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J/Ψ Λ Pentaquark Description of the $P_{c\bar{c}s}(4459)^0$

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Abstract
A first-order pentaquark model is utilized to model the $P_{c\bar{c}s}(4459)^0$ resonance. The $P_{c\bar{c}s}(4459)^0$ is modeled as a weakly bound J/Ψ meson plus Λ baryon molecular state. A first-order model predicts $1/2^-$ and $3/2^-$ spin and parity values that include the $3/2^-$ experimental value. The predicted mass of 4448.1 MeV/c^2 is within about 1% of the two candidate experimental values (4471.7 and 4458.8 MeV/c^2).

Keywords: First-Order Pentaquark Mass Formula, $P_{c\bar{c}s}(4459)^0$, Cluster Model, Quark Model, and J/Ψ Λ Quasimolecular Resonance

1. Introduction

The Bell and Bell II Collaboration [1] recently evaluated data samples of 102 million Υ(1S) events and 158 million Υ(2S) events collected by the Belle detector. The Collaborations searched for $udsc\bar{c}$ pentaquark states decaying to J/ΨΛ, and found evidence of the $P_{c\bar{c}s}(4459)^0$ state with a local significance of 3.3 standard deviations. The $P_{c\bar{c}s}(4459)^0$ mass values from the Ball and Bell II (4471.7 MeV/c^2) [1] and LHCb data (4458.8 MeV/c^2) [2] show small differences. Ref. 2 reported the $P_{c\bar{c}s}(4459)^0$ has a $3/2^-$ assignment.

In view of the Belle and Belle II [1] and LHCb [2] analyses, this paper analyzes the $P_{c\bar{c}s}(4459)^0$ molecular state in terms of a first-order pentaquark model. This state is modeled as a J/Ψ + Λ cluster that is in a weakly bound meson plus baryon molecular configuration. The meson and baryons are defined utilizing the methodology of Zel'dovich and Sakharov [3, 4]. First-order models were previously used to describe other possible pentaquarks [5-12].

2. Formalism

The first-order pentaquark model weakly couples a meson (m) and baryon (b). Mesons and baryons are modeled using the approach of Refs. 3 and 4 to determine their respective masses:

$$M_m = \delta_m + m_1 + m_2 + b\,(m_0^2 / m_1 m_2)\, \sigma_1 \cdot \sigma_2 \tag{1}$$

$$M_b = \delta_b + m_1 + m_2 + m_3 + (b/3)\,[(m_0^2 / m_1 m_2)\, \sigma_1 \cdot \sigma_2 + (m_0^2 / m_1 m_3)\, \sigma_1 \cdot \sigma_3 + (m_0^2 / m_2 m_3)\, \sigma_2 \cdot \sigma_3] \tag{2}$$

where δ_m = 40 MeV/c^2, δ_b = 230 MeV/c^2, m_i is the mass of the quark comprising the meson (i = 1, 2) or baryon (i = 1, 2, 3), m_0 is the average mass of a first generation quark, and b = 615 MeV/c^2. In Eq. 1, $\sigma_1 \cdot \sigma_2$ = -3/4 or 1/4 for a pseudoscalar or vector meson, respectively.

In Eq. 2, 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;

$$\sigma_2 \cdot \sigma_3 = ¼ \text{ and } \sigma_1 \cdot \sigma_2 = \sigma_1 \cdot \sigma_3 = -1/2 \tag{3}$$

If the baryon contains three different quarks, then the values of $\sigma_i \cdot \sigma_j$ are defined by the methodology of Refs. 3 and 4.

The first-order mass formula assumes that the meson and baryon reside in their ground states, and there is zero angular momentum between the meson and baryon clusters. If excited states are involved, the difference in masses between the excited and ground states must be considered. The methodology for addressing excited states is outlined in Refs. [5-12].

Eqs. 1 and 2 utilize effective quark masses. These masses were determined by Griffiths [13] for d, u, s, c, b, and t quarks that have the values 340, 336, 486, 1550, 4730, and 177000 MeV/c^2, respectively. Using the convention of the Standard Model [13, 14], the quarks are grouped into three generations: [d(-1/3), u(+2/3)], [s(-1/3), c(+2/3)], and [b(-1/3), t(+2/3)] [13, 14]. Quark charges are given within the parentheses in terms of the unit charge.

3. Results and Discussion

The $P_{c\bar{c}s}(4459)^0$ is modeled as a J/Ψ + Λ pentaquark that has component J^π values of 1^- and $1/2^+$, respectively. Given these values, the total spin and parity of the $P_{c\bar{c}s}(4459)^0$ is:

$$J^\pi(P_{c\bar{c}s}(4459)^0) = J^\pi(J/\Psi) \times 0 \times J^\pi(\Lambda) = 1^- \times 0 \times 1/2^+ = 1/2^-, 3/2^- \quad (4)$$

These values are include the experimental analysis value of $3/2^-$ [2].

The $P_{c\bar{c}s}(4459)^0$ mass predicted by the model is given by the relationship,

$$M(P_{c\bar{c}s}(4459)^0) = M(J/\Psi) + M(\Lambda) + \Phi \quad (5)$$

where **Φ** is the interaction between the clusters. In the first-order pentaquark model this interaction is assumed to be much smaller than the cluster masses and is ignored. The meson (baryon) mass is obtained from Eq. 1(2). Using Eq. 5 and the first order methodology of Eqs. 1 and 2, lead to a predicted $P_{c\bar{c}s}(4459)^0$ mass of 4448.1 MeV/c^2. This result is within about 1% of the measured experimental values [1, 2].

4. Conclusions

A first-order approach is utilized to model the $P_{c\bar{c}s}(4459)^0$ as a J/Ψ + Λ pentaquark. This resonance is described as a weakly bound meson plus baryon pentaquark molecular state. The model incorporates a primitive coupling structure that includes the $1/2^-$ and $3/2^-$ values. This range of values includes the experimental analysis $3/2^-$ value. The first-order mass model leads to a predicted $P_{c\bar{c}s}(4459)^0$ mass of 4448.1 MeV/c^2 that is within about 1% of the range of the experimental values.

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