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First-Order Model for Determining the Characteristics of the Ω_{cc}^{+} and Ξ_{cc}^{+} Baryons

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Abstract

The LHCb Collaboration recently observed the existence of the Ω_{cc}^{+} baryon and confirmed the Ξ_{cc}^{+} resonance. These states are important because they complete the SU(4)$_f$ spin-1/2 20-plet of ground-state baryons.

These structures are investigated as weakly coupled ccs and ccd baryons. Baryon masses and their spin and parity assignments are defined utilizing the methodology of Zel'dovich and Sakharov. The first-order models provides a set of J$^{\pi}$ values including the experimental 1/2^{+} value. Model mass predictions are within about 2% of the LHCb values.

Keywords: First-Order Mass Formula, Ω_{cc}^{+} and Ξ_{cc}^{+} Baryons, Resonances, Cluster Model, and Quark Model

1. Introduction

In Ref. 1, the LHCb Collaboration observed the existence of the Ω_{cc}^{+} baryon and confirmed the Ξ_{cc}^{+} resonance. The measured mass of the Ω_{cc}^{+} is 3725.9 MeV/c², and the mass of the Ξ_{cc}^{+} is 3619.97 MeV/c^{2e}. These states complete the SU(4)$_f$ spin-1/2 20-plet of ground-state baryons [1].

This paper investigates the Ω_{cc}^{+} and Ξ_{cc}^{+} structures as weakly coupled ccs and ccd baryons, respectively. The baryon substructures of these pentaquarks are defined utilizing the first-order methodology of Zel'dovich and Sakharov [2, 3]. First-order models were previously used to describe other baryons [4, 5].

The methodology of Refs. [2-5] provides a primitive angular momentum coupling structure and a methodology to predict the baryon mass. Previous calculations [4-15] have provided reasonable results for baryons and multiquark systems.

2. Formalism

The first-order baryon model uses the approach of Refs. 2 and 3 to determine mass values utilizing the relationship:

$$\mathbf{M_b = \delta_b + m_1 + m_2 + m_3 + (b/3)\,[(m_0^2 / m_1 m_2)\,\sigma_1\cdot \sigma_2 + (m_0^2 / m_1 m_3)\,\sigma_1\cdot \sigma_3 + (m_0^2 / m_2 m_3)\,\sigma_2\cdot \sigma_3]} \quad (1)$$

Where δ_b = 230 MeV/c^2, m_i is the mass of the quark comprising the baryon (i = 1, 2, 3), m_0 is the average mass of a first generation quark, and b = 615 MeV/c^2. In Eq. 1, the values of $\sigma_i\cdot \sigma_j$ depend on the baryon spin. For a J = 3/2 baryon, $\sigma_i\cdot\sigma_j$ has the value 1/4. If the total baryon spin is 1/2 and it has two *identical* quarks q_2 and q_3, the values of $\sigma_i\cdot \sigma_j$ are:

$$\sigma_2\cdot \sigma_3 = 1/4 \text{ and } \sigma_1\cdot \sigma_2 = \sigma_1\cdot \sigma_3 = -1/2 \quad (2)$$

If the baryon contains three different quarks, then the values of $\sigma_i\cdot \sigma_j$ are defined by the methodology of Refs. 2 and 3.

The first-order mass formula assumes that the baryon resides in its ground state, and there is zero angular momentum between the quarks. If excited states are involved, the difference in masses between the excited and ground states must be considered. The baryon methodology was also utilized in Refs. 6-15.

Eq. 1 utilizes effective quark masses. These masses were determined by Griffiths [16] for d, u, s, c, b, and t quarks that have the values 340, 336, 486, 1550, 4730, and 177000 MeV/c^2, respectively. Using the convention of the Standard Model [16, 17], the 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)] [16, 17]. Quark charges are given within the parentheses in terms of the unit charge e.

3. Results and Discussion

The Ω_{cc}^{+} and Ξ_{cc}^{+} are modeled as ccs and ccd systems, respectively. The spin and parity assignments are provided by the primitive coupling structure of the assumed baryon structures. Masses are obtained from the application of Eq. 1.

3.1 Predicted Spin and Parity Assignments

Given these ccs and ccd assignments, the total spin and parity of the assumed configurations, within the scope of the first-order model, are obtained by coupling the quark spins. The baryon spin couples the three quarks each with $J^{\pi}=1/2^{+}$.

Therefore, the Ω_{cc}^{+} and Ξ_{cc}^{+} baryons can assume the values:

$$J^{\pi}(\Omega_{cc}^{+} \text{ and } \Xi_{cc}^{+}) = 1/2^{+} \otimes 1/2^{+} \otimes 1/2^{+} = 1/2^{+}, 3/2^{+} \quad (3)$$

The 1/2+ value is in agreement with the experimental value [1].

3.2 Predicted Mass Values

The Ω_{cc}^{+} and Ξ_{cc}^{+} mass values, as predicted by the first-order model, are given by Eq. 1 utilizing a ccs and ccd configuration, respectively. The first order methodology [2, 3] leads to the values summarized in Table 1.

Table 1: Ω_{cc}^{+} and Ξ_{cc}^{+} Mass and J^{π} Values

Baryon	First-Order Model			Experiment		
	Configuration	J^{π}	Mass (MeV/c^2)	Configuration	J^{π}	Mass (MeV/c^2)
Ω_{cc}^{+}	ccs	$1/2^{+}, 3/2^{+}$	3787.3	ccs	$1/2^{+}$	3725.9
Ξ_{cc}^{+}	ccd	$1/2^{+}, 3/2^{+}$	3628.0	ccd	$1/2^{+}$	3619.97

Model spin and parity values include the experimental $1/2^{+}$ value [1] as well as a $3/2^{+}$ assignment. The model spin and parity methodology is primitive and does not distinguish between these assignments.

The mass values are also in reasonable agreement with the data [1]. Model mass values for the Ω_{cc}^{+} (Ξ_{cc}^{+}) are within about 1.6% (0.2%) of the experimental values [1]. These results are consistent with the accuracy of previous calculations [4-15].

4. First-Order Baryon 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 quarks also limits the evaluation of possible states.

The values for the effective quark masses [16] are not definitive. Interactions are not rigorously modeled, and necessitates an assumed weak coupling structure. Although the weak coupling assumption appears to be reasonable, the exact magnitude for the interaction strength between the quark clusters is unknown [4-15]. 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 [4-15] for candidate baryon systems.

5. Justification for the Weak Coupling Assumption

The weak coupling assumption is based upon basic quantum chromodynamics (QCD) formulation [18, 19]. In particular, this assumption is derived from the nature of QCD expansions related to the nature of the color interaction.

The quark charges are related to the number of colors (N_c) incorporated into the fundamental QCD methodology. For example, the first generation quark charges within SU(N_c) are:

$$Q_d = \frac{1}{2}\left(\frac{1}{N_c} - 1\right)e \quad (4)$$

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

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 [18, 19].

A key assumption of the first-order mass formula of Eq. 1 is weak coupling between the two clusters. In particular, the model utilized in this paper assumes the baryon is defined by quark clusters with the interaction between the clusters providing a minimal contribution to the baryon mass. Within the scope of this mass formula, the quark cluster interaction is assumed in Eq. 1 to be weak and sufficiently small to be ignored.

This assumption is justified because QCD can be investigated as an expansion in $1/N_c$ [20, 21]. The large N_c limit reduces to a field theory of weakly interacting meson-like objects composed of quarks. 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 [20, 21] is well accepted in elementary particle physics and leads to the Okubo-Zweig-Iizuka (OZI) rule [22-24] and the Skyrme model [25, 26]. 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 [20, 21]. This situation is also a characteristic of Eq. 1.

6. Conclusions

The existence of the Ω_{cc}^{+} and Ξ_{cc}^{+} baryons was recently confirmed by the LHCb Collaboration. These states are important because they complete the $SU(4)_f$ spin-1/2 20-plet of ground-state baryons [1].

The Ω_{cc}^{+} and Ξ_{cc}^{+} baryons are investigated as weakly coupled ccs and ccd structures. Baryon masses and their spin and parity assignments are defined utilizing the methodology of Zel'dovich and Sakharov. The first-order models provides a set of J^{π} values including the experimental $1/2^{+}$ value. Model mass predictions are within 2% of the LHCb values.

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