Possible Tetraquark Explanation for the J/ψK0S Structure Observed in Proton-Proton Collision Data at Center-of-Mass Energies of 7, 8, and 13 TeV

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Abstract

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The LHCb Collaboration provided data that supports a $J/\psi K^0_S$ structure, denoted as $T^\theta_{\psi s1}(4000)^0$, using an amplitude analysis of $B^0 \rightarrow J/\psi \phi K^0_S$ decay. The structure of the $J/\psi K^0_S$ is investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound J/ψ plus K^0_S meson clusters. The first-order tetraquark mass formula provides a predicted mass of 3694 MeV/c^2 that is within about 8% of the experimental value of 3991 MeV/c^2 with a $J^\pi = 1^+$ prediction. The data does not distinguish between 1^+ and 1^- states.

KEYWORDS: Tetraquark Model for the $T^\theta_{\psi s1}(4000)^0$; First-Order Mass Formula; Quark Model; Cluster Model.

1.0 Introduction.

The conventional quark model suggests that mesons and baryons are composed of a pair of quark-antiquark pairs (qq-bar) and three quarks (qqq) configurations. However, exotic states beyond the conventional quark model[1,2] have been and continue to be observed. Quantum chromodynamics (QCD), does not exclude the existence of more exotic configurations. These include multiquark states with more than three valence quarks and antiquarks, hybrid configurations with gluonic excitations and quarks, and glueballs that are composed only of gluons.

LHCb Collaboration[3] provided data that supports a $J/\psi K^0_S$ structure using an amplitude analysis of $B^0 \rightarrow J/\psi \phi K^0_S$ decay. The analysis was based on proton-proton collision data, at center-of-mass energies of 7, 8, and 13 TeV. A significance of 4.0 standard deviations for a $J/\psi K^0_S$ structure, named $T^\theta_{\psi s1}(4000)^0$, is noted at a mass of 3991 MeV/c^2. The data does not distinguish between $J^\pi = 1^+$ and 1^- states. When isospin symmetry for the charged and neutral $T^\theta_{\psi s1}(4000)$ states is assumed, the resonance significance increases to 5.4 standard deviations.

Given the uncertainty in the structure of the $T^\theta_{\psi s1}(4000)^0$ system, this paper investigates its structure in terms of a $J/\psi + K^0_S$ tetraquark. A first-order tetraquark model has been successful in the description of a number of systems[4-19], and its description using these first-order models is a reasonable approach to investigate the $T^\theta_{\psi s1}(4000)^0$ structure.

2.0 Model and Formulation

Zel'dovich and Sakharov[20,21] 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_m) formula of Refs. 4 - 19 is:

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

where m_1 (m_2) are the mass of the first (second) quark comprising the meson, m_0 is the average mass of a first generation quark[20,21], 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[21].

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[21].

In formulating the tetraquark mass formula, effective quark masses provided by Griffiths[22] 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. The effective masses are utilized in Eq. 1.

These 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)][23]. 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 $T^{\theta}_{\psi s1}(4000)^0$ Modeled as a $J/\psi + K^0_S$ Tetraquark

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

$$J^{\pi} = J^{\pi}(1) \bigotimes L \bigotimes J^{\pi}(2)$$

where the first-order mass formula assumes a minimally interacting L=0 configuration[4-19] between the two meson clusters. Eq. 2 provides a primitive J^{π} assignment using the possible meson clusters.

The first-order mass formula used in this paper partitions the tetraquark into two meson (m_1 and m_2) clusters. Using this structure, the tetraquark mass formula involving ground state meson clusters is assumed to have the form[4-19]

$$M(m_1 + m_2) = M_m(m_1) + M_m(m_2) + \Phi \quad (3)$$

where Φ 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 a quasimolecular four quark systems whose basic character is a weakly bound meson-meson system where the mesons reside in their ground states.

4.0 Results and Discussion

The angular momentum coupling from Eq. 2 and the first-order mass formula of Eqs. 1 and 3 are used to construct the $T^{\theta}_{\psi s1}(4000)^0$ tetraquark state. As noted previously, the spin and parity assignment for the tetraquark state is derived from Eq. 2. Following Refs. 4 – 19, the first-order mass formula only provides a primitive spin and parity assignment for the meson-meson cluster configuration.

The angular momentum coupling from Eq. 2 and the first-order mass formula of Eqs. 1 and 3 are used to construct the $J/\psi + K^0_S$ tetraquark states. Eq. 2 yields the spin and parity assignment for the $J/\psi + K^0_S$ tetraquark state[3,23].

$$J^{\pi}(T^{\theta}_{\psi s1}(4000)^0) = J^{\pi}(K^0_s) \otimes L \otimes J^{\pi}(J/\Psi) = 0^- \otimes 0 \otimes 1^- = 1^+ \quad (4)$$

The 1^+ assignment is consistent with the data[3] that suggests the spin assignment is either 1^+ or 1^-.

The tetraquark mass is obtained from Eqs. 1 and 3. For the the $J/\psi + K^0_S$ tetraquark. Eq. 3 is rewritten as:

$$J^{\pi}(T^{\theta}_{\psi s1}(4000)^0) = M_m(J/\Psi) + M_m(K^0_s) \quad (5)$$

The first-order mass result of 3694 MeV/c^2 is about 8% less than the experimental value of 3991 MeV/c^2. Model results for the spin and parity and associated mass are in reasonable agreement with data[3].

5.0 Conclusions

The structure of the $T^{\theta}_{\psi s1}(4000)^0$ state is investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound $J/\psi + K^0_S$ meson clusters. The first-order tetraquark mass formula provides a predicted mass of 3694 MeV/c^2 that is within about 8% of the experimental value of 3991 MeV/c^2 with a $J^{\pi} = 1^+$ prediction. The data does not distinguish between 1^+ and 1^- states.

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