state has no preferred axis at $\delta = 0$ the $m_s = 1$ and $m_s = 0$ states are degenerate. Thus the isosinglet tensor potential vanishes at $\delta = 0$. We also note that the repulsion in the even parity isotriplet channel is greater than in the isosinglet channel, as it should be.

It should be stressed that the configurations used in the present calculation are not in general eigenstates of total angular momentum. It is feasible but tedious to arrange for definite values of J with spherical bags. Such a calculation might permit the separation of the spin-orbit and spin-spin components. The central potential component in the present calculation is, however, dependent on angular momentum, since it incorporates a centrifugal barrier. This makes it difficult to compare even and odd parity curves.

Finally, a word of caution about interpreting these results in terms of a two-body potential is in order. The inertia $m(\delta)$ associated with variations in δ is very unlikely to be the same as the reduced mass of two nucleons. The choice of this parameter is somewhat arbitrary. To emphasize this point, consider that when $\delta = 0$ in the even parity states all of the quarks are in the same orbital. There is accordingly a finite spread in the separation of two three-quark clusters. The r. m. s. separation increases monotonically with δ. A measure of this average separation can be obtained by using the baryon number density $\psi^\dagger\psi$ as a probability distribution for the quark orbitals. The expression

$$r_{12}^2 = \langle r^2 \rangle = \frac{1}{9} \langle : \int \psi^\dagger r^2 \psi \, dV - 5 \int \psi^\dagger \vec{r} \psi \, dV \cdot \int \psi^\dagger \vec{r}' \psi \, dV' : \rangle$$

gives such a measure. It is plotted in Fig. 4 as a function of δ for typical even and odd parity states. If fission were permitted, the value of r_{12} would approach δ asymptotically.

In the absence of a better understanding of bag dynamics the results must be interpreted qualitatively. They appear to be satisfactory in this regard.

7. Other Quark Models

(i) Potential in the non-relativistic oscillator model

The closest related calculation is that of Liberman.[23] He uses a non-relativistic colored quark model with a modified two-body harmonic oscillator potential:

$$V_{ij} = -\lambda_i \cdot \lambda_j \left[v(r_{ij}) + \frac{1}{6}\left(\frac{\hbar}{M_Q c}\right)^2 \sigma_i \cdot \sigma_j \nabla^2 v(r_{ij}) \right]$$

where $v(r) = Kr^2/2$. The spin-coupling term is motivated by vector exchange.[24] The associated spin-orbit and tensor terms are not considered. The quark mass and spring constant are adjusted to give the correct masses for the nucleon and Δ particle. A two-center gaussian wave function is constructed for six quarks and the expectation value of the hamiltonian is calculated a la Born-Oppenheimer with one variational parameter. The interaction energy as a function of the separation of the centers is obtained.

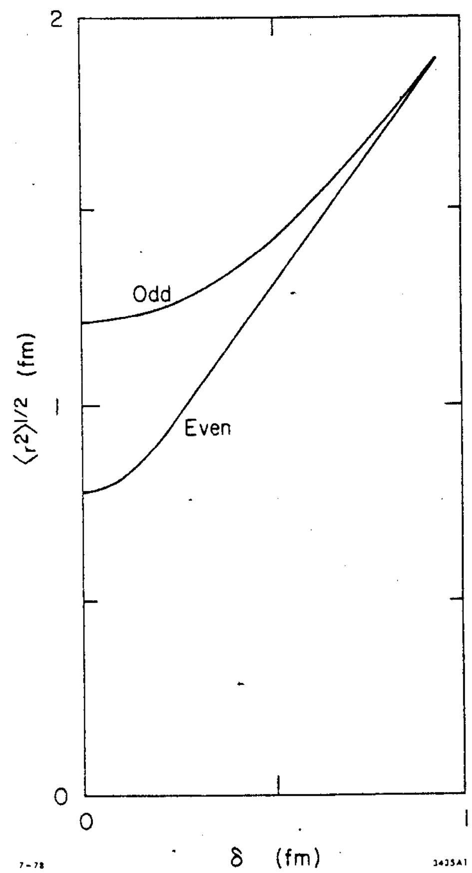


Fig. 4 — Root mean square "inter-nucleon separation" vs. separation parameter for typical even and odd parity two-nucleon states in the spherical bag.

The model has a distinct advantage in ease of computation. However, no claim is, of course, made that the model is obviously related to a comprehensive theory of the strong interactions such as QCD. Surely confining effects in multiquark systems, because they are strong, must arise from many-body interactions and are not reducible to a two-body interaction. Nonetheless, Liberman's results are interesting because the model does have at least some of the features of one gluon exchange—an attractive central term and a color-spin interaction. Indeed when his results are compared with the bag model results there are some striking similarities. The non-relativistic model also puts the $I=0$, $S=0$ curve above that of the $I=1$, $S=1$. Likewise for $I=1$, $S=0$ versus $I=1$, $S=1$. The tensor terms were not calculated in the non-relativistic model. The chief difference between the calculations lies in the strong intermediate range attraction found in the bag model. No negative potential was found in any channel in Liberman's one-parameter variational calculation. Whether the non-relativistic calculation could be improved by changing the shape of the potential and by using a better variational wave function, or whether this difference is of fundamental importance remains to be seen.

(ii) Electromagnetic form factor in the oscillator model

Kobushkin has calculated the electromagnetic form factors of the deuteron in a non-relativistic oscillator model with a deuteron wave function which incorporates a six-quark core component with all quarks in the lowest oscillator mode.[28] With his relativistic extension of the model he finds that a 2% core component contributes appreciably at large q^2. The result is interesting, but a more thoroughgoing relativistic treatment would, of course, be preferable.

(iii) Symmetries of the six-quark oscillator

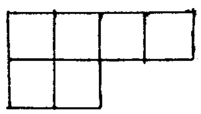
Symmetry analyses based on the non-relativistic oscillator model are often a useful way to look for qualitative features of the interaction. Matveev and Sorba, and Smirnov and Tchuvil'sky[25] observe that the six-quark single orbital state in the deuteron channel can be decomposed on a two-baryon basis

$$| S^6 \rangle = \alpha | NN \rangle + \beta | \Delta\Delta \rangle + \gamma | B_8 B_8 \rangle$$

where B_8, B_8 represents the four possible color octet channels. The NN component represents only 1/9 of the state:

$$| \alpha |^2 = 1/9 ; \quad | \beta |^2 = 4/45 ; \quad | \gamma |^2 = 4/5 .$$

Although an adiabatic contraction of the six-quark system results in a 100% overlap with the configuration $| S^6 \rangle$, perhaps one should think of the overlap parameter α^2 as the probability of reaching this configuration at high energies $T_{cm} \gtrsim 1$ GeV where some sort of a sudden approximation should be used. In the same vein we note that the configuration with the largest overlap with the even-parity two-nucleon channel in our two-orbital description has a spatial orbital symmetry given by the Young tableau



which can be constructed out of four quarks in the S orbital and two in the P orbital. In the non-relativistic oscillator language such a wave function contains a term with a dependence on the relative separation which goes like r^2, and so contains a node near the origin.[26] Perhaps this is the way repulsion manifests itself at higher energies.

(iv) Exchange effects in two-nucleon scattering

Kislinger recently circulated an optimistic note in which low energy scattering of nucleons was considered from the standpoint of the quark-gluon model.[27] The fundamental interaction involved an exchange of a gluon when the nuclei were sufficiently close, followed by an interchange of quarks so as to restore the color singlet property of the nucleons. The same quarks which coupled to the gluon were the ones which were exchanged. The calculation proceeds to consider a non-relativistic reduction of the exchange amplitude (massive quarks with no relative motion within the nucleon). What emerges is a crude effective two-nucleon potential with the proper sign for the spin-orbit term. This result is amusing and the method deserves further study and refinement.

8. Conclusion

In the past few years considerable progress has been made toward formulating a successful theory of the strong interactions. The quark-gluon model offers great promise in unraveling the mystery of the short-range two-nucleon interaction. Moreover, it may be possible to use low energy nuclear physics to distinguish between phenomenological models of quark confinement. The MIT bag model seems to give a reasonable qualitative description of the short-range interaction, but it needs a dynamical formulation before it can be tested more quantitatively.

Since the construction of hadrons has become a few-body problem, elementary particle physicists will benefit considerably from the theoretical experience of nuclear physics in dealing with such problems.

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