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Description of the H Dibaryon in Terms of a First-Order Hexaquark Mass Formula

JJ Bevelacqua
Bevelacqua Resources, 7531 Flint Crossing Circle SE, Owens Cross Roads, AL 35763, United States of America

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Corresponding Author: **JJ Bevelacqua**

Abstract
The H dibaryon is modeled as a ΛΛ state in terms of a first-order hexaquark mass formula. Λ baryon masses are determined from the mass formula of Zel'dovich and Sakharov.
The H dibaryon mass is determined to be 2602 MeV/c^2. This predicted value is about 10-20% larger than the various experimental values. This state is predicted to have J^{π} values of 0^+ and 1^+. A 0^+ H baryon assignment is predicted by analysis of experimental data.
The predicted mass of the H baryon state provides a crucial test of the validity of the proposed first-order mass formula and its weak coupling structure. Moreover, this mass formula provides a general framework to calculate hexaquark masses.

Keywords: Hexaquark Mass Formula, H Baryon, Quark Model, and Cluster Model

1. Introduction
Multiquark systems are of interest from both experimental and theoretical perspectives. This paper investigates the H baryon in terms of a ΛΛ hexaquark system.

1.1 History of Multiquark Systems
The possibility that hadrons could exist with structures beyond conventional qq or qqq quark configurations was noted by Gell-Mann [1]. Previous searches of multiquark systems have appeared, but some were later invalidated following additional analysis [2]. However, a sample of experimental work suggests the existence of both tetraquark [3-5] and pentaquark [6] structures. These studies open the possibility of additional exotic quark structures [7].
Given the existence of tetraquark and pentaquark structures, it is possible that more complex quark configurations exist. These configurations would include hexaquarks and these structures are considered in this paper. These multiquark states are of theoretical and experimental interest and merit attention.
Although no definitive hexaquark states have been confirmed, experimental effort is suggestive of possible hexaquark configurations [8-10]. These possible hexaquark states arise from interpretation of baryon-baryon resonances.
The first possible hexaquark candidate was observed in exclusive and kinematically complete measurements [8, 9] of the fusion reactions p n → d π^0 π^0 and p n → d π^+ π^- that revealed a narrow resonance-like structure in the total cross section at a mass ≈ 2380 MeV/c^2 with a width ≈ 70 MeV/c^2. Additional evidence for this structure has been found in the p n → p p π^0 π^- reaction. This possible state has been interpreted as a **ΔΔ** dibaryon hexaquark state [8, 9].
Although not confirmed as a second candidate hexaquark state, the BESIII Collaboration [10] suggests the existence of a possible p p-bar hexaquark resonance structure by studying the reaction J/Ψ → γ η′ π^+ π^-. Two models were utilized to characterize the η′ π^+ π^- line shape around 1.85 GeV/c^2. One model explicitly incorporates the opening of a decay threshold in the mass spectrum, and another uses a coherent sum of two resonant amplitudes. Both fits reproduce the data with good agreement, and suggest the existence of either a broad state around 1.85 GeV/c^2 with strong couplings to the p p-bar final states or a narrow state just below the p p-bar mass threshold. The models suggest either a p p-bar molecular state or bound state with greater than 7σ significance.
Previous theoretical studies investigated a limited set of hexaquark candidates based primarily on combinations of baryon structures. Theoretical studies include a (1) chiral constituent quark model [11], (2) baryon-antibaryon resonance model using a chromomagnetic interaction [12], (3) dispersion relation technique [13], (4) string model using the strong coupling regime of quantum chromodynamics [14], and (5) coupled channels resonating group method [15]. The theoretical calculations were limited in scope to a small set of quark configurations in these studies (i.e., uuddsQ systems (Q = c or b) [11], q q q q-bar q-bar q-bar systems [12], dibaryon resonances based on u, d, and s quarks [13], systems based on a light quark (q) with unit mass (m) and a

heavy quark (Q) with a mass of m, 2m, 3m, 4m, and 5m with q^3Q^3 and q-bar^3 Q^3 configurations [14], and only u and d quark systems [15]).

1.2 Current H Dibaryon Study

As noted in Ref. 16, observations by gravitational wave detectors provide new information regarding the structure of neutron stars. Theoretical predictions are complicated by our lack of data regarding matter at the extreme densities that can be encountered in these stars. In addition to the expected particles (e.g., neutrons, protons, electrons and muons), hyperons and exotic particles such as dibaryons could exist in neutron stars. Given the extreme densities is also possible that the cores of the heavier stars could contain deconfined quarks and gluons [16].

Leong *et al* [16] investigated the equation of state for dense nuclear matter in β equilibrium as a vehicle to explore the possibility of a doubly strange dibaryon H particle. Consistent with experimental constraints, the mass of the H dibaryon in free space is taken to be near the ΛΛ threshold. The H dibaryon was originally described by Jaffe [17, 18] suggesting a 0^+ assignment with a mass of 2150 MeV/c^2. Ref. 16 suggests a mass in the range of 2247 – 2269 MeV/c^2. The H dibaryon with spin and isospin zero, baryon number 2 and strangeness −2 was first proposed in 1977 as a deeply bound, exotic six-quark bag [17, 18]. Ref. 16 also proposes an H* baryon with a mass 2335 MeV/c^2.

In this paper, the H dibaryon is investigated using a first-order mass formula that was previously used to examine tetraquark [19-29], pentaquark [30], and hexaquark and other exotic quark configurations [31]. The model's extension to the H dibaryon is a logical extension of previous efforts. In particular, the H dibaryon is assumed to be comprised of two weakly coupled Λ baryon structures.

2. Model Formulation

Zel'dovich and Sakharov [32, 33] proposed a semiempirical mass formula that provides a prediction of mesons and baryons in terms of effective quark masses. Within this formulation, quark wave functions are assumed to reside in their lowest 1S state. These mass formulas are used as the basis for deriving a first-order hexaquark mass formula. In particular, the model utilized in this paper assumes the hexaquark is partitioned into two baryon clusters with the interaction between the clusters providing a minimal contribution to the mass. In addition, zero angular momentum is assumed to exist between the clusters.

The baryon (b) mass (M) formula of Refs. 32 and 33 is:

$$M_b = \delta_b + m_1 + m_2 + m_3 + \frac{b_b}{3}\left(\frac{m_o^2}{m_1 m_2}\sigma_1 \cdot \sigma_2 + \frac{m_o^2}{m_1 m_3}\sigma_1 \cdot \sigma_3 + \frac{m_o^2}{m_2 m_3}\sigma_2 \cdot \sigma_3\right) \quad (1)$$

Where m_i labels the three baryon quarks (i = 1, 2, and 3) and δ_b and b_b are 230 MeV and 615 MeV, respectively [33]. In Eq. (1), m_1, m_2, and m_3 are the mass of the first, second, and third quark comprising the baryon, m_o is the average mass of first generation quarks [2, 34], and the σ_i (i = 1, 2, and 3) are the spin vectors for the quarks incorporated into the baryon.

In Eq. 1, the values of $\sigma_i \cdot \sigma_j$ depend on the baryon spin. For a J = 3/2 baryon, $\sigma_i \cdot \sigma_j$ has the value 1/4. If the total baryon spin is 1/2 and it has two *identical* quarks q_2 and q_3, the values of $\sigma_i \cdot \sigma_j$ are $\sigma_2 \cdot \sigma_3 = 1/4$ and $\sigma_1 \cdot \sigma_2 = \sigma_1 \cdot \sigma_3 = -1/2$. If the baryon contains three different quarks, then the values of $\sigma_i \cdot \sigma_j$ are defined by the methodology of Refs. 32 and 33.

The first-order mass formula assumes that the baryon resides in its ground state, and there is zero angular momentum between the quarks. If excited states are involved, the difference in masses between the excited and ground states must be considered.

In formulating the hexaquark mass formula, effective quark masses provided by Griffiths [34] are utilized. The effective masses for d, u, s, c, b, and t quarks are 340, 336, 486, 1550, 4730, and 177000 MeV/c^2, respectively. These masses are utilized in Eq. 1.

These six quarks are arranged in three generations: [d(-1/3 e), u(+2/3 e)], [s(-1/3 e), c(+2/3 e)], and [b(-1/3 e), t(+2/3 e)] [2,34]. The three generations are specified by the square brackets and the quark charges (in terms of the unit charge e) are given within parentheses.

The first-order mass formula used in this paper partitions the H dibaryon into two Λ baryon clusters. The weak coupling structure is incorporated to minimize model complexity, which is consistent with an initial first-order formulation. In addition, the dibaryon mass formula is assumed to have the following form for the H mass (M_H) coupling:

$$\mathbf{M_H = M_\Lambda(1) + M_\Lambda(2) + \Phi} \quad (2)$$

Where $\mathbf{\Phi}$ defines the interaction between the two Λ baryon clusters designated by i = 1, 2. Within the scope of this mass formula, the baryon-baryon cluster interaction is assumed to be sufficiently small, relative to the cluster masses, to be ignored. Accordingly, Eq. 2 represents a quasimolecular six quark system whose basic character is a weakly bound baryon-baryon system.

The mass relationships of Eqs. 1 and 2 do not uniquely predict the total angular momentum of the final hexaquark state, but do permit spin coupling to be specified for the individual baryon clusters. In addition, the angular momentum between the clusters is assumed to be zero. Specific angular momentum assignments based on the first-order mass formula for the hexaquark states are provided in subsequent discussion.

3. Weak Coupling Approximation

The weak coupling approximation is based on fundamental quantum chromodynamics (QCD) arguments [35, 36]. One boson exchange as well as lattice gauge calculations provide numerical simulation results that support these QCD arguments [35, 36].

In addition, the quark charges are related to the number of colors (N_c) incorporated into the QCD formulation [35, 36]. For example, the first generation quark charges within SU(N_c) are:

$$Q_d = \frac{1}{2}\left(\frac{1}{N_c} - 1\right) \tag{3}$$

$$Q_u = \frac{1}{2}\left(\frac{1}{N_c} + 1\right) \tag{4}$$

For conventional QCD using 3 colors, the expected d and u electric charges are obtained. The importance of QCD expansions involving $1/N_c$ is outlined in this section to illustrate the basis for the weak coupling assumption.

A key assumption of the first-order mass formula of Eq. 2 is weak coupling between the two clusters. In particular, the model utilized in this paper assumes the hexaquark is partitioned into two clusters with the interaction between the clusters providing a minimal contribution to the hexaquark mass. Within the scope of this mass formula, the cluster-cluster interaction is assumed in Eqs. 1 and 2 to be weak, and sufficiently small to be ignored.

This assumption is justified because QCD can be formulated as an expansion in $1/N_c$ [37, 38]. The large N_c limit reduces to a field theory of weakly interacting meson-like objects. The physical situation with $N_c = 3$ retains many of the characteristics of the $N_c \rightarrow \infty$ limit, and further justifies the weak coupling approximation.

The $1/N_c$ expansion [37, 38] is well accepted in elementary particle physics and leads to the Okubo-Zweig-Iizuka (OZI) rule [39-41] and the Skyrme model [42, 43]. In addition, the $1/N_c$ expansion in QCD reduces to a weakly interacting meson theory, and the meson-meson and associated cluster-cluster interactions are regarded to be small [37, 38]. This situation is also a characteristic of Eqs. 1 and 2.

4. Results and Discussion

The model results address the description of ΛΛ dibaryon state in terms of a first-order hexaquark mass formula. Λ baryon masses are determined from the basic mass formula of Eq. 1. The dibaryon mass, modeled in terms of a first-order hexaquark mass formula, is provided by Eq. 2.

4.1 H Baryon Spin and Parity

The spin and parity of the H dibaryon is limited by the first order model that assumes zero angular momentum between the clusters:

$$J^{\pi}(H) = J^{\pi}(\Lambda) \otimes 0 \otimes J^{\pi}(\Lambda) \tag{5}$$

Since the Λ has $J^{\pi} = 1/2^{+}$, the H dibaryon can assume either 0^{+} or 1^{+} values. The 0^{+} value is agreement with experiment [16-18].

4.2 H Baryon Mass

The H dibaryon mass value, as predicted by the first-order model, is derived from Eqs. 1 and 2. Table 1 summarizes the model results and values from Refs. 16 and 17.

Table 1: Comparison of H Baryon Characteristics

State	J^{π}	Mass (MeV/c^2)	Reference
H	0^{+}	2150	17
H	0^{+}	2247-2269	16
H^{*}	1^{+}	2335	17
H	0^{+}, 1^{+}	2602	This Work

The first order methodology [32, 33] leads to a predicted mass of 2602 MeV/c^2. This value is about 10-20% larger than the various experimental values [16, 17]. These results are less accurate than previous first-order model calculations [19-31].

5. Model Uncertainties and Weaknesses

Although the first-order mass approach provides reasonable results in the description of tetraquark [19-29], pentaquark [30], and hexaquark and other exotic quark configurations [31], it has a number of uncertainties and weaknesses. These include:

1. The quark masses are model dependent and can assume a range of values [2, 34].
2. The cluster-cluster interaction is not definitively known. Although it is small relative to the combined cluster masses forming a tetraquark, pentaquark, or hexaquark, its value has not been well established. However, fundamental QCD arguments, one boson exchange calculations, QCD calculations, and quark model calculations suggest the cluster-cluster interaction is essentially negligible relative to the individual cluster masses.
3. The angular momentum coupling structure is primitive. Hexaquark angular momentum is defined by the individual cluster J^{π} values, but zero angular momentum is assumed between the clusters. This approach allows a range of J^{π} values, but does not define a definitive angular momentum configuration.
4. Limited quark-quark effects are allowed in Eq. 1. There is no consideration of higher order quark or gluon influenced terms.

6. Conclusions

Model results address the description of the ΛΛ dibaryon state in terms of a first-order hexaquark mass formula. Λ baryon masses are determined from the basic mass formula of Eq. 1. The dibaryon mass, modeled in terms of a first-order hexaquark mass formula, is provided by Eq. 2.

ΛΛ dibaryon masses in terms of a first-order hexaquark mass formula are determined to be 2602 MeV/c^2. This predicted value is about 10-20% larger than the various experimental results. The model states are predicted to have J^{π} values of 0^+ and 1^+. A 0^+assignment is predicted in Refs. 16 and 17.

The predicted mass of the H baryon state provides a crucial test of the validity of the proposed first-order mass formula and its weak coupling structure. Moreover, this mass formula provides a general framework to calculate hexaquark masses.

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