Open Peer Review on Qeios

Possible Description of the J/Ψ p and J/Ψ p-bar Structures in Terms of a First-Order Pentaquark Mass Formula

Joseph Bevelacqua

Funding: The author(s) received no specific funding for this work.

Potential competing interests: The author(s) declared that no potential competing interests exist.

Abstract

Recently proposed J/Ψ p and J/Ψ p-bar pentaquark structures are investigated using a first-order mass formula. This mass relationship is based on weakly bound meson plus baryon clusters and provides a reasonable prediction of the proposed pentaquark masses.

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].

In Ref. 2, the LHCb Collaboration published an amplitude analysis of flavor-untagged B^0_s → J/Ψ p p-bar decays using a sample of 797 ± 31 events reconstructed with the LHCb detector. The data suggests a new structure in the J/Ψ p and J/Ψ p-bar systems with a mass of 4337 MeV/c^2. The statistical significance depends on the assigned J^π values in the range of 3.1 to 3.7 σ for the $1/2^+$ and $3/2^+$ assignments, respectively. Although negative parity states were considered (i.e., $1/2^-$ and $3/2^-$), the analysis of Ref. 2 favored the positive parity assignments. In view of the limited sample size, Ref. 2 notes that it is not possible to definitively distinguish between different J^π quantum numbers. Even though the results of Ref. 2 fall below the accepted 5 σ value for establishing a new pentaquark, the proposed state merits additional investigation.

This paper investigates the recently proposed J/Ψ p and J/Ψ p-bar pentaquark structures using a first-order mass formula. The proposed methodology was previously used to examine tetraquark[3-13], pentaquark[14], and hexaquark and other exotic quark configurations[15,16].

2.0 Model Formulation

Zel'dovich and Sakharov[17,18] 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. 17 and 18 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[19,20], 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[18].

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

In a similar manner, the baryon (b) mass formula[17,18] is:

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

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

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[18]. 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[18] q_2, and q_3

$\sigma_2 \cdot \sigma_3 = 1/4$ (3)

$\sigma_1 \cdot \sigma_2 = \sigma_1 \cdot \sigma_3 = -1/2$ (4)

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

In formulating the pentaquark mass formula, effective quark masses provided by Griffiths[19] 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)][20]. 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:

$M = M_m + M_b + \Phi$ (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 p and J/Ψ p-bar pentaquark systems, the first cluster is a J/Ψ meson and the remaining cluster is a J = 1/2 baryon (i.e., a proton or antiproton).

This 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 p and J/Ψ p-bar pentaquarks. Since antiquark masses and spins are identical, both pentaquarks have the same mass and angular momentum.

The first-order-mass formula predicts J/Ψ p and J/Ψ p-bar pentaquarks have a mass of 4236 MeV/c^2. This prediction is about 2.3% smaller than the measured value of 4337 MeV/c^2.

The first-order mass formula also predicts the J^π values for the proposed J/Ψ p and J/Ψ p-bar pentaquarks. The values are determined by the angular momentum coupling structure of the J/Ψ and proton imposed by the first-order mass formula

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

The J values are in agreement with the proposed values of Ref. 2, but the parity values are reversed. Ref. 2 assumes a p-wave state that reverses the parity. Given the significance of the proposed pentaquarks that are in the range of 3.1 – 3.7 σ, both the mass and J^π values are not definitively established[2].

4.0 Conclusions

Recently proposed J/Ψ p and J/Ψ p-bar pentaquark structures are investigated using a first-order mass formula incorporating weakly interacting meson plus baryon clusters. A first-order mass formula predicts pentaquark states having a mass of 4236 MeV/c^2. This prediction is about 2.3% smaller than the measured value of 4337 MeV/c^2. Although the model predicts J values in agreement with Ref. 2, the parity values are not in agreement.

References

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

2) LHCb Collaboration, Phys. Rev. Lett. **128**, 062001 (2022).

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

4) 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).

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

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

7) 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.

8) 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.

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

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

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

12) 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.

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

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

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

16) 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.

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

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

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

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