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# Possible D D-bar Tetraquark Explanations for the R(3780)

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**Abstract**
The R(3780) is investigated using a first-order tetraquark model. A D D-bar configuration is evaluated assuming weakly interacting D and D-bar meson clusters. The R(3780) model yields a $J^{\pi} = 0^{+}$ value. A mass of 3730 MeV/$c^2$ is predicted by the model. This value is about 2% smaller the value suggested by the BESIII Collaboration.

**Keywords:** R(3780) Tetraquark, First-Order Mass Formula, Quark Model, Cluster Model

## 1. Introduction

In Ref. 1, the BESIII Collaboration reported measurements of the e + e− → hadrons cross section at center-of-mass energies from 3.645 to 3.871 GeV. These data suggest a complex system composed of multiple resonances. These resonances could include heavy cc, molecular, hadro-charmonium, and hybrid charmonium states and tetraquarks.

Ref. 1 specifically noted the R(3780) resonance. Since this resonance is near the D D-bar threshold, it is possible that the R(3780) is a D D-bar tetraquark. This possibility is investigated in this paper.

The R(3780) is investigated in terms of a first-order tetraquark model. This model is based on the semiempirical mass formula of Zel'dovich and Sakharov [2, 3]. The first-order tetraquark model provides the R(3780) mass as well $J^{\pi}$ value. Since the first-order model is limited in scope, it only permits a primitive angular momentum coupling structure. Other tetraquark systems [4-23] 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 [2, 3]. 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 [2, 3].

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

In Eq. 1, $\delta_m$ is defined to have the value 40 MeV/$c^2$ [3], 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 $m_o$ [24, 25]. The scalar product of the quark spin vectors ($\boldsymbol{\sigma_1 \cdot \sigma_2}$) is -3/4 and +1/4 for pseudoscalar and vector mesons, respectively [3].

Effective quark masses provided by Griffiths [24] 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 [24]. 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)] [23, 24]. The specific quark charges, in units of the unit charge e, are given within parentheses.

## 3. First-Order Mass Formula for the D D-bar R(3780) Resonance

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

$$\mathbf{J^{\pi}} = J^{\pi}(1) \text{ x } L \text{ x } J^{\pi}(2) \qquad (2)$$

The first-order model summarized in Eq. 2 only provides a primitive angular momentum coupling structure for the $J^{\pi}$ assignment, and L = 0 is a limiting condition 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 [5-23].

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

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 DD-bar configuration is evaluated assuming weakly interacting D and D-bar meson clusters. The DD-bar tetraquark is modeled as a $0^-$ c u-bar cluster coupled to a $0^-$ c-bar u meson cluster. This tetraquark has a $0^-$ x 0 x $0^-$ = $1^+$ assignment. No spin assignment was provided in Ref. 1.

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

$$\mathbf{M(D + D\text{-}bar)} = M(D) + M(D\text{-bar}) + \Phi \quad (4)$$

Using Eq. 4 and the first-order mass formula of Eq. 1, a mass of 3730 MeV/$c^2$ is predicted. This value is about 3% smaller than the value of Ref. 1.

## 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 $J^{\pi}$ 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 [24] are not definitive. Although the weak coupling assumption appears to be reasonable, the exact magnitude for the interaction strength between the clusters is unknown [4-23]. 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 [4-23] for candidate tetraquark systems.

## 5. Conclusions

The R(3739) mass and $J^{\pi}$ value are investigated using a first-order tetraquark model. A D D-bar configuration is evaluated assuming weakly interacting D and D-bar meson clusters. The R(3730) model yields a $J^{\pi} = 0^+$ value. A mass of 3730 MeV/$c^2$ is predicted by the model. This value is about 2% smaller than the value suggested by BESIII Collaboration.

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