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F-56

ANL-HEP-CP--86-81

DE87 001574

MODELS OF MULTIQUARK STATES*

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ABSTRACT

The success of simple constituent quark models in single-hadron physics and their failure in multiquark physics is discussed, emphasizing the relation between meson and baryon spectra, hidden color and the color matrix, breakup decay modes, coupled channels, and hadron-hadron interactions via flipping and tunneling of flux tubes. Model-independent predictions for possible multiquark bound states are considered and the most promising candidates suggested. A quark approach to baryon-baryon interactions is discussed.

1. INTRODUCTION AND DEDICATION--"WHERE IS THE PHYSICS?"

Gabriel Karl[1] has shown how results in remarkable agreement with with experimental hadron spectroscopy have been obtained from simple constituent quark models using effective two-body interactions with properties motivated by QCD although not rigorously derived.[1,2,3] But this approach has broken down completely in the multiquark sector, where not a single prediction has been confirmed by experiment.

Why does Gabriel Karl's beautiful picture fall apart at $N > 3$? One answer was given in another context by Y. Yamaguchi's response in 1960 to the question "Has there been any thought about the problem of...?" "No! Many calculations, no thought!"

One of the earliest and still valid theoretical investigations at the intersections between particle and nuclear physics used a "nuclear physics approach to hadrons". The matrix elements for effective interactions are obtained from the 2-body problem. These are then used for predictions in the N-body problem.[4,5] This approach has been very successful for predicting the baryon spectrum from the meson spectrum. In 1966 Sakharov and Zeldovich[4] obtained

*Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

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the mass relation

$$M_\Lambda - M_N = \frac{3}{4}\lfloor M_{K^*} - M_\rho \rfloor + \frac{1}{4}\lfloor M_K - M_\pi \rfloor \ .$$

177 MeV 180 MeV

This paper is dedicated in honor of the 65th birthday of a pioneering contributor to the intersections between particle and nuclear physics--unable to attend this meeting--Andrei D. Sakharov.

Hadron physics is very different from electroweak physics, where there has always been a standard model, and experiments either test reliable predictions or look for new physics beyond the standard model. Even though we now believe the correct theory for hadron physics to be QCD, nobody knows how to use QCD to calculate the hadron spectrum. A collective effort by theorists and experimentalists is needed with experimental data guiding the theorists in constructing QCD-motivated models, and with the predictions of these models as guides to future experiments. A successful implementation of this program will at least teach us how to use QCD for hadron physics. It may also lead to the discovery of new types of hadrons suggested by QCD, like glue balls, hybrids or multiquark exotics. It may give us insight into the early universe or astrophysical puzzles like Cygnus-X3. It may even lead to evidence for new physics beyond the standard model.

It is interesting to look at Standard Model Physics and Hadron Physics with a "burger model". These days in America everything has been burger-ized. There are beefburgers, fishburgers, pizzaburgers, shrimpburgers, etc. etc. Even the U.S. Supreme Court has been burgerized, with Chief Justice Earl Warren replaced by Warrenburger. Fast-Food outfits have put so much other junk into their burgers that one very popular TV commercial showed a lady asking "Where's the beef?" This tradition has been followed by the Fast-Physics calculators, who have put so much other junk into their physicsburgers that one can ask "Where's the physics?".

There are two kinds of physicsburgers. The electroweak burger has a thick slice of solid predictions on a base of a well defined standard model, covered with a reliable calculation, and garnished with data, Monte Carlo, computer programs and χ^2 fits. The physics is clear. The hadron burger has a base of ad hoc assumptions, covered with free parameters and nothing else and garnished with "reliable" data, Monte Carlo, computer programs and χ^2 fits. There is usually a nearby waste basket filled with rejected "unreliable" data. One can well ask "Where is the physics?"

There are two approaches to using QCD for hadron physics: the southern fundamentalist approach and the northern iconoclastic approach.

The fundamentalists believe that "In the beginning God created the Bag", and follow the implications of the Bag with religious fervor. The lunatic fringe believe that the "n" in Big Bang cosmology is a typographical error and that all multiquark physics is describable with a Big Bag. They lose all contact with the real world as they follow their religion and send experimentalists on wild goose chases for nonexistent objects like narrow baryonium states.

The iconoclasts are atheists (or asakists - from the Greek ΣΑΚΚΟΣ) who refuse to believe anything and are always looking for alternative models in case their favorite model is wrong. Even when they have invented the great standard model for which they eventually get the Nobel Prize, they do not browbeat experimentalists into looking for the phenomena predicted by their model, like charm and weak strangeness-conserving neutral currents. Instead they produce a plethora of alternative models with five quarks, six quarks, eight quarks, new unobserved heavy leptons, etc. to explain all possible disagreements of their right standard model with wrong experiments.

North and south in this context refer of course to locations of the two great centers of particle physics on Massachusetts Avenue, Harvard and M.I.T. (Nit-picking purists may point out that they are really Northwest and Southeast). The correct approach for experimentalists is to recognize that all these diverse types of theorists contribute to our understanding of physics. It is good that we have them, rather than one party line. But just as any good experimenter is very careful to look for all kinds of biases and acceptance criteria before drawing conclusions from a particular set of experimental data, he should also be aware of all the biases and acceptance criteria that go into any theoretical paper before drawing conclusions from their predictions. The key question is "Where is the physics?"

Two examples of these two approaches are the H-dibaryon predicted by Jaffe[6] (M.I.T.) and the prediction of the Λ magnetic moment by DeRujula et al (Harvard).[3]

Jaffe's six-quark-bag calculation predicted the existence of the H and estimated its mass. Where is the physics? Solid general QCD-symmetry arguments show that the H should be the most stable dibaryon. The mass prediction clearly does not include all the right physics. Any bound state near the Λ-Λ threshold must have a Λ-Λ piece in its wave function that decreases exponentially and continues well outside the boundary of any bag. This has been pointed out by Jaffe, but overlooked by others who use his result. This exponential tail reduces the kinetic energy and lowers the mass. Experimental seaches for the H should have high priority, but no mass prediction should be taken seriously unless it manifestly contains all the right physics. For example, any calculation which says that the lowest dibaryon state with the H quantum numbers has a mass greater than the mass of two Λ's must be missing some physics.

DeRujula et al predicted the Λ magnetic moment by using the Δ-nucleon and Σ^*-Σ splittings to estimate flavor-SU(3) symmetry breaking and predicted μ_Λ = -0.61 n.m. This was later confirmed with surprising precision by experiment which found exactly the same value, μ_Λ = -0.61 n.m.,

Where is the physics? It is in the natural assumptions that (1) The Λ moment is entirely due to the strange quark. (2) The SU(3) prediction, $\mu_\Lambda = -(1/3)\,\mu_p$, must be multiplied by the ratio of the strange quark moment to the down quark moment. (3) Hyperfine splittings are due to "color-magnetic" quark-quark interactions which are proportional to the product of quark "color-magnetic moments". (4) The electromagnetic magnetic moments of the quarks are proportional to the color magnetic moments; thus the ratio of the strange quark moment to the down quark moment is given by the ratio of the Σ^*-Σ and Δ-nucleon mass splittings.

Assuming that assumed quark magnetic moments are Dirac moments with a scale determined by some effective quark mass'[7] and using the Λ-nucleon mass difference as the mass difference between the strange and nonstrange quarks,[4,8] gives a completely different prediction for μ_Λ with exactly the same value, μ_Λ = -0.61 n.m.

The physics input here is that the same "effective quark mass" which may include all kinds of complicated quark-gluon interactions appears both in the quark magnetic moment and in the hadron masses. Why this should be so is an open question, left to be solved by QCD theorists. But the simple constituent quark model, with its manifestly simple physics, appears here as a bridge between the experimental data and the fundamental QCD description.[1]

2. THE NUCLEAR APPROACH TO MULTIQUARK HADRONS--"WHERE'S THE PHYSICS?"

2.1 Beyond Gabriel Karl's Standard Model

To go beyond N=3 we must recognize the new physics arising in multiquark configurations[12], where confinement of the color field no longer requires confinement of the system and different properties arise in different domains. Any model for N>3 must pass the following two tests.

1. Can a given model predict N=3 spectroscopy from N=2? If not, throw it away. It won't predict N>3. This kills the bag and skyrmion.

2. Can a model good for N=2,3 handle the new physics beyond N=3? If not, throw it away. It will predict nonsense. This kills the naive potential models.
   Needed! One prediction that works!

Multihadron states at large distances have color flux confined within hadrons and no color field nor long range interactions between them. At intermediate distances interactions between separated hadrons can occur when flux tubes flip from one configuration to another. At short distances there are many ways of connecting the constituents with flux tubes and no obvious optimum configuration. So far there is no tractable model with all the proper characteristics in these three domains and which matches smoothly between them. The problem resembles nuclear reactions which go via a "compound nucleus" intermediate state, but with the additional complications of the color degree of freedom, confinement and flux tubes.

Some of these difficulties would be avoided in a strongly bound multiquark state where only the small distance behaviour is relevant. The experimental discovery of such a strongly bound state would provide valuable information about how QCD works in multiquark systems. So far none have been found, and theoretical guidance directing searches for promising candidates is of great interest.

2.2 From N=2 to N=3

In the quark-antiquark and three-quark systems the coupling of the colors of the constituents to a color singlet is unique, and the color degree of freedom factorizes out to leave a single Schroedinger equation in the space, spin and flavor variables. Mesons and baryons are made of the same quarks with an effective two-body interaction V satisfying the relation[9,10,11,12]:

$$\langle q(x_1)q(x_2);3^*|V|q(x_1)q(x_2);3^*\rangle = (1/2)\langle q(x_1)\bar{q}(x_2);1|V|q(x_1)\bar{q}(x_2);1\rangle \quad (1.1)$$

where $|q(x_1)q(x_2);3^*\rangle$ and $|q(x_1)\bar{q}(x_2);1\rangle$ denote respectively quark-quark and quark-antiquark states with the color antitriplet (3*) and color singlet (1) couplings at the points x_1 and x_2.

Potential models which replace the interactions via the color field by static confining potentials have recently been justified by QCD arguments and lattice gauge calculations for heavy quarkonium states. The relation (2.1) for additive two-body interactions in baryons is easily derived by noting that the color field and the interaction obtained from lattice gauge calculations in a color-singlet baryon become the same as in the quark-antiquark configuration in mesons whenever two of the three quarks in the baryon are at the same point.[9,12,13] However, no QCD argument yet shows that baryons can be described by an effective potential with only two-body forces, nor justifies a potential model for hadrons composed of light quarks. The commonly used "color-exchange" force with the color dependence of one-gluon exchange in all channels satisfies the relation (2.1), but a very different spatial dependence from that of one gluon exchange is obtained from lattice gauge calculations or phenomenological fits to hadron spectra. Thus any justification from QCD for the use of additive two-body effective interactions with realistic radial dependence in hadron spectroscopy must include appreciable multigluon contributions and explain why they do not give appreciable three-body forces. The use of the relation (2.1) has recently led to new successful prediction of baryon masses with meson masses as input.[13] It therefore seems reasonable to extrapolate the approach for larger N. But there are new problems.

2.3 The New Physics Beyond N = 3.

The essential features of multiquark physics are exhibited in the simple example of meson-meson scattering with the possibility of quark exchange; e.g.

$$K^-(s\bar{u}) + K^o(d\bar{s}) \rightarrow \pi^-(d\bar{u}) + \phi(s\bar{s}). \qquad (2.2)$$

It is also interesting to note that if there were only two colors, so that a diquark can also be a color singlet, analogous to the baryon in the three-color case, an additional reaction could occur:

$$K^-(s\bar{u}) + K^o(d\bar{s}) \rightarrow B(ds) + \bar{B}(\bar{u}\bar{s}). \qquad (2.3)$$

where B and $\bar{B}$ denote diquark baryons and antibaryons in two-color QCD.

The analog of these reactions in abelian QED is fermion exchange in positronium-muonium scattering:

$$(e^+e^-) + (\mu^+\mu^-) \rightarrow (e^+\mu^-) + (\mu^+e^-) \qquad (2.4)$$

In Abelian QED the dynamics of the reaction (2.4) can be described by a static two-body coulomb interaction between each pair, having the form

$$V_{ij} = q_i q_j \, V(r_{ij}) \qquad (2.5)$$

where q_i and q_j are the charges of the particles and $V(r_{ij})$ is just the coulomb interaction. The value of the interaction is completely determined by the positions of the particles, and the coulomb field of each particle extends throughout all space. Thus even when the two bound states are separated by a large distance, there are long range Van-der-Waals forces between them.

In nonabelian QCD the color flux is confined to flux tubes within hadrons and is not determined completely by the positions of the particles. There is no color field nor Van-der-Waals force between separated hadrons.

Consider the case where the four particles in the reactions (2.2) and (2.3) are at the corners of a tetrahedron. The forces between the particles will depend upon the location of the flux tubes connecting them. In three-color QCD there are two equivalent ways of drawing the flux tubes, as each quark has two possible antiquarks with which it can be connected. In two-color QCD there are three equivalent ways of drawing the flux tubes, since the baryon-antibaryon configuration is also allowed. Thus in contrast to QED, the interactions are not completely determined by the positions of the particles with all necessary information about the field included in the static potential. Additional information about the field configuration is necessary, because the fields are not determined by the positions of the particles alone; there are several ways of drawing the flux tubes for a given configuration.

Attempts to express this additional degree of freedom using the color variable have had some apparent success in the four-body system.[10] The two ways of drawing the flux tubes have been placed in one-to-one correspondence with the two ways of coupling the colors of the quarks and antiquarks to make a color singlet. A "color-exchange" potential of the form (2.5) with color matrices replacing charges is a 2 X 2 matrix in color space and its eigenvectors can be interpreted as corresponding to the two ways of drawing flux tubes. However, this correspondence is a numerical accident occurring in the three-color-four-body system. With only two colors, there are three ways of drawing the flux tubes, including the "baryon-antibaryon" coupling (2.3), but the potential matrix is still only 2 x 2 in color space. A similar situation occurs in the six-quark baryon-baryon system with three colors, where the color matrix is 5 x 5, but there are 10 ways to draw flux tubes.

The new effects in multiquark configurations have been summarized in ref. 12. We list them briefly here:

A. Hidden-Color" and the Color Matrix. Multiquark systems contain pairs which are neither in color singlet nor color antitriplet states. The interactions in such hidden color states are not defined by eq. (1.1) and completely unknown, with no theoretical basis nor experimental information available. The color dependence no longer factorizes, since the colors of the constituents can be coupled in different ways to form an overall color singlet, and the Schroedinger equation is a nontrivial matrix equation in color space.

B. Breakup Decay Modes and Coupled Channels. A multiquark system is not confined and can break up into separated color singlet clusters. Multiquark dynamics involve coupled channels with the size of the S matrix determined by the number of ways in which asymptotic states can be defined as two color singlet clusters. This is particularly important for the H dibaryon which can break up into a $\Lambda\Lambda$ state.

C. Motion of Flux Tubes -- Flipping and Tunneling. The Coulomb fields of muonium and positronium spread out through all space, cancel exactly only when the proton and electron are exactly at the same point and give rise to long range power-law Van der Waals forces. The QCD color field is confined to flux tubes within hadrons and gives no long range interactions between hadrons. Forces between hadrons arise in QCD from the motion or flipping of flux tubes from one configuration to another through a domain of energetically less favorable configurations.[14,15] This motion is a tunneling process which gives an interaction decreasing exponentially with the distance between color singlet hadrons.

Any model with additive two-body interactions like (2.5) between hadron constituents gives power-law forces between separated hadrons, rather than exponentially decreasing forces, if it has confining forces within hadrons. Flux-tube physics can be introduced to give confining forces within clusters and no forces between clusters.[14,15] This requires defining how to draw flux tubes in the physically interesting domain where the distance between hadrons is comparable to the hadron size. Placing the flux tubes in the spatial configuration which has minimum energy for a given spatial configuration of the quarks implies instantaneous flipping of flux tubes each time the quarks move through a configuration where two flux tube configurations become degenerate.[14]

At very short range, one can imagine motion of the multiquark system in some kind of mean color field or bag which does not change violently as the quarks move. How to connect the well defined asymptotic states at large distances with a bag picture at short distances is not known. Uncertainties in what happens at intermediate range where flipping and tunneling occur have not been resolved, neither by theoretical derivations nor by experimental tests of phenomenological models. The physics resembles that of nuclear reactions, where a "compound nucleus" basis of states is used when all the particles are within a small volume, a basis of asymptotic states describes the breakup channels and there is no simple relation between the two bases. The P-matrix formalism of Jaffe and Low[16] follows the nuclear example.

Despite numerous attempts to include flux-tube dynamics, no treatment has yet made contact with either experimental data or rigorous theory.

3. THE SEARCH FOR MULTIQUARK BOUND STATES USING KNOWN HADRON PHYSICS

The experimental discovery of a convincing candidate for a multiquark bound state would be a significant breakthrough for our understanding of multiquark spectroscopy and of how QCD operates in mutiquark systems. So far no such states have been found, although the δ and S^* mesons are possible candidates[15,16] with insufficient experimental evidence either for or against. Theoretical predictions suggesting experimental searches for multiquark bound states are therefore of particular interest.

3.1 Two approaches to model-independent predictions.

Attempts to construct "nearly model-independent" bound multiquark wave functions whose properties can be reasonably well predicted from conventional hadron spectroscopy have been discussed in Refs. 12 and 13. Reliable estimates of multiquark binding are possible only when unknown hidden color contributions can be neglected. We note the following two approaches:

A. Hyperfine binding. The observation that hyperfine (color magnetic) energies are much larger than binding energies of multihadron states suggests that the energy difference between bound states and breakup channels in multiquark systems is dominated by the hyperfine interaction. This hyperfine dominance is expressed quantitatively by noting that the N-Δ mass difference $M(\Delta)-M(N)$ is much larger than the deuteron binding energy $M(n) + M(p) - M(d)$,

$$M(\Delta)-M(N) \gg M(n) + M(p) - M(d) \qquad (3.1)$$

B. Heavy Quark Binding. Hidden color interactions may also be negligible in systems like two heavy antiquarks and two light quarks. If the relative motion and structure of the two-heavy-antiquark wave function can be separated from the motion of the two light quarks relative to the heavy antidiquark, the four-body problem is then broken up into a two-body problem and a three-body problem with only color triplet and antitriplet two-body couplings.

3.2. Systems Dominated by the Hyperfine Interaction

3.2.1 Meson "Alpha-Particle" Configurations. The hyperfine energy has been calculated for systems of two quarks and two antiquarks in a spatially symmetric s-wave state with a radial wave function such that each pair has the relative radial dependence of a corresponding meson wave function. Such "alpha-particle" meson wave functions have been shown not to give bound multiquark states.[12,18]

3.2.4 Dibaryons and the H Dibaryon. The same approach applied to the six quark system shows that one of the most promising candidates for a bound multiquark state is the H dibaryon predicted by Jaffe[16] with strangeness -2 and spin zero. The recent suggestion connecting the H with Cygnus X3 events[19] requires it to be stable against the first-order-weak Λ-nucleon decay.

$$M(H) < M(\Lambda) + M(N). \qquad (3.2)$$

Thus

$$M(N) + M(\Xi) - M(H) > M(\Xi) - M(\Lambda) > M(\pi), \qquad (3.3)$$

and the mass of the H is below the threshold for pion production by stopped Ξ's in the reaction

$$\Xi + N \quad H + \pi . \tag{3.4}$$

The pion produced in the reaction (3.4) provides a distinctive signature against a very low background.[12] For stopped Ξ's or a low momentum Ξ beam below the conventional pion production threshold no other open channel can give prompt pion production.

Theoretical calculations[6] predict higher dibaryon states in an octet of SU(3) flavor including an (I=1, S=-2) Ξ-nucleon resonance which can decay into H-π. This resonance could enhance the cross section for the reaction (3.4), and also the reaction

$$K^- + d \rightarrow H^{*-} + K^+ \rightarrow H + K^+ + \pi^- \tag{3.5}$$

This reaction has been proposed[20] for an H search with the K^+ and π^- forming a K^{*0}. It is also of interest to look for the H^{*-}.

The inequality (3.2) increases the energy release and therefore reduces the cross section in the reaction suggested for producing the H in deuterium[20]

$$\Xi + d \rightarrow H + n. \tag{3.6}$$

In this reaction the momentum of the final neutron is generally believed to come from its Fermi momentum in the wave function of the initial deuteron state. The cross section is therefore suppressed for high values of the neutron momentum by a deuteron form factor at the nucleon (not quark) level. It might be of interest to cover the low H-mass region in this experiment by looking for the reactions

$$\Xi^- + d \rightarrow H + n + \pi^0 \tag{3.7}$$

$$\Xi^- + d \rightarrow H + p + \pi^- . \tag{3.8}$$

No convincing theoretical argument places the mass of the H either above or below the N-Λ threshold. Searches for this particle have so far been inconclusive and the question is still open. Experiments including both a pion detector sensitive to the reactions (3.4), (3.7) or (3.8) as well as a neutron detector sensitive to the reaction (3.6) can detect the H over a wide mass range.

3.2.2 Baryon "Alpha-Particle" Configurations. Consider the system of twelve nonstrange quarks in a spatially symmetric s-wave state with a radial wave function such that each pair has the relative radial dependence of a quark pair in the nucleon wave function. This configuration has the spin, isospin and baryon number quantum numbers of an alpha particle, but does not describe the physical alpha particle. This "closed-shell" configuration has been shown[12] to have the color-spin couplings of four Δ's with a high hyperfine energy, of the order of four times the N-Δ splitting. This high energy could be the source of the repulsive core in the nucleon-nucleon force as discussed below.

3.2.3 Meson "Deuteron-like" Configurations. Meson-meson states can be loosely bound by short-range interactions barely strong enough to bind a single state with tails in the wave functions going beyond the range of the potential as in simple models of the deuteron. Qualitative predictions for such states indicate that the δ and S^* mesons might indeed be $K\bar{K}$ bound states.[17,18]

3.3 Heavy Diquark Meson Configurations.

In systems containing heavy quarks the hyperfine interaction is much lower and no longer dominates completely over the color electric interaction. The higher mass particles are allowed by the uncertainty principle to come much closer together than light quark pairs, and therefore to be much deeper in the coulomb-like potential at short distances. In such systems the color-electric force also becomes important in binding.[12,13,21]

The first states where color-electric binding may be important are configurations with two light quarks and two heavy antiquarks; e.g. $(ud\bar{c}\bar{c})$. Because the two heavy particles both have the same baryon number, either both quarks or both antiquarks, the allowed breakup channels have the two in separated mesons. Thus the additional binding produced by the possibility of having them very close together increases stability against breakup.

The masses of such states can be estimated from the masses of known hadrons, and indicate that an axial vector $(ud\bar{c}\bar{c})$ meson is on the bordeline of stability, while the $(ud\bar{b}\bar{b})$ state is found to be stable against strong decays. The experimental production and detection of such states appears to be very difficult.

4. THE QUARK APPROACH TO BARYON-BARYON INTERACTIONS

The interactions between nucleons are generally described as a short-range repulsive core, an intermediate range attraction, and a long range tail attributed to one-pion exchange. Attempts to obtain these properties from a more fundamental quark picture have focused primarily on the short range repulsion, explained as an effect of the Pauli principle. The intermediate range attraction might be attributed to gluon exchanges. The pion exchange is generally put in by hand at this stage, since there does not seem to be any hope of describing this part of the interaction before QCD provides a good description from first principles of the pion and its emission and absorption. Most treatments assume certain specific models and obtain results by detailed calculations. We examine here some normally overlooked simple and general results which are model-independent and follow from symmetry principles.

Consider a system of six nonstrange quarks at very short distances, with a wave function totally symmetric in space and having a finite value when all six quarks are at the same space point. The allowed color singlet states for six nonstrange quarks with this space symmetry have the following spin-isospin quantum numbers:

(I=3;S=0) and (I=0;S=3).	These quantum numbers occur in the Δ-Δ system.
(I=2;S=1) and (I=1;S=2).	These quantum numbers occur in the Δ-Δ and Δ-N systems.
(I=1;S=0) and (I=0;S=1).	These quantum numbers occur in the Δ-Δ and N-N systems.

States with the following quantum numbers do not occur:

(I=3;S=2) and (I=2;S=3) found in the Δ-Δ system.
(I=2;S=2) and (I=1;S=1) found in the Δ-N system.

The following states which are not found in any dibaryon system also do not occur:

(I=3;S=3), (I=3;S=1), (I=1;S=3) and (I=0;S=0).

From these results the following general conclusions can be drawn:

1. No states allowed for the six-quark system are forbidden for the dibaryon system. Thus there are no exotic six-quark states at short distances with quantum numbers forbidden for a dibaryon system and no bound states of quarks at short distances which are forbidden by known selection rules to couple to the dibaryon system.

2. The four "exotic" states (I=3;S=3), (I=3;S=1), (I=1;S=3) and (I=0;S=0), which are not found at short distances and do not occur for asymptotic dibaryon systems have quantum numbers which would occur in the Δ-Δ and/or nucleon-nucleon systems if they were not equivalent fermions, but are forbidden by the Pauli principle at the baryon level. These states therefore play no role in dibaryon physics.

3. The states (I=3;S=2) and (I=2;S=3) which are allowed for the Δ-Δ system and the states (I=2;S=2) and (I=1;S=1) which are allowed for the Δ-nucleon system are not allowed states for six quarks at short distances. These states would not be Pauli forbidden if the Δ and nucleon were elementary fermions. However, they are forbidden at short distances for composite baryons made of the same quarks, as the Pauli principle forbids placing two quarks with the same quantum numbers in a spatially symmetric state.

For example, a Δ-Δ state with charge +3, spin 2 and spin projection +2 on the z-axis is a perfectly good state for two elementary Δ's. One can be in a spin state with m=3/2 and the other with m=1/2. However, if each Δ is made of three u-quarks, the m=2 Δ-Δ state has four u-quarks with spin up and two with spin down. Since there are only three colors, the Pauli principle forbids the four u-quarks with parallel spins from being in a symmetric spatial state. Similar arguments hold for the other states allowed by Pauli for two elementary baryons and forbidden for six quarks. These dibaryon states must always see a repulsive core in any phenomenological description at the baryon level, independent of the dynamical interactions between the baryons.

4. The states (I=3;S=0) and (I=0;S=3) allowed for the six quark system and having only one allowed dibaryon state; namely Δ-Δ, have exactly the same spin-isospin couplings both at short range and as asymptotic states. There is no effective repulsion due to the Pauli principle at short distances because these six-quark states have no pair of quarks with the same quantum numbers. For example the Δ-Δ system with charge 3, with one Δ having m=3/2 and the other m=-3/2, is simply a color singlet state of three u-quarks with "spin up" and a color singlet state of three u-quarks with "spin down". This state of the Δ-Δ system feels no repulsive core due to Pauli effects. Thus a relatively weak attractive interaction at short range might produce binding. These channels offer the best candidates for possible bound dibaryons.

5. The remaining states (I=2;S=1) and (I=1;S=2), allowed for the Δ-Δ and Δ-N systems, and (I=1;S=0) and (I=0;S=1), allowed for the Δ-Δ and N-N systems, each have two allowed asymptotic dibaryon states but only a single allowed six-quark state at short distances. Here there is a complicated interplay of the Pauli principle and dynamics. Consider the nucleon-nucleon state with I=0;S=1, m=1; i.e. the quantum numbers of a deuteron with spin up. Each nucleon has m=1/2. The proton has a piece in its wave function with both u-quarks in a state with m=1/2. The neutron has a piece in its wave function in which the u-quark is in a state with m=1/2. The six-quark description of this asymptotic dibaryon state thus has a piece in its wave function with three u-quarks all having m=+1/2. When the two nucleons are very close together, the Pauli principle allows these three u-quarks to be at the same point only if they are in the antisymmetric color singlet state. But the u quark in the neutron is coupled to a color singlet with the two d-quarks in the neutron and has no color correlation with the two u-quarks in the proton. Thus this piece of the wave function has the three u-quarks in a mixture of color singlet and color octet states, with the probability of color singlet being only 1/9. Thus we see that when the two nucleons come close together, only certain pieces of the wave function are allowed; other pieces are forbidden or "Pauli blocked". The same is true for the Δ-Δ system with these quantum numbers.

The two channels are therefore necessarily coupled at short distances. If the dynamics allow the two baryon clusters to come close enough together to remove the "Pauli-blocked" pieces of the asymptotic wave function, the remaining wave function must have both nucleon-nucleon and Δ-Δ components and there will be transitions between these two asymptotic states as a result of the "wave-function-rearrangement" imposed by the Pauli principle at the quark level.

A repulsive core in the nucleon-nucleon interaction can be produced by combining the Pauli blocking effect with the hyperfine interaction dominant at short distances. Two nucleons can be pushed together so that their constituent quark wave functions overlap only by modifying the wave function to exclude the Pauli-blocked pieces. This automatically introduces a Δ-Δ component which has a higher interaction energy by at least twice the nucleon-Δ mass splitting. The contribution of this Δ-Δ energy to the total energy depends upon the volume in which this component of the wave function exists. This volume cannot be made arbitrarily small, even though the Pauli-blocking occurs only when the two particles are at the same point, because the Heisenberg uncertainty principle prevents the Δ-Δ piece of the wave function from being confined to a small volume without paying a large price in kinetic energy. This combination of statistics, hyperfine interactions and kinetic energy has been called the "Pauli-Fermi-Heisenberg" repulsive core and may be quantitatively responsible for the observed repulsion in nucleon-nucleon interactions.

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