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Proposed T_{bc} Tetraquark Near the $B^*\bar{D}$ Threshold

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Abstract
The proposed T_{bc} tetraquark near the $B^*\bar{D}$ threshold is investigated using a first-order model assuming weakly interacting $b\bar{u}$ plus $c\bar{d}$ meson clusters. The T_{bc} model yields a $J^\pi = 0^+$ and 1^+ values in agreement with other analysis, and also suggests a 2^+ possible assignment. Depending on the assumed spin and parity of each meson cluster, the model yields mass values in the range of 6.9028 – 7.0804 GeV/c^2. These values are in reasonable agreement of 7.0944 – 7.1514 GeV/c^2 with proposed lattice QCD values.

Keywords: T_{bc} Tetraquark, First-Order Mass Formula, Quark Model, Cluster Model

1. Introduction
Alexandrou *et al.* [1] observed sharp peaks in the B - $\bar{D}$ and B^* - $\bar{D}$ scattering rates close to the thresholds. These resonances are associated with shallow bound states, a few MeV or less below these thresholds. In addition, Ref. 1 found hints for resonances with masses of order 100 MeV above these thresholds. In Ref. 2 these states were assigned possible $J^\pi = 0^+$ and 1^+ values. In addition, Ref. 3 reported a $J^\pi = 1^+$ $b\bar{c}ud$ tetraquark bound states using lattice QCD 43 MeV below the B^* - $\bar{D}$ threshold.
These results suggest possible a T_{bc} tetraquark with a mass between 7.0944 and 7.1514 GeV/c^2 with possible $J^\pi = 0^+$ and 1^+ values. Definitive experimental results have not yet been published.
The T_{bc} is investigated in terms of a first-order tetraquark model. This model is based on the semiempirical mass formula of Zel'dovich and Sakharov [4, 5]. The first-order tetraquark model provides the T_{bc} mass as well its J^π value. Since the first-order model is limited in scope, it only permits a primitive angular momentum coupling structure. Other tetraquark systems [6-27] were reasonably described by the first-order model.

2. Model and Formulation
The proposed first-order model is based on the semiempirical mass formula of Zel'dovich and Sakharov [4, 5]. This model assumes that two weakly bound meson clusters form the tetraquark, with zero angular momentum between the clusters.
The mesons (m) mass (M) is defined to have the form [4, 5]:

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

In Eq. 1, δ_m is defined to have the value 40 MeV/c^2 [5], and m_i is the mass of the quark comprising the meson cluster (i = 1 and 2). The average mass of a first generation quark (u and d) is m_o [28, 29]. The scalar product of the quark spin vectors ($\sigma_1 \cdot \sigma_2$) is -3/4 and +1/4 for pseudoscalar and vector mesons, respectively [5].
Effective quark masses provided by Griffiths [28] are used to determine the meson cluster mass. The d, u, s, c, b, and t quarks have effective mass values of 340, 336, 486, 1550, 4730, and 177000 MeV/c^2, respectively [28]. Following the convention of the Standard Model, these quarks are grouped into three generations: [d(-1/3), u(+2/3)], [s(-1/3), c(+2/3)], and [b(-1/3), t(+2/3)] [28, 29]. The specific quark charges, in units of the unit charge e, are given within parentheses.

3. First-Order Mass Formula for the $b\bar{u}$ plus $c\bar{d}$ Meson Cluster Description of the T_{bc} Tetraquark
The first-order mass formula only provides a limited angular momentum coupling structure, and the spin of a tetraquark is derived from the angular momentum coupling of the two meson clusters:

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

The first-order model summarized in Eq. 2 only provides a primitive angular momentum coupling structure for the J^π assignment, and the angular momentum between the clusters is zero (L = 0). These are limiting conditions of the model. Detailed meson cluster structural information, and strong coupling between the clusters are not included in the model formulation.

These aforementioned simplifications minimize model complexity, and permit the tetraquark mass formula to have the form [6-27]:

$$M = M_m(1) + M_m(2) + \Phi \quad (3)$$

In Eq. 3, the two meson clusters are denoted by the numbers 1 and 2, and the individual meson cluster mass is given by Eq. 1. The final term in Eq. 3 (Φ) is the interaction between the meson clusters that is assumed to be negligible relative to the magnitude of the meson masses. Accordingly, Eq. 3 suggests a quasimolecular four quark system that is characteristic of a weakly bound meson-meson system.

The T_{bc} configuration is evaluated assuming weakly interacting $b\bar{u}$ plus $c\bar{d}$ meson clusters. The T_{bc} is modeled as the four possible configurations: a 0^- and 1^- $(c\bar{d})$ meson cluster coupled to a 0^- and 1^- $(b\bar{u})$ meson cluster. These assignments and their various couplings are provided in Table 1. The T_{bc} model yields a $J^\pi = 1^+$ value in agreement with other analysis [1], and also suggests 0^+ and 2^+ possible assignments.

The predicted first-order mass is based on Eq. 3:

$$M(T_{bc}) = M(c\bar{d}) + M(b\bar{u}) + \Phi \quad (4)$$

Using Eq. 4 and the first-order mass formula of Eq. 1, mass values for the various meson cluster angular momentum configurations are provided in Table 1. Depending on the assumed spin and parity of each meson cluster, the model yields mass values in the range of 6.9028– 7.0804 GeV/c^2. These values are in reasonable agreement with proposed 7.0944 – 7.1514 GeV/c^2 lattice QCD values [1-3].

Table 1: Model Results for the Proposed T_{bc} Tetraquark near the $B^*\bar{D}$ threshold

Meson Cluster - 1			Meson Cluster - 2			T_{bc}	
Configuration	J^π	Mass (GeV/c^2)	Configuration	J^π	Mass (GeV/c^2)	Mass (GeV/c^2)	J^π
$b\bar{u}$	0^-	5.0728	$c\bar{d}$	0^-	1.8300	6.9028	0^+
$b\bar{u}$	0^-	5.0728	$c\bar{d}$	1^-	1.9633	7.0361	1^+
$b\bar{u}$	1^-	5.1171	$c\bar{d}$	0^-	1.8300	6.9471	1^+
$b\bar{u}$	1^-	5.1171	$c\bar{d}$	1^-	1.9633	7.0804	$0^+,1^+,2^+$

4. First-Order Tetraquark Model Uncertainties and Limitations

There are a number of uncertainties and limitations that affect the model results. The limited angular momentum coupling structure restricts the available J^π values that can be evaluated. In addition, assuming zero angular momentum between the clusters also limits the evaluation of possible states.

The values for the effective quark masses [28] are not definitive. Although the weak coupling assumption appears to be reasonable, the exact magnitude for the interaction strength between the clusters is unknown [6-27]. The coupling strength will likely depend on the physical properties of the interacting systems. In spite of these uncertainties, the model continues to provide reasonably credible results [6-27] for candidate tetraquark systems.

5. Justification for the Weak Coupling Assumption

The quark charges are related to the number of colors (N_c) incorporated into the fundamental quantum chromodynamics (QCD) formulation [30, 31]. For example, the first generation quark charges within SU(N_c) are:

$$Q_d = \frac{1}{2}\left(\frac{1}{N_c} - 1\right)e \quad (5)$$

$$Q_u = \frac{1}{2}\left(\frac{1}{N_c} + 1\right)e \quad (6)$$

For conventional QCD using 3 colors, the expected d and u electric charges are obtained. The importance of QCD expansions involving $1/N_c$ illustrates the weak coupling assumption [32, 33].

A key assumption of the first-order mass formula of Eqs. 1, 3, and 4 is weak coupling between the two clusters. In particular, the model utilized 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. Within the scope of this mass formula, the meson-meson cluster interaction is assumed in Eq. 4 to be weak and sufficiently small to be ignored.

This assumption is justified because QCD can be investigated as an expansion in $1/N_c$ [32, 33]. The large N_c limit reduces to a field theory of weakly interacting meson-like objects. The physical situation with $N_c = 3$ retains many of the characteristics of the $N_c \to \infty$ limit, and further justifies the weak coupling approximation.

The $1/N_c$ expansion [32, 33] is well accepted in elementary particle physics and leads to the Okubo-Zweig-Iizuka (OZI) rule [34-36] and the Skyrme model [37, 38]. In fact, in the $1/N_c$ expansion, QCD is reduced to a weakly interacting meson theory, and the meson-meson interaction is regarded to be small [32, 33]. This situation is also a characteristic of Eqs. 3 and 4.

6. Conclusions

The proposed T_{bc} tetraquark near the $B^*\bar{D}$ threshold is investigated using a first-order model assuming weakly interacting $b\bar{u}$ plus $c\bar{d}$ meson clusters. This weak coupling approximation is based on the $1/N_c$ expansion that is well accepted in elementary particle physics and leads to the Okubo-Zweig-Iizuka (OZI) rule and the Skyrme model. In addition, in the $1/N_c$ expansion, QCD is reduced to a weakly interacting meson theory, and the meson-meson interaction is regarded to be small. This situation is also a characteristic of Eqs. 3 and 4.

The T_{bb} model yields a $J^{\pi} = 0^{+}$ and 1^{+} values in agreement with other analysis, and also suggests a 2^{+} possible assignment. Depending on the assumed spin and parity of each meson cluster, the model yields mass values in the range of 6.9028 – 7.0804 GeV/c^2. These values are in reasonable agreement with proposed 7.0944 – 7.1514 GeV/c^2 lattice QCD values.

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