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Possible Description of the J/Ψ Λ Structure at 4338.2 MeV in Terms of a First-Order Pentaquark Mass Formula

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Abstract

A recently proposed $J^{\pi} = 1/2^{-}$, J/Ψ Λ ($P^{\Lambda}_{\Psi s}$) pentaquark structure at 4338.2 MeV/c^2 is investigated using a first-order mass formula. This mass relationship is based on weakly bound meson plus baryon clusters, and provides a reasonable prediction (within about 1%) of the proposed pentaquark mass. The first order mass formula model predicts possible $J^{\pi} = 1/2^{-}$ and $3/2^{-}$ assignments for the $P^{\Lambda}_{\Psi s}$.

1.0 Introduction

The possibility that hadrons could exist with structures beyond conventional qq or qqq quark configurations was noted by Gell-Mann[1]. These structures have been observed with the most recent example noted by the LHCb Collaboration[2,3].

In Refs. 2 and 3, the LHCb Collaboration reported an analysis of $B^{-} \rightarrow J/\Psi\Lambda$ p-bar decays. The analyses of Refs. 2 and 3 suggest the first pentaquark containing an s quark and the first with $J^{\pi} = 1/2^{-}$. This proposed $P^{\Lambda}_{\Psi s}$ pentaquark has a c c-bar u d s content with a mass[3] of 4338.2 ± 0.7 ± 0.4 MeV/c^2.

This paper investigates the recently proposed $P^{\Lambda}_{\Psi s}$ pentaquark structure using a first-order mass formula. The proposed methodology was previously used to examine tetraquark[4-14], pentaquark[15,16], and hexaquark and other exotic quark configurations[17,18].

2.0 Model Formulation

Zel'dovich and Sakharov[19,20] proposed a semiempirical mass formula that provides a prediction of mesons and baryons masses in terms of effective quark masses. Within this formulation, quark wave functions are assumed to reside in their lowest s state. These mass formulas are used as the basis for deriving a first-order pentaquark mass formula. In particular, the model proposed in this paper assumes the pentaquark is partitioned between two and three quark clusters with the interaction between the clusters providing a minimal contribution to the pentaquark mass.

The meson (m) mass (M) formula of Refs 19 and 20 is:

$$M_m = \delta_m + m_1 + m_2 + b_m \left[\frac{m_0^2}{m_1 m_2} \sigma_1 \cdot \sigma_2 \right] (1)$$

where m_1 (m_2) are the mass of the first (second) quark comprising the meson, m_0 is the average mass of a first generation quark[21,22], and the σ_i (i = 1 and 2) are the spin vectors for the quarks incorporated into the meson. The parameters δ_m and b_m are 40 MeV and 615 MeV, respectively[20].

The last term in Eq. 1 represents the spin-spin interaction of the quarks and $\boldsymbol{\sigma_1 \cdot \sigma_2}$ is the scalar product of the quark spin vectors. $\boldsymbol{\sigma_1 \cdot \sigma_2}$ has the value -3/4, +1/4 for pseudoscalar and vector mesons, respectively.

In a similar manner, the baryon (b) mass formula[19,20] is:

$$M_b = \delta_b + m_1 + m_2 + m_3 + Z \quad (2a)$$

$$Z = \frac{b_b}{3}\left[\frac{m_0^2}{m_1 m_2}\sigma_1 \cdot \sigma_2 + \frac{m_0^2}{m_1 m_3}\sigma_1 \cdot \sigma_3 + \frac{m_0^2}{m_2 m_3}\sigma_2 \cdot \sigma_3\right] \quad (2b)$$

where the 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[20]. For a particle with a total baryon spin 1/2, the following prescription is used if the baryon (comprised of three quarks q_1, q_2, and q_3) contains two identical quarks[20] q_2 and q_3

$$\boldsymbol{\sigma_2 \cdot \sigma_3 = 1/4} \quad (3)$$

$$\boldsymbol{\sigma_1 \cdot \sigma_2 = \sigma_1 \cdot \sigma_3 = -1/2} \quad (4)$$

For completeness, the reader should note that $q \cdot \sigma_j$ has the value +1/4 for a J= 3/2 baryon.

These basic $q_i \cdot \sigma_j$ relationships must be modified if the baryon contains three different quarks. This modified approach must be applied to the lambda baryon that consists of u d and s quarks. The methodology is detailed, and described in Ref. 20.

In formulating the pentaquark mass formula, effective quark masses provided by Griffiths[21] are utilized. These 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 Eqs. 1 and 2.

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(-1/3e), t(+2/3 e)][22]. The three generations are specified by the square brackets and the quark charges are given within parenthesis in terms of the proton charge e.

The first-order mass formula used in this paper partitions the pentaquark into two clusters. The first cluster is a meson and the remaining cluster is a baryon. Zero angular momentum is assumed between the two clusters. These simplifications are incorporated to minimize model complexity that is consistent with an initial first-order formulation. In addition, the pentaquark mass formula (M) is assumed to have the form:

$$\mathbf{M = M_m + M_b + \Phi} \quad (5)$$

where Φ defines the interaction between the meson and baryon clusters. Within the scope of this mass formula, the meson-baryon cluster interaction is assumed to be weak and sufficiently small to be ignored. Accordingly, Eq. 5 represents a quasimolecular five quark system whose basic character is a weakly bound meson-baryon system. In the case of the J/Ψ Λ pentaquark system, the first cluster is a J/Ψ meson and the remaining cluster is a Λ baryon.

The mass formula of Eq. 5 does not uniquely predict the total angular momentum of the pentaquark state, but does permit spin coupling to be specified for the individual meson and baryon clusters. In addition, the angular momentum between the clusters is assumed to be zero.

3.0 Results and Discussion

Eq. 5 is used to calculate the mass of the J/Ψ Λ pentaquark. The first-order-mass formula predicts the J/Ψ Λ pentaquark has a mass of 4374.1 MeV/c^2. This prediction is about 0.8% larger than the measured value of 4338.2 MeV/c^2.

The first-order mass formula also predicts J^π values for the proposed J/Ψ Λ pentaquark. However, the angular momentum coupling structure of the first-order mass formula approach is somewhat primitive since the angular momentum between the clusters is limited to zero. The values are determined by the angular momentum coupling structure of the J/Ψ (1^-) and lambda ($1/2^+$) imposed by the first-order mass formula

$$\mathbf{1^- \times 0 \times 1/2^+ = 1/2^-, 3/2^-} \quad (6)$$

The $1/2^-$ value is in agreement with the proposed value of Refs. 2 and 3.

4.0 Conclusions

The recently proposed J/Ψ Λ pentaquark structure is investigated using a first-order mass formula incorporating weakly interacting meson plus baryon clusters. A first-order mass formula predicts a $P^{\Lambda}_{\Psi s}$ pentaquark state having a mass of 4374.1 MeV/c^2. This prediction is about 0.8% larger than the measured value of 4338.2 MeV/c^2. The model predicts J^π values of $1/2^-$ and $3/2^-$. The $1/2^-$ value is in agreement with Refs. 2 and 3. However, the model's primitive angular momentum coupling structure does not distinguish between these values.

References

1) M. Gell-Mann, Phys. Lett. **8**, 214 (1964).

2) LHCb Collaboration results reported at the 41st International Conference on High Energy Physics (ICHEP 2022). 6-13 July 2022. Bologna, Italy (2022).

3) E. S. Norella and C.Chen, Particle Zoo 2.0: New Tetra- and Pentaquarks at LHCb: On behalf of the LHCb collaboration, CERN Seminar 5th July, 2022.

4) J. J. Bevelacqua, First-Order Tetraquark Mass Formula, Physics Essays **29**, 198 (2016).

5) J. J. Bevelacqua, Description of the X(5568) and Proposed 750 GeV/c^2 State in Terms of a First-Order Tetraquark Mass Formula, Physics Essays **29**, 367 (2016).

6) J. J. Bevelacqua, Fusion of doubly heavy mesons into a tetraquark, Physics Essays **31**, 167 (2018).

7) J. J. Bevelacqua, Possible Tetraquark Explanation for the Proposed X(3872), Physics Essays **32**, 469 (2019).

8) J. J. Bevelacqua, Description of the X(6900) as a Four Charmed Quark State in Terms of a First-Order Tetraquark Mass Formula, QEIOS **KLXLKJ**, 1 (2020).
https://doi.org/10.32388/KLXLKJ.

9) J. J. Bevelacqua, Description of the X(2900) as an Open Flavor Tetraquark in Terms of a First-Order Mass Formula, QEIOS **OVLMEB**, 1 (2020).
https://doi.org/10.32388/OVLMEB.

10) J. J. Bevelacqua, Possible Tetraquark Explanation for the Proposed $Z_{cs}(3985)^-$, QEIOS **GLTEU2**, 1 (2021).
https://doi.org/10.32388/GLTEU2.

11) J. J. Bevelacqua, Possible Tetraquark Explanation for the X(6200), QEIOS**J6AFYW**, 1 (2021). https://doi.org/10.32388/J6AFYW.

12) J. J. Bevelacqua, Possible Tetraquark Explanation for the T_{cc}^{+}, QEIOS **OMDGAQ**, 1 (2021). https://doi.org/10.32388/OMDGAQ.

13) J. J. Bevelacqua, Possible Tetraquark Explanation for the Proposed $Z_{cs}(4000)^{+}$ and $Z_{cs}(4220)^{+}$, QEIOS **PPLMWV**, 1 (2021). https://doi.org/10.32388/PPLMWV.

14) J. J. Bevelacqua, Possible Tetraquark Explanations for the Proposed X(4630) and X(4685), QEIOS. **7EGF85**, 1 (2021). https://doi.org/10.32388/7EGF85.

15) J. J. Bevelacqua, First-Order Pentaquark Mass Formula, Physics Essays**29**, 107 (2016).

16) J. J. Bevelacqua, Possible Description of the J/Ψ p and J/Ψ p-bar Structures in Terms of a First-Order Pentaquark Mass Formula, QEIOS **6KVPY6**, 1 (2022). https://doi.org/10.32388/6KVPY6

17) J. J. Bevelacqua, Description of Selected Hexaquark States in Terms of a First-Order Mass Formula, Physics Essays **31** (1), 104 (2018).

18) J. J. Bevelacqua, Description of ΩΩ, $\Omega_{ccc}\Omega_{ccc}$, and $\Omega_{bbb}\Omega_{bbb}$ Dibaryon States in Terms of a First-Order Hexaquark Mass Formula, QEIOS**27N2QF**, 1 (2022). https://doi.org/10.32388/27N2QF.

19) Ya. B. Zel'dovich and A. D. Sakharov,*Kvarkovaia struktura i massy sil'novzaimodeistvuyushchikh chastits*, Yad. Fiz. **4**, 395 (1966).

20) A. D. Sakharov, Mass formula for mesons and baryons, Sov. Phys. JETP**51**, 1059 (1980).

21) D. Griffiths, *Introduction to Elementary Particles*, 2nd ed., (Wiley-VCH, Weinheim, 2008).

22) Particle Data Group, Review of Particle Physics, Prog. Theor. Exp. Phys.**2020**, 083C01 (2020).