Possible Tetraquark Explanation for the Proposed X(3960)

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Abstract

The recently proposed X(3960) structure is investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound $D_s^+ + D_s^-$ meson clusters. The first-order tetraquark mass formula provides a reasonable prediction (within about 1.3%) of the measured mass, and predicts a $J^\pi = 0^+$ in agreement with data.

1.0 Introduction

The LHCb Collaboration recently reported the observation of a D_s^+ (c s-bar) + D_s^- (c-bar s) tetraquark candidate from an analysis of $B^+ \rightarrow D_s^+ D_s^- K^+$ decays[1,2]. Refs. 1 and 2 reported this exotic state with the possible quark content of c c-bar s s-bar with a mass of 3955 ± 6 ± 11 MeV/c2. The LHCb Collaboration's data suggests a 0^+ assignment for this candidate state designated as the X(3960).

The LHCb Collaboration[1,2] also reported the observation of two new additional tetraquarks $T^a_{cs\text{-}bar0}(2900)^{++}$ and $T^a_{cs\text{-}bar0}(2900)^0$, as well as a pentaquark $P^\Lambda_{\psi s}(4338)$. These states will be addressed in subsequent publications.

In this paper, the first-order tetraquark mass formulas of Refs. 3 - 12 are applied to evaluate the possible mass and J^π value of the candidate X(3960) tetraquark. This mass relationship is based on a weakly bound X(3960) structure based on D_s^+ (c s-bar) + D_s^- (c-bar s) meson clusters.

2.0 Model and Formulation

Zel'dovich and Sakharov[13,14] 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. 3 - 12 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[15,16], 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[14].

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[14].

In formulating the tetraquark mass formula, effective quark masses provided by Griffiths[15] 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)][16]. 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 X(3960)

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

$J^\pi = J^\pi(1) \times L \times J^\pi(2)$ (2)

where the first-order mass formula assumes a minimally interacting L=0 configuration[3-12] between the meson clusters. Eq. 2 provides a primitive J^π assignment. Both the D_s^+ and D_s^- have a 0^- assignment. Applying Eq. 2 yields a $0^- \times 0 \times 0^- = 0^+$ assignment in agreement with data[1,2].

The first-order mass formula used in this paper partitions the tetraquark into two meson clusters. These clusters include the D_s^+ and D_s^- pseudoscalar mesons (sm). Using this structure, the tetraquark mass formula involving ground state meson clusters is assumed to have the form[3-12]

$M(D_s^+ + D_s^-) = M_{sm} + M_{sm} + \Phi$ (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 the X(3960) structure as 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 X(3960) state. As noted previously, the spin and parity assignment for the X(3960) state is derived from Eq. 2. The resulting $J^\pi = 0^+$ assignment is in agreement with Refs. 1 and 2. As noted in Refs. 3 – 12, the first-order mass formula only provides a primitive spin and parity assignment for the meson-meson cluster configuration.

Eqs. 1 and 3 lead to a predicted X(3960) mass of 4012 MeV/c^2. This result is about 1.3% larger than the experimental value[1,2]. Although these results are encouraging, they are based on a first-order mass formula with a number of uncertainties including the assumed quark masses[15], and the magnitude of the meson-meson cluster interaction. However, the model does provide an initial description of the X(3960) state that is reasonable agreement with the experimental data[1,2].

5.0 Conclusions

The recently proposed X(3960) structure[1,2] is investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound $D_s^+ + D_s^-$ meson clusters.

The assumed $D_s^+ + D_s^-$ configuration leads to a mass result that is within about 1.3% of the measured X(3960) value[1,2]. The predicted first-order J^π value of 0^+ is also in agreement with data. These results suggest the X(3960) structure[1,2] is a weakly bound $D_s^+ + D_s^-$ meson cluster system.

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