Possible Tetraquark Explanation for the Proposed T_{cc}^+

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Abstract

The recently proposed T_{cc}^+ structure is investigated using a first-order tetraquark mass formula. This mass relationship is based on weakly bound $D^{*+}(c \text{ d-bar}) + D^0(c \text{ u-bar})$ 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 antiquarks¹. The tetraquark occurs as a narrow peak in the $D^0 D^0 \pi^+$ meson mass spectrum, just below the $D^0(c \text{ u-bar}) + D^{*+}(c \text{ d-bar})$ mass threshold, with a statistical significance exceeding 20 standard deviations¹. The T_{cc}^+ is the longest-lived exotic matter particle discovered to date based on its width of about 400 keV¹. As noted in Fig. 1 of Ref. 1, the mass is about 3875 MeV/c², 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 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:

$$M_m = \delta_m + m_1 + m_2 + b_m [m_0^2 / (m_1 m_2)] \sigma_1 \cdot \sigma_2 \quad (1)$$

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^{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/c² and 615 MeV/c², respectively¹¹.

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, respectively¹¹.

In formulating the tetraquark mass formula, effective quark masses provided by Griffiths¹² are utilized. These effective masses for d, u, s, c, b, and t quarks are 340, 336, 486, 1550, 4730, and 177000 MeV/c², 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

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

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^- , respectively¹³. The first-order mass formula $J^\pi = 1^+$ assignment¹ for the T_{cc}^+ follows naturally from the $0^- \times 0 \times 1^-$ coupling structure of Eq. 2.

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}

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

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 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}:

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

where

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

and Δ is the $D^{*+} - D^+$ energy difference (140.61 MeV/c²)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 $3928.76 \text{ MeV}/c^2$ that is that is about 1.4% larger than the $3875 \text{ MeV}/c^2$ experimental value¹.

Although these results are encouraging, they are based on a first-order mass formula with a number of uncertainties including the assumed quark masses¹² 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 value¹. 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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