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Double Charm Baryons $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$

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Abstract
An application of the first-order model of Zel'dovich and Sakharov is used to determine the theoretical double charm baryon masses for the $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$. The primitive spin structure of the model predicts $1/2^+$ and $3/2^+$ assignments for these double charm baryons. A first-order Ξ_{cc}^{++} baryon mass is calculated to be within about 2% of the experimental value. The Ξ_{cc}^{+} was recently reported, but no definitive mass or spin assignment were provided. A Ω_{cc}^{+} has also been postulated. Theoretical masses for the $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ baryons are also provided in this paper. The calculated masses depend on the J^π value following the formulation of the first-order model.

Keywords: Double Charm Baryons, Quark Model, Masses

1. Introduction

Multiplets of baryon and meson states are predicted by the quark model [1-3]. Those lowest energy group of states is composed of the lightest four quarks (u, d, s, c) that form SU(4) multiplets [4]. Numerous states with zero or one charm quark have been discovered, and some mesons have two charm quarks [4, 5]. Ref. 4 observed a baryon (ccu) with two charm quarks (i.e., Ξ_{cc}^{++}). The LHCb Collaboration [4] also suggested the existence of additional double charm baryons (i.e., $\Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$). Each of these double charm baryons are predicted to have $J^\pi = 1/2^+$ [4]. Ref. 5 provides a mass of 3621.4 MeV/c^2 for the Ξ_{cc}^{++}.
Recently, the LHCb Collaboration discovered a new particle composed of two charm quarks and one down quark (Ξ_{cc}^{+}) [6]. No mass or J^π values were provided in the press release [6]. This paper estimates the masses of these double charm baryons using a first-order model [7, 8]. In view of the uncertainties in the J^π assignments, the first-order model calculations were performed for both possible $1/2^+$ and $3/2^+$ values.

2. Formalism

The baryon (b) mass is determined utilizing the methodology of Zel'dovich and Sakharov [7, 8].

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

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:

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

If the baryon contains three different quarks, then the values of $\sigma_i \cdot \sigma_j$ are defined by the methodology of Refs. 7 and 8.
Eq. 1 utilizes effective quark masses. These masses were determined by Griffiths [9] 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 [5, 9], 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)]. Quark charges are given within the parentheses in terms of the unit charge e.

3. Results and Discussion

The theoretical $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ baryon masses and their associated J^{π} values are determined within the scope of the first-order approach [7, 8]. These results are theoretical and should serve as a guide for future experimental efforts that investigate double charm baryons.

3.1 Predicted Spin and Parity Assignments

The $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ structures are modeled using the approach of Refs. 7 and 8. Given these cluster configurations, the total spin and parity of the assumed configurations within the scope of the first-order model are:

$$J^{\pi}(t\,t\,t) = \frac{1}{2}^{+} \otimes \frac{1}{2}^{+} \otimes \frac{1}{2}^{+} = \frac{1}{2}^{+}, \frac{3}{2}^{+} \quad (3)$$

3.2 Predicted Mass Values

The $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ mass values as predicted by the first-order model are determined by Eq. 1. Using this relationship, the $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ mass values are presented in Table 1 for both possible spin and parity values.

Table 1: Predicted and Experimental $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ Masses

Baryon	Quark Content	J^{π}	Mass Values (MeV/c^2)	
			This Work	Experiment[a]
Ξ_{cc}^{+}	ccd	$1/2^+$	3628.0	-----
Ξ_{cc}^{++}	ccu	$1/2^+$	3623.5	3621.4
Ω_{cc}^{+}	ccs	$1/2^+$	3787.3	-----
Ξ_{cc}^{+}	ccd	$3/2^+$	3694.7	-----
Ξ_{cc}^{++}	ccu	$3/2^+$	3690.9	-----
Ω_{cc}^{+}	ccs	$3/2^+$	3834.0	-----

[a] Ref. 4.

4. Results and Discussion

The first-order model results for both possible J^{π} values are provided in Table 1. Ref. 4 predicts a $1/2^+$ value for the Ξ_{cc}^{++} and other double charm baryons, but Ref. 5 does not provide a definitive spin and parity value.

An experimental mass value of 3621.4 MeV/c^2 is within 0.1% (2%) of the $1/2^+$ ($3/2^+$) first- order model results. Mass values are also predicted for the $\Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$. Although there are no corresponding experimental values, the results are internally consistent with the calculated masses summarized in Table 1 and the limited experimental data [4, 5].

5. Conclusions

The first-order model of Zel'dovich and Sakharov is used to determine theoretical the $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ baryon masses. The primitive spin structure of the model predicts $1/2^+$ and $3/2^+$ for the $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ baryons. First-order model results are within 2% of the available experimental mass value for the Ξ_{cc}^{++}.

The Ξ_{cc}^{+} was recently reported, but no definitive mass or spin assignment were provided, and an Ω_{cc}^{+} has also been postulated. Theoretical masses for the $\Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ baryons depend on the J^{π} value following the formulation of the first-order model. The predicted masses for the double charm $\Xi_{cc}^{++}, \Xi_{cc}^{+}, \text{and}\, \Omega_{cc}^{+}$ baryons appear to be internally consistent.

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