Research Article

Possible Tetraquark Explanations for the Proposed Zcs(4000)+ and Zcs(4220)+

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The recently proposed $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ structures are investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound J/Ψ(c c-bar) + K^+ (u s-bar) meson clusters and their excited states. The first-order tetraquark mass formula provides a reasonable prediction (within 8%) of the measured masses.

1.0 Introduction

The LHCb Collaboration recently reported the first observation of two charged $Z_{cs}{}^+ \rightarrow J/\psi K^+$ tetraquark states from an updated amplitude analysis of the $B^+ \rightarrow J/\psi\phi K^+$ decay[1]. Ref. 1 reported these exotic states with the unique quark content of c c-bar u s-bar that decay to the $J/\psi K^+$ final state. The LHCb Collaboration's $J/\psi K^+$ result[1] is based on the combined proton-proton collision data at center-of-mass energies of 7, 8, and 13 TeV. An observation of two $X \rightarrow J/\psi\phi$ states was also reported, and will be addressed in a subsequent publication.

This paper investigates the possible tetraquark structure of two $Z_{cs}{}^+ \rightarrow J/\psi K^+$ states. The narrower $Z_{cs}(4000)^+$ state has a mass of 4003 MeV/c^2. Its spin and parity are determined to be 1^+ with high significance. The broader $Z_{cs}{}^+$ (4220) state with a 5.9σ significance could be 1^+ or 1^-. The 1^+ assignment is supported by a 2σ difference over the 1^- configuration. Other spin-parity assignments are ruled out at 4.9σ level.

In this paper, the first-order tetraquark mass formulas of Refs. 2 - 10 are applied to evaluate the possible mass and J^π values of the $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ tetraquarks. This mass relationship is based on weakly bound $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ structures based on J/Ψ(c c-bar) + K^+ (u s-bar) meson clusters and their excited states.

2.0 Model and Formulation

Zel'dovich and Sakharov[11,12] 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 meson mass formulas are used as the basis for deriving a first-order tetraquark mass formula. In particular, the model proposed in this paper assumes the tetraquark is partitioned into two meson clusters with the interaction between the clusters providing a minimal contribution to the tetraquark mass.

The meson mass (M) formula of Refs. 2 - 10 is:

$$\mathbf{M_m = \delta_m + m_1 + m_2 + b_m\,[m_o^2 / (m_1\, m_2)]\ \sigma_1 \cdot \sigma_2} \quad (1)$$

where m_1 (m_2) are the mass of the first (second) quark comprising the meson, m_o is the average mass of a first generation quark[11,12], 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/c^2 and 615 MeV/c^2, respectively[12].

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 and +1/4 for pseudoscalar and vector mesons, respectively[12].

In formulating the tetraquark mass formula, effective quark masses provided by Griffiths[13] 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 Eq. 1.

The six quarks are arranged in three generations: [d(-1/3), u(+2/3)], [s(-1/3), c(+2/3)], and [b(-1/3), t(+2/3)] [14]. The three generations are specified by the square brackets and the quark charges [in elementary charge units (e)] are given within parentheses.

3.0 First-Order Mass Formula for the $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$

The spin of a tetraquark within the first order mass formula is determined by coupling the two meson clusters

$$\mathbf{J^\pi = J^\pi(1)\ x\ L\ x\ J^\pi} \quad (2)$$

where the first-order mass formula assumes a minimally interacting L=0 configuration[2,3] between the meson clusters. Eq. 2 provides a primitive J^π assignment using the possible meson clusters noted in

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Table 1.

The first-order mass formula used in this paper partitions the tetraquark into two meson clusters. For the $Z_{cs}(4000)^+$, the first cluster is a K^+ scalar meson (sm) and the remaining cluster is a $J/\Psi(1S)$ vector meson (vm). These simplifications are incorporated to minimize model complexity which is consistent with an initial first-order mass formulation. In addition, the general $Z_{cs}(4000)^+$ tetraquark mass formula is assumed to have the form[2,3]

$$\mathbf{M = M_{sm} + M_{vm} + \Phi} \quad (3)$$

where $\mathbf{\Phi}$ defines the interaction between the meson clusters. Within the scope of this mass formula, the meson-meson cluster interaction is assumed to be weak and sufficiently small to be ignored. Accordingly, Eq. 3 represents the $Z_{cs}(4000)^+$ as a quasimolecular four quark system whose basic character is a weakly bound meson-meson system.

The $Z_{cs}(4220)^+$ state is modeled using two possible configurations based on the data of Ref. 1. These configurations include $\Psi(2S) + K^+$ and $J/\Psi(1S) + K^{*+}$ that involve excited mesons and not their ground states described in Eq. 3.

3.1 $Z_{cs}(4220)^+$ State Modeled as $\Psi(2S) + K^+$ Meson Clusters

In the $\Psi(2S) + K^+$ configuration, the scalar meson is K^+ and the vector meson is $\Psi(2S)$. For the $Z_{cs}(4220)^+$, the vector meson is the $\Psi(2S)$ and not the $J/\Psi(1S)$ ground state. Since the first-order $Z_{cs}(4220)^+$ tetraquark mass formula involves an excited $\Psi(2S)$ meson cluster, the mass formula is modified to account for this excitation energy[2,3]:

$$\mathbf{M = M_{sm} + M_{vm}^{*} + \Phi} \quad (4)$$

where

$$\mathbf{M_{vm}^{*} = M_{vm} + \Delta(\Psi(2S) - J/\Psi(1S))} \quad (5)$$

and Δ is the $\Psi(2S) - J/\Psi(1S))$ energy difference (589.2 MeV/c^2) [14].

3.2 $Z_{cs}(4220)^+$ State Modeled as $J/\Psi(1S) + K^{*+}$ Meson Clusters

In the $J/\Psi(1S) + K^{*+}$ configuration, the scalar K^+ meson is replaced by its excited K^{*+} state that is a vector meson. The remaining cluster is the $J/\Psi(1S)$ vector meson. Since the first-order $Z_{cs}(4220)^+$

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tetraquark mass formula involves an excited K^{*+} meson cluster, the mass formula of Eq. 3 is modified to account for this excitation energy[2,3]:

$$\mathbf{M = M_{vm} + M^{*}_{sm\rightarrow vm} + \Phi} \ (6)$$

where

$$\mathbf{M^{*}_{sm\rightarrow vm} = M_{sm} + \Delta(K^{*+} - K^{+})} \ (7)$$

and Δ is the $\mathbf{K^{*+} - K^{+}}$ energy difference (397.983 MeV/c^2) [14].

4.0 Results and Discussion

The angular momentum coupling from Eq. 2 and the first-order mass formula of Eqs. 1 and 3-7 are used to construct the $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ states. First-order mass formula model results are summarized in Table 1.

Table 1

$Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ Tetraquark Structures

	Experiment[a]		First-Order Mass Formula		
Tetraquark	**Mass (MeV/c^2)**	**J^π**	**Configuration**	**Mass (MeV/c^2)**	**J^π**
$Z_{cs}(4000)^+$	4003	1^+	$J/\Psi(1S) + K^+$	3687	1^+
$Z_{cs}(4220)^+$	4220	1^+	$\Psi(2S) + K^+$	4276	1^+
$Z_{cs}(4220)^+$	4220	1^+	$J/\Psi(1S) + K^{*+}$	4085	$0^+, 1^+, 2^+$

[a] Ref. 1.

The spin and parity assignments for these states are derived from Eq. 2:

$J^\pi [Z_{cs}(4000)^+] = 1^- \times 0 \times 0^- = 1^+$ ($J/\Psi(1S) + K^+$ configuration)

$J^\pi [Z_{cs}(4220)^+] = 1^- \times 0 \times 0^- = 1^+$ ($\Psi(2S) + K^+$ configuration)

$J^\pi [Z_{cs}(4220)^+] = 1^- \times 0 \times 1^- = 0^+, 1^+, 2^+$ ($J/\Psi(1S) + K^{*+}$ configuration)

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The first-order mass formula provides a reasonable representation of the $Z_{cs}(4000)^+$ tetraquark structure. The $J/\Psi(1S) + K^+$ configuration results in a mass of 3687 MeV/c^2 that is that is about 7.9% smaller than the 4003 MeV/c^2 experimental value[1]. The predicted 1^+ assignment is in agreement with Ref. 1.

The $Z_{cs}(4220)^+$ state is modeled using two possible configurations. Using the $\Psi(2S) + K^+$ configuration, the model results predict a mass of 4276 MeV/c^2 that is about 1.3% larger than the experimental 4220 MeV/c^2 value of Ref. 1. The predicted 1^+ assignment is in agreement with Ref. 1.

The second $Z_{cs}(4220)^+$ model configuration is $J/\Psi(1S) + K^{*+}$. Using this configuration, the first-order mass formula predicts a mass of 4085 MeV/c^2 that is about 3.2% smaller than the measured value[1]. The predicted 1^+ assignment is in agreement with Ref. 1. The model also allows 0^+ and 2^+ assignments that are not supported by Ref. 1.

Although these results are encouraging, they are based on a first-order mass formula with a number of uncertainties including the assumed quark masses[13] and the magnitude of the meson-meson cluster interaction. However, the model does provide an initial description of the $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ states that is reasonable agreement with the experimental data[1].

5.0 Conclusions

The recently proposed $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ structures are investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound J/Ψ(c c-bar) + K^+ (u s-bar) meson clusters and their excited states.

The $J/\Psi(1S) + K^+$ configuration results in a mass of 3687 MeV/c^2 that is that is about 7.9% smaller than the 4003 MeV/c^2 experimental $Z_{cs}(4000)^+$ value[1]. Using the $\Psi(2S) + K^+$ configuration for the $Z_{cs}(4220)^+$, the model results predict a mass of 4276 MeV/c^2 that is about 1.3% larger than the experimental 4220 MeV/c^2 value of Ref. 1. The second $Z_{cs}(4220)^+$ configuration is $J/\Psi(1S) + K^{*+}$ predicts a mass of 4085 MeV/c^2 that is about 3.2% smaller than the measured value[1].

All aforementioned configurations predict a 1^+ assignment for both states that is in agreement with Ref. 1. The $J/\Psi(1S) + K^{*+}$ $Z_{cs}(4220)^+$ configuration also predicts 0^+ and 2^+ assignments that are not consistent with data.

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