Research Article

Possible Tetraquark Explanation for the Proposed Tcc+

Joseph Bevelacqua[1]

1. Independent researcher

The recently proposed $T_{cc}{}^{+}$ structure is investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound D^{*+}(c d-bar) + D^{0}(c u-bar) meson clusters and provides a reasonable prediction (within about 1.4%) of the measured $T_{cc}{}^{+}$ mass.

1.0 Introduction

CERN's LHCb experiment presented the discovery of a new tetraquark at the 2021 European Physical Society Conference on High Energy Physics (EPS-HEP)[1]. The new particle, labeled as the $T_{cc}{}^{+}$ is comprised of two c quarks and u and d antiquarks[1]. The tetraquark occurs as a narrow peak in the $D^{0}D^{0}\pi^{+}$ meson mass spectrum, just below the D^{0} (c u-bar) + D^{*+} (c d-bar) mass threshold, with a statistical significance exceeding 20 standard deviations[1]. The $T_{cc}{}^{+}$ is the longest-lived exotic matter particle discovered to date based on its width of about 400 keV[1]. As noted in Fig. 1 of Ref. 1, the mass is about 3875 MeV/c^{2}, but no spin-parity values are provided.

Based on Ref. 1, the $T_{cc}{}^{+}$ tetraquark candidate would couple to the D^{0} + D^{*+} channel. The $T_{cc}{}^{+}$ tetraquark has unit positive charge with a most likely c u-bar c d-bar quark configuration.

In this paper, the first-order tetraquark mass formulas of Refs. 2 - 9 are applied to evaluate the possible configuration of the $T_{cc}{}^{+}$ state. The first-order model is utilized to predict both the mass and J^{π} value of the $T_{cc}{}^{+}$ tetraquark.

2.0 Model and Formulation

Zel'dovich and Sakharov[10,11] proposed a semiempirical mass formula that provides a prediction of mesons and baryons in terms of effective quark masses. Within this formulation, quark wave

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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 clusters with the interaction between the clusters providing a minimal contribution to the tetraquark mass.

The meson mass (M) formula of Refs. 2 and 3 is:

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

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[10,11], 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[11].

The last term in Eq. 1 represents the spin-spin interaction of the quarks and $\sigma_1 \cdot \sigma_2$ is the scalar product of the quark spin vectors. $\sigma_1 \cdot \sigma_2$ has the value -3/4 and +1/4 for pseudoscalar and vector mesons, respectively[11].

In formulating the tetraquark mass formula, effective quark masses provided by Griffiths[12] 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.

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)] [13]. The three generations are specified by the square brackets and the quark charges are given within parentheses.

3.0 First-Order Mass Formula for the T_{cc}^+

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

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

where the first-order mass formula assumes a minimally interacting L=0 configuration[2,3] between the meson clusters. No J^π assignment was provided in Ref. 1. Eq. 2 provides a J^π assignment using the possible meson clusters noted in Ref. 1. These include the D^0 and D^{*+} with J^π values of 0^- and 1^-, respectively[13]. The first-order mass formula $J^\pi = 1^+$ assignment[1] for the T_{cc}^+ follows naturally from the $0^- \times 0 \times 1^-$ coupling structure of Eq. 2.

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The first-order mass formula used in this paper partitions the tetraquark into two meson clusters. The first cluster is a D^0 scalar meson (sm) and the remaining cluster is a D^{*+} vector meson (vm). These simplifications are incorporated to minimize model complexity which is consistent with an initial first-order formulation. In addition, the general tetraquark mass formula is assumed to have the form[2,3]

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

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 a quasimolecular four quark system whose basic character is a weakly bound meson-meson system.

3.1 D^0 + D^{*+} Meson Clusters

In the $D^0 + D^{*+}$ configuration, the scalar meson is D^0 and the vector meson is D^{*+}. For the $T_{cc}{}^+$, the vector meson is the D^{*+} and not the D^+ ground state. Since the first-order $T_{cc}{}^+$ tetraquark mass formula involves an excited D^{*+} meson cluster, the mass formula is modified to account for this excitation energy[2,3]:

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

where

$$\mathbf{M_{vm}{}^* = M_{vm} + \Delta(D^{*+} - D^+)} \qquad (5)$$

and Δ is the $D^{*+} - D^+$ energy difference (140.61 MeV/c^2) [13].

4.0 Results and Discussion

The angular momentum coupling from Eq. 2 and the first-order mass formula of Eqs. 1 and 3-5 are used to construct a $T_{cc}{}^+$ state. This state is modeled as noted in Sections 3.1.

The first-order mass formula provides a reasonable representation of the $T_{cc}{}^+$ tetraquark structure. The $D^0 + D^{*+}$ configuration results in a mass of 3928.76 MeV/c^2 that is that is about 1.4% larger than the 3875 MeV/c^2 experimental value[1].

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Although these results are encouraging, they are based on a first-order mass formula with a number of uncertainties including the assumed quark masses[12] and the magnitude of the meson-meson cluster interaction. However, the model does provide an initial description of the T_{cc}^+ mass and provides a $J^\pi = 1^+$ assignment in terms of a tetraquark structure.

5.0 Conclusions

The first-order mass formula predicts $D^0 + D^{*+}$ configuration for the T_{cc}^+. Weakly bound $D^0 + D^{*+}$ meson clusters lead to a predicted mass that is within about 1.4% of the measured value[1]. Although Ref. 1 does not provide a J^π assignment for the T_{cc}^+, the model suggests a $J^\pi = 1^+$ assignment derived from Eq. 2.

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