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Possible Description of the Excited States of the Neutral Charmed Omega in Terms of a First-Order Pentaquark Mass Formula

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Abstract

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Recently proposed sscqq-bar pentaquark structures for the excited states of the neutral charmed omega are investigated using a first-order mass formula incorporating weakly interacting qq-bar meson and $\Omega^0{}_c$ baryon clusters. The results are compared to the predictions of the LHCb Collaboration.

The first-order pentaquark mass formula has typically yielded results within about 10% of the experimental mass values. Using this criterion, the $\Omega^0{}_c(2770)$, $\Omega^0{}_c(3000)$, $\Omega^0{}_c(3050)$, $\Omega^0{}_c(3065)$, $\Omega^0{}_c(3090)$, $\Omega^0{}_c(3119)$, and $\Omega^0{}_c(3185)$ states could be described by the ssc + uu-bar and ssc + dd-bar pentaquarks with the meson clusters uu-bar and dd-bar having a pseudoscalar configuration. The $\Omega^0{}_c(3185)$ is also described by the ssc + ss-bar with the ss-bar in a pseudoscalar state. In a similar manner, the $\Omega^0{}_c(3327)$ state could be described by the ssc + uu-barand ssc + dd-bar pentaquarks with the meson clusters uu-bar and dd-bar having a vector configuration, and a ssc + ss-bar pentaquark with the meson cluster ss-bar having a pseudoscalar configuration. The model is not sufficiently refined to distinguish between these states.

The only state with a specified J^π assignment is the $\Omega^0{}_c(2770)$. The Particle Data Group specifies a $3/2^+$ assignment. The first-order pentaquark allows both $1/2^+$ and $3/2^+$ values for all $\Omega^0{}_c$ excited states.

KEYWORDS: Pentaquark, first-order mass formula, quark model, excited states of the neutral charmed omega

1.0 Introduction

The possibility that hadrons could exist with structures beyond conventional qq or qqq quark configurations was noted by Gell-Mann[1]. Numerous data obtained by several collaborations (Belle, BABAR, LHCb, and BESII) produced exotic hadrons that appear to be inconsistent with the conventional quark model[2,3]. These structures have been suggested with a recent example noted in Ref. 4.

The LHCb Collaboration[4], recently reported the observation of new $\Omega^0{}_c$ excited states decaying to a $\Xi^+{}_c K^-$ final state.

As noted in Ref. 4, these Ω^0_c states have been studied from a variety of perspectives. Theoretical studies interpreted these states as excited bound states, baryon-meson molecular or quasibound states, and sscqq-bar pentaquark states[4]. These Ω^0_c states are ideal candidates than can be investigated using a first-order mass formula that has provided reasonable explanations for pentaquarks[6-11].

In order to determine the mass values as well as spin and parity assignments of these states, the first-order mass formula will be utilized. The states will be modeled as ssc baryon + qq-bar meson pentaquark structure. The model results will be compared to the excited states noted in Refs. 4 and 5: $\Omega^0_c(2770)$, $\Omega^0_c(3000)$, $\Omega^0_c(3050)$, $\Omega^0_c(3065)$, $\Omega^0_c(3090)$, $\Omega^0_c(3119)$, $\Omega^0_c(3185)$, and $\Omega^0_c(3327)$.

This paper utilizes the first-order mass formula model of Refs. 6-11 to investigate the Ω^0_c excited states. The model weakly couples an ssc baryon and a qq-bar meson. Given the masses of the proposed excited states only u, d, and s quarks provide candidates for the excited state Ω^0_c pentaquark configurations. The proposed methodology was previously used to examine other pentaquark configurations[6-11].

2.0 Model Formulation

Zel'dovich and Sakharov[12,13] proposed a semiempirical mass formula that provides a prediction of mesons and baryons masses in terms of effective quark masses. Within this formulation, quark wave functions are assumed to reside in their lowest S state. These mass formulas are used as the basis for deriving a first-order pentaquark mass formula. In particular, the model proposed in this paper assumes the pentaquark is partitioned between two and three quark clusters with the interaction between the clusters providing a minimal contribution to the pentaquark mass.

The meson (m) mass (M) formula of Refs. 12 and 13 is:

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

where m_1 (m_2) is the mass of the first (second) quark comprising the meson, m_0 is the average mass of a first generation quark[5,14], 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[13].

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

In a similar manner, the baryon (b) mass formula[12,13] is:

$$M_b = \delta_b + m_1 + m_2 + m_3 + Z(2a)$$

$$Z = \frac{b_b}{3}\left[\frac{m_0^2}{m_1 m_2}\sigma_1 \cdot \sigma_2 + \frac{m_0^2}{m_1 m_3}\sigma_1 \cdot \sigma_3 + \frac{m_0^2}{m_2 m_3}\sigma_2 \cdot \sigma_3\right] (2b)$$

where the m_i labels the three baryon quarks (i = 1, 2, and 3) and a_b and b_b are 230 MeV and 615 MeV, respectively[13]. For a particle with a total baryon spin 1/2, the following prescription is used if the baryon (comprised of three quarks q_1, q_2, and q_3) contains two identical quarks[13] q_2, and q_3

$$\sigma_2 \cdot \sigma_3 = 1/4 \quad (3)$$

$$\sigma_1 \cdot \sigma_2 = \sigma_1 \cdot \sigma_3 = -1/2 \quad (4)$$

For completeness, the reader should note that $\sigma_i \cdot \sigma_j$ has the value +1/4 for a J= 3/2 baryon. In addition, these basic $\sigma_i \sigma_j$ relationships must be modified if the baryon contains three different quarks. The methodology is detailed, and described in Ref. 13.

In formulating the pentaquark mass formula, effective quark masses provided by Griffiths[14] 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 Eqs. 1 and 2.

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(-1/3e), t(+2/3 e)] [5]. The three generations are specified by the square brackets and the quark charges are given within parenthesis in terms of the proton charge e.

The first-order mass formula used in this paper partitions the pentaquark into two clusters. The first cluster is a meson (m) and the remaining cluster is a baryon (b). Zero angular momentum is assumed between the two clusters. These simplifications are incorporated to minimize model complexity that is consistent with an initial first-order formulation. In particular, the pentaquark mass formula (M) is assumed to have the form:

$$M = M_m + M_b + \Phi \quad (5)$$

where Φ defines the interaction between the meson and baryon clusters. Within the scope of this mass formula, the meson-baryon cluster interaction is assumed to be weak and sufficiently small to be ignored. Accordingly, Eq. 5 represents a quasimolecular five quark system whose basic character is a weakly bound meson-baryon system. In the case of the sscqq-bar pentaquark system, the first cluster is a qq-bar meson and the remaining cluster is an ssc baryon.

The first-order pentaquark model only permits a primitive coupling structure between the clusters

$$J^\pi(\text{sscqq-bar}) = J^\pi(\text{ssc}) \times L \times J^\pi(\text{qq-bar}) \quad (6)$$

where L is the angular momentum between the clusters. Following the prescriptions of Ref. 13, the ssc baryon with two identical s quarks has a J^π(ssc) = $1/2^+$. The values utilized in Eq. 6 are J^π(ssc) = $1/2^+$, J^π(qq-bar) = 0^+, 1^+ and L = 0. Eq. 6

admits the following spin and parity for the Ω^0_c pentaquark states: $1/2^+$ and $3/2^+$. The coupling structure of Eq. 6 does not uniquely predict the spin and parity of the pentaquark state, and only provides a range of candidate J^π values for the Ω^0_c excited states.

3.0 Results and Discussion

Eqs. 1, 2, and 5 are used to calculate the mass of the sscqq-bar pentaquark. Only the u, d, and s quarks have masses that fall within the range of the values specified in Refs. 4 and 5. The first-order-mass formula predicts a range of sscqq-bar pentaquark masses as summarized in Table 1.

3.1 Ω^0_c(2770), Ω^0_c(3000), Ω^0_c(3050), Ω^0_c(3065), Ω^0_c(3090), Ω^0_c(3119), and Ω^0_c(3185)

The first-order mass formula has typically yielded results within about 10% of the experimental mass values[6-11]. Table 1 compares the measured results from Refs. 4 and 5 to the first-order pentaquark model results using this 10% value. Using this criterion, the Ω^0_c(2770), Ω^0_c(3000), Ω^0_c(3050), Ω^0_c(3065), Ω^0_c(3090), Ω^0_c(3119), and Ω^0_c(3185) states could be described by the ssc + uu-bar and ssc + dd-bar pentaquarks with the meson clusters uu-bar and dd-bar having a pseudoscalar configuration[13]. The model is not sufficiently refined to distinguish between these states. However, the sscqq-bar pentaquark model does represent the Ω^0_c(2770), Ω^0_c(3000), Ω^0_c(3050), Ω^0_c(3065), Ω^0_c(3090), Ω^0_c(3119), and Ω^0_c(3185) states within a 10% accuracy. The Ω^0_c(3185) is also described by the ssc + ss-bar with the ss-bar in a pseudoscalar state[13].

The only state with a specified J^π assignment is the Ω^0_c(2770). Ref. 5 specifies a $3/2^+$ assignment. The first-order pentaquark allows both $1/2^+$ and $3/2^+$ values. Neither Refs. 4 nor 5 provide a spin and parity assignment for the other excited states. The model allows for the possibility of $1/2^+$ and $3/2^+$ values. Additional data would be useful in characterizing these states as well as applicability of the first-order pentaquark model.

Table 1 Predicted First-Order Pentaquark Characteristics of the ssc + qq-bar Configurations

Model[a]	Mass (MeV/c^2)	J^π	Possible Ω^0_c Excited State[b]
ssc + uu-bar(0)	2991	$1/2^+$, $3/2^+$	Ω^0_c(2770), Ω^0_c(3000), Ω^0_c(3050), Ω^0_c(3065), Ω^0_c(3090), Ω^0_c(3119), and Ω^0_c(3185)
ssc + uu-bar(1)	3614	$1/2^+$, $3/2^+$	Ω^0_c(3327)
ssc + dd-bar(0)	3010	$1/2^+$, $3/2^+$	Ω^0_c(2770), Ω^0_c(3000), Ω^0_c(3050), Ω^0_c(3065), Ω^0_c(3090), Ω^0_c(3119), and Ω^0_c(3185)
ssc + dd-bar(1)	3618	$1/2^+$, $3/2^+$	Ω^0_c(3327)
ssc + ss-bar(0)	3535	$1/2^+$, $3/2^+$	Ω^0_c(3185) and Ω^0_c(3327)
ssc + ss-bar(1)	3832	$1/2^+$, $3/2^+$	---

[a]The values in parenthesis (total spin of the meson cluster) indicates a pseudoscalar meson (0) or vector meson (1).

[b]The first-order mass formula value is within 10% of the experimental mass.

3.2 Ω^0_c(3327)

Using the 10% criterion, the Ω^0_c(3327) state could be described by the ssc + uu-barand ssc + dd-bar pentaquarks with the meson clusters uu-bar and dd-bar having a vector configuration, and a ssc + ss-bar pentaquark with the meson clusters ss-bar having a pseudoscalar configuration[13]. The model is not sufficiently refined to distinguish between these pentaquark states and the experimental predictions.

No spin and parity assignment is provided for the Ω^0_c(3327) state[4,5]. The model allows for the possibility of $J^\pi = 1/2^+$ and $3/2^+$ values.

4.0 Conclusions

The first-order mass formula has typically yielded results within about 10% of the experimental mass values[6-11]. Using this criterion, the Ω^0_c(2770), Ω^0_c(3000), Ω^0_c(3050), Ω^0_c(3065), Ω^0_c(3090), Ω^0_c(3119), and Ω^0_c(3185) states could be described by the ssc + uu-bar and ssc + dd-bar pentaquarks with the meson clusters uu-bar and dd-bar having a pseudoscalar configuration. The Ω^0_c(3185) is also described by the ssc + ss-bar with the ss-bar in a pseudoscalar state[13].

In a similar manner, the Ω^0_c(3327) state could be described by the ssc + uu-barand ssc + dd-bar pentaquarks with the meson clusters uu-bar and dd-bar having a vector configuration, and a ssc + ss-bar pentaquark with the meson clusters ss-bar having a pseudoscalar configuration. The model is not sufficiently refined to distinguish between these states.

The only state with a specified J^π assignment is the Ω^0_c(2770)[4,5]. Ref. 5 specifies a $3/2^+$ assignment. The first-order pentaquark allows both $1/2^+$ and $3/2^+$ values for all Ω^0_c excited states.

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