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$\Xi_c\bar{D}$, Λ η_c, and Λ J/Ψ Pentaquark Descriptions of Structures Near 4465 Mev/c^2

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Abstract
A first-order pentaquark models is utilized to model the $P_{cs}(4459)$ and $P_{cs}(4472)$ resonances as weakly coupled meson and baryon clusters. $\Xi_c\bar{D}$, Λ η_c, and Λ J/Ψ pentaquark configurations are used in the analysis. A first-order model predicts a $1/2^-$ ($\Xi_c\bar{D}$, Λ η_c,) or $1/2^-$ and $3/2^-$ (Λ J/Ψ) assignment for these three pentaquark configurations. An analysis by Wang *et al*. predicts the $P_{cs}(4459)$ [$P_{cs}(4472)$] has a $3/2^-$ ($1/2^-$) assignment. Given the accuracy of the first-order model, all assumed configurations are representative of the experimental mass in the vicinity of 4465 Mev/c^2.

Keywords: First-Order Pentaquark Mass Formula, $P_{cs}(4459)$ and $P_{cs}(4472)$ Resonances, Cluster model, Quark Model, and $\Xi_c\bar{D}$, Λ η_c, and Λ J/Ψ Quasimolecular Resonances

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 $P_{cs}(4459)$ state with a local significance of 3.3 standard deviations. The $P_{cs}(4459)$ mass values from the Bell 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 $P_{cs}(4459)$ has a $3/2^-$ assignment.

In a subsequent analysis, Ref. 3 addressed the mass splitting between the LHCb Collaboration's $P_{cs}(4459)$ and the Belle Collaboration's $P_{cs}(4472)$ pentaquarks, identifying them as $3/2^-$ and $1/2^-$ states, respectively. Wang *et al.* [3] predict several new molecular candidates in the 4.3–4.7 GeV mass region. One of these states is the $\Xi_c\bar{D}$ pentaquark with a $1/2^-$ spin assignment.

This paper investigates the $P_{cs}(4459)$ and $P_{cs}(4472)$ structures as weakly coupled $\Xi_c\bar{D}$, Λ η_c, and Λ J/Ψ pentaquarks. Comparison with previous reviews of these states is also provided. The meson and baryon substructures of these pentaquarks are defined utilizing the methodology of Zel'dovich and Sakharov [4, 5]. First-order models were previously used to describe other possible experimentally observed pentaquarks [6-15].

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. 4 and 5 to determine their respective masses:

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

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

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:

$$\sigma_2 \cdot \sigma_3 = 1/4 \text{ and } \sigma_1 \cdot \sigma_2 = \sigma_1 \cdot \sigma_3 = -1/2 \quad (3)$$

If the baryon contains three different quarks, then the values of $\sigma_i \cdot \sigma_j$ are defined by the methodology of Refs. 4 and 5.
The first-order mass formula assumes that the meson and baryon reside in their ground states, and there is zero angular momentum between the 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. 6-15.
Eqs. 1 and 2 utilize effective quark masses. These masses were determined by Griffiths [16] 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 [16, 17], 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)] [16, 17]. Quark charges are given within the parentheses in terms of the unit charge.

3. Results and Discussion

The $P_{cs}(4459)$ and $P_{cs}(4472)$ are modeled as three separate weakly coupled $\Xi_c \bar{D}$, $\Lambda\ \eta_c$, and Λ J/Ψ pentaquarks. The spin and parity assignments are provided by the primitive coupling structure of the assumed pentaquark structures. Masses are obtained from the application of Eqs. 1 and 2.

3.1 Predicted Spin and Parity Assignments

The $P_{cs}(4459)$ and $P_{cs}(4472)$ structures are modeled as weakly coupled $\Xi_c \bar{D}$, $\Lambda\ \eta_c$, and Λ J/Ψ pentaquarks. Given these cluster assignments, the total spin and parity of the assumed configurations within the scope of the first-order model are:

$$J^\pi(J/\Psi) \times 0 \times J^\pi(\Lambda) = 1^- \times 0 \times 1/2^+ = 1/2^-, 3/2^- \quad (4)$$

$$J^\pi(\eta_c) \times 0 \times J^\pi(\Lambda) = 0^- \times 0 \times 1/2^+ = 1/2^- \quad (5)$$

$$J^\pi(\bar{D}) \times 0 \times J^\pi(\Xi_c) = 0^- \times 0 \times 1/2^+ = 1/2^- \quad (6)$$

3.2 Predicted Mass Values

The $P_{cs}(4459)$ and $P_{cs}(4472)$ structure mass values ($M(P_{cs})$), as predicted by the first-order model, are given by the following relationships assuming the three meson-baryon configurations:

$$M(P_{cs}) = M(J/\Psi) + M(\Lambda) + \Phi \quad (7)$$

$$M(P_{cs}) = M(\eta_c) + M(\Lambda) + \Phi \quad (8)$$

$$M(P_{cs}) = M(\bar{D}) + M(\Xi_c) + \Phi \quad (9)$$

Where **Φ** is the interaction between the clusters. In the first-order pentaquark model **Φ** 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. 7-9 and the first order methodology of Eqs. 1 and 2, leads to the values summarized in Table 1.

Table 1: Possible Pentaquark Descriptions of the $P_{cs}(4459)$ and $P_{cs}(4471)$

Configuration	J^π	Mass (MeV/c^2)	Source
$\Xi_c \bar{D}$	$1/2^-$	4322.2-4430.4	Ref. 3
$\Xi_c \bar{D}$	$1/2^-$	4428.6	This work
$\Lambda\ \eta_c$	$1/2^-$	4418.9	This work
Λ J/Ψ	$1/2^-, 3/2^-$	4448.1	This work and Ref. 15
$P_{cs}(4459)$	$3/2^-$	4458.8	Refs. 1-3
$P_{cs}(4471)$	$1/2^-$	4471.7	Refs. 1 and 3

The results for the pentaquark masses and their spin and parity assignments are summarized in Table 1. Given the accuracy of the first-order model, all assumed configurations are representative of the experimental structures in the vicinity of 4465 MeV/c^2. The model is not sufficiently accurate to distinguish between the assumed meson-baryon configurations.
The spin and parity assignments overlap the values predicted in Refs. 1 – 3. However, the primitive approach of the first-order model is not sufficiently accurate to provide a definitive assignment.

4. Conclusions

A first-order pentaquark models is utilized to model the $P_{cs}(4459)$ and $P_{cs}(4472)$ resonances as weakly coupled meson and baryon clusters including the $\Xi_c \bar{D}$, $\Lambda\ \eta_c$, and Λ J/Ψ configurations. A first-order model predicts a $1/2^-$ ($\Xi_c \bar{D}$, $\Lambda\ \eta_c$,) or $1/2^-$ and $3/2^-$ (Λ J/Ψ) assignment for these three pentaquark configurations. An analysis by Wang *et al.* predicts the $P_{cs}(4459)$ [$P_{cs}(4472)$] has a $3/2^-$ [$1/2^-$] assignment. Given the accuracy of the first-order model, all assumed mass and J^π configurations are representative of the experimental mass in the vicinity of 4465 Mev/c^2. However, the first-order model is not sufficiently accurate to provide more definitive mass and spin assignments.

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