Description of the X(2900) as an Open Flavor Tetraquark in Terms of a First-Order Mass Formula

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Abstract

A recently discovered X(2900) tetraquark candidate having four different flavor quarks is investigated using a first-order mass formula. This mass relationship is based on two weakly bound meson clusters. The first-order mass formula provides a reasonable prediction of 2908 MeV/c^2 for the measured X(2900) tetraquark mass with possible spins of 0, 1, and 2. Experimental model dependent analysis suggests a tetraquark mass of 2866.3 MeVc^2 for a spin 0 state and 2904.1 MeV/c^2 for a spin 1 state.

1.0 Introduction

The possibility that hadrons could exist with structures beyond conventional qq or qqq quark configurations was noted by Gell-Mann[1]. Additional theoretical work addressed the basic properties of multi-quark hadrons within an effective quark model of Quantum Chromodynamics (QCD)[2,3]. More quantitative arguments of multi-quark hadrons utilizing multi-quark potentials were studied in lattice QCD[4,5].

Previous searches of multiquark systems have appeared, but most were later invalidated following additional analysis[6]. However, subsequent experimental work continues to suggest the existence of both tetraquark[7-9] and pentaquark[10] structures. These studies open the possibility of additional exotic structures[11,12].

An additional structure has been recently observed in the $B^+ \rightarrow D^+ D^- K^+$ mass spectrum[13]. In particular, the LHCb Collaboration reported a possible exotic four quark structure in a number of channels including the $D^{*-}K^{*+}$ channel[13] investigated in this paper. The LHCb model dependent results suggest possible spin 0 and spin 1 states having masses of X_0(2900) = 2866.3 MeV/c^2 and X_1(2900) = 2904.1 MeV/c^2, respectively. This is the first observation of an open flavor tetraquark state composed of four different flavors.

This paper describes the candidate X(2900) tetraquark structure in terms of a first-order mass formula that successfully described the $Z_c(3900)^0$ and $Z(4430)^-$ tetraquarks[14], X(6900) tetraquark[15], X(5568) tetraquark[16], fusion of heavy mesons into a tetraquark[17], and proposed X(3872) tetraquark[18]. The first-order mass formula is a reasonable choice for investigating the X(2900). In addition, the existence of a tetraquark state composed of quark clusters of four different flavors is of theoretical interest.

2.0 Model Formulation

Zel'dovich and Sakharov[19,20] 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 mass formulas are used as the basis for deriving a first-order tetraquark mass formula. 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. In addition, zero angular momentum is assumed to exist between the clusters.

This model was previously used to investigate tetraquark[14-18], pentaquark[21], and hexaquark[22] structures. These models are based on the baryon and meson mass relationships of Refs. 19 and 20.

The meson (m) mass (M) formula of Refs. 19 and 20 is:

$$M_m = \delta_m + m_1 + m_2 + b_m \frac{m_0^2}{m_1 m_2} \sigma_1 \cdot \sigma_2 \quad (1)$$

where m_1 (m_2) are the mass of the first (second) quark comprising the meson, m_o is the average mass of a first generation quark[23,24], 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 and 615 MeV, respectively[20]. In Eq. 1, the mesons are assumed to be in their lowest energy state. Since the meson cluster is assumed to reside in its lowest energy state, any excited meson cluster must include a correction term equal to the mass difference between the ground and excited states (See Eq. 5).

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[20].

In formulating the tetraquark mass formula, effective quark masses provided by Griffiths[23] 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 e), u(+2/3 e)], [s(-1/3 e), c(+2/3 e)], and [b(-1/3 e), t(+2/3 e)][24]. The three generations are specified by the square brackets and the quark charges are given within parentheses.

The quark charges are related to the number of colors (N_c) incorporated into the fundamental quantum chromodynamics (QCD) formulation[25,26]. For example, the first generation quark charges within SU(N_c) are:

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

$$Q_u = \frac{1}{2}\left(\frac{1}{N_c} + 1\right)e \quad (3)$$

For conventional QCD using 3 colors, the expected d and u electric charges are obtained. The importance of QCD expansions involving 1/N_c is outlined in Section 2.1 to illustrate the weak coupling assumption.

The first-order mass formula used in this paper partitions the tetraquark into two meson clusters. Following the possible X(2900) tetraquark structure[13], the meson clusters are assumed to be a D^{*-} meson ($J^\pi = 1^-, d\bar{c}$) weakly coupled to a K^{*+} meson ($J^\pi = 1^-, u\bar{s}$). However, the model as defined in previous publications is based on the lowest energy meson states (i.e., a D^- meson ($J^\pi = 0^-, d\bar{c}$) weakly coupled to a K^+ meson ($J^\pi = 0^-, u\bar{s}$) with excited state masses added to Eq. 1 using the approach noted in subsequent discussion (See Eqs. 4 and 5).

The weak coupling structure is incorporated to minimize model complexity, which is consistent with an initial first-order formulation. For the X(2900), the tetraquark mass formula M' (excluding any cluster excitation) is based on the following form:

$$M' = M_{sm1}[K^+] + M_{sm2}[D^-] + \Phi \quad (4)$$

where defines the interaction between the meson clusters, and $M_{sm1(2)}$ represents the K^+ and D^- scalar meson clusters defined by Eq. 1. 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. 4 represents a quasimolecular four quark system whose basic character is a weakly bound meson-meson system. As noted previously, both clusters are $J^\pi = 0^-$ scalar mesons (i.e., K^+ and D^-). For the X(2900) state, Eq. 4 is used as the starting point to provide the predicted mass value within the first-order approach for a tetraquark that has one or two excited meson clusters.

For the physical X(2900), the individual meson clusters are in excited states K^{*+} and D^{*-} and not the lowest energy meson (K^+ and D^-) states as assumed in the first order mass formula of Eq. 4. Therefore, the mass formula of Eq. 4 is modified following the methodology of Ref. 14:

$$M = M' + \Delta_1(K^{*+} - K^+) + \Delta_2(D^{*-} - D^-) \quad (5)$$

where Δ_1 is the K^{*+} - K^+ mass difference (891.76 MeV/c^2 – 493.677 MeV/c^2) and Δ_2 is the D^{*-} - D^- mass difference (2010.26 MeV/c^2 – 1869.65 MeV/c^2)[24].

The mass relationships of Eqs. 1, 4 and 5 do not predict the total angular momentum of the final tetraquark state, but do permit primitive spin coupling to be specified for the individual meson clusters. In addition, the angular momentum between the clusters is assumed to be zero. Specific angular momentum assignments based on the first-order mass formula for the X(2900) state are provided in subsequent discussion.

2.1 Justification for the Weak Coupling Assumption

A key assumption of the first-order mass formula of Eqs. 1, 4, and 5 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 $1/N_c$[27,28]. 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 $N_c \rightarrow \infty$ limit, and further justifies the weak coupling approximation.

The $1/N_c$ expansion[27,28] is well accepted in elementary particle physics and leads to the Okubo-Zweig-Iizuka (OZI) rule[29-31] and the Skyrme model[32,33]. 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[27,28]. This situation is also a characteristic of Eqs. 4 and 5.

3.0 Results and Discussion

The reader should note that the uncertainties in quark masses are likely much larger than any error caused by ignoring the cluster-cluster interaction. Therefore, a detailed quantification or further discussion of the cluster-cluster interaction within the first-order mass formula is not warranted.

The X(2900) data did not suggest a unique spin and parity assignment for this candidate state[13]. Each excited meson cluster (i.e., K^{*+} and D^{*-}) has $J^\pi = 1^-$. Given the weak coupling structure with zero angular momentum between the meson clusters, the first-order mass formula has a $\{ J^\pi(1) \otimes (L = 0) \otimes J^\pi(2) \}$angular momentum structure that reduces to $\{ 1^- \otimes 1^- \}$ for possible 0^+, 1^+, and 2^+ structures for the X(2900). The notation $J^\pi(i)$ for i = 1 and 2 represents the two excited meson clusters comprising the X(2900) tetraquark. Although the LHCb data do not support a definitive angular momentum assignment, spin 0 and 1 values were noted as possible assignments in the model dependent analysis[13]. These values are consistent with the primitive spin assignment of the weak coupling model proposed in this paper.

Eqs. 1, 4, and 5 are used to calculate the first-order mass formula results corresponding to the possible X(2900) state. The first-order mass formula of Eq. 5 predicts 2908 MeV/c^2 for the K^{*+} vector meson plus D^{*-} vector meson clusters. The experimental values derived from a model dependent analysis suggests spin 0 and spin 1 masses of X_0(2900) = 2866.3 MeV/c^2 and X_1(2900) = 2904.1 MeV/c^2, respectively[13]. The model value of Eqs. 1, 4, and 5 are 0.14 and 1.5% larger than the experimental spin 1 and spin 0 model analysis, respectively[13]. These results for the proposed X(2900) value are better than the expected accuracy of a first-order mass formula. This prediction suggests that the $K^{*+} + D^{*-}$ meson clusters form a quasimolecular tetraquark structure that is a possible representation for the proposed X(2900) state. Other calculations[34,35] also yield a reasonable description of the X(2900).

Lü et al.[34] systematically calculate the mass spectra of open charm and bottom tetraquarks within an extended "relativized" quark model. The four-body relativized Hamiltonian includes the following terms: (1) Coulomb potential, (2) confining potential, (3) spin-spin interactions, and (4) relativistic corrections. The resulting relations are solved using a variational method. Lü et al.[34] find that the predicted masses of four 0^+ open flavor states are 2765, 3065, 3152, and 3396 MeV/c^2. The authors of Ref. 34 suggest that their results disfavor the assignment of the newly observed X_0(2900) as a compact tetraquark. The 2765 and 3065 MeV/c^2 values are in reasonable agreement with the X(2900) experimental mass[13]. In addition, the results of Lü et al.[34] do not appear to rule out the weakly bound or quasimolecular structure proposed in this paper.

Zhang[35] explored the possibility of the X(2900) as an open charm tetraquark state with $J^\pi = 0^+$ using QCD sum rules. The results of Ref. 35 suggests a value of 2.75 – 2.77 GeV/c^2 for the X(2900). This range is in reasonable agreement with the experimental mass[13].

The theoretical results of this work and the work of Refs. 34 and 35 offer different possible models for the X(2900). All of these models are in reasonable agreement with the experimental value[13].

As noted previously, the predicted X(2900) first-order mass formula would be expected to underestimate the actual mass because the model assumes no contribution from the cluster-cluster interaction (Φ). Since the cluster-cluster interaction creates additional binding, the model will tend to underestimate the tetraquark mass. However, the X(2900) result is essentially in agreement with the data. This adds further support to the weakly bound nature of the X(2900) tetraquark.

4.0 Conclusions

The recently discovered tetraquark candidate X(2900) having the K^{*+} and D^{*-} structure is investigated using a first-order mass formula incorporating weakly interacting meson clusters. This first-order mass formula predicts that the X(2900) state has a mass of 2908 MeV/c^2 which is in reasonable agreement with the measured value[13]. The proposed X(2900) state is also reasonably described by the assumed four flavor quark structure utilizing two excited meson clusters.

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