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First-Order Model for Determining the Characteristics of the Λ_c^+ Baryon

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Abstract

The ALICE Collaboration recently addressed the existence of the Λ_c^+ baryon. This group noted that the hadronization of heavy quarks constitutes an important probe of the quark-gluon plasma.

The Λ_c^+ is investigated as a weakly coupled udc structure.

This baryon's mass and spin and parity assignment 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 8% of the experimental value.

Keywords: First-Order Mass Formula, Λ_c^+ Baryon, Charm Resonance, Cluster Model, and Quark Model

1. Introduction

Ultrarelativistic heavy-ion collisions provide an important method for probing quantum chromodynamics under extreme temperature and energy density conditions ^[1, 2]. As noted by the ALICE Collaboration ^[1], the hadronization of heavy quarks constitutes an important probe of the quark-gluon plasma created in these collisions. Due to their large masses, heavy quarks are predominantly produced in these ultrarelativistic collisions. These quarks comprise charmed baryons including the Λ_c^+ .

In this context, the studies of charm baryons, including the Λ_c^+ , are essential to understand charm hadronization. Various theoretical approaches have been developed to describe the production of charmed hadrons in heavy-ion collisions. These include statistical models, transport models, and quark recombination models ^[1, 2]. Similar baryon systems have been evaluated using the methodology of Zel'dovich and Sakharov ^[3, 4] with reasonably credible results.

This paper investigates the Λ_c^+ structure as a weakly coupled udc baryon. The methodology of Refs. ^[3-7] provides a primitive angular momentum coupling structure and a methodology to predict the baryon mass. Previous calculations ^[5-17] provided reasonable results for baryons and multi-quark systems involving baryons.

2. Formalism

The first-order baryon model uses the approach of Refs. 3 and 4 to determine mass values utilizing the relationship:

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

Where $\delta_b = 230 \text{ MeV}/c^2$, 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 $b = 615 \text{ MeV}/c^2$. 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. 3 and 4.

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. 5-17.

Eq. 1 utilizes effective quark masses. These masses were determined by Griffiths ^[18] 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 ^[18, 19], the

quarks are grouped into three generations: $[d(-1/3), u(+2/3)]$, $[s(-1/3), c(+2/3)]$, and $[b(-1/3), t(+2/3)]$ ^[18, 19]. Quark charges are given within the parentheses in terms of the unit charge e .

3. Results and Discussion

The Λ_c^+ is modeled as a udc system. The spin and parity assignments are provided by the primitive coupling structure of the assumed baryon structure. Masses are obtained from the application of Eq. 1.

3.1 Predicted Spin and Parity Assignments

Given the udc configuration, the total spin and parity of the Λ_c^+ baryons, within the scope of the first-order model, is obtained by coupling the quark spins. The baryon spin couples the three quarks each with $J^\pi = 1/2^+$. Therefore, the Λ_c^+ baryons can assume the values:

$$J^\pi(\Lambda_c^+) = 1/2^+ \otimes 1/2^+ \otimes 1/2^+ = 1/2^+, 3/2^+ \quad (3)$$

Model spin and parity values include the experimental $1/2^+$ value ^[1, 2, 19] as well as a $3/2^+$ assignment. The model spin and parity methodology is primitive and does not distinguish between these assignments.

3.2 Predicted Mass Values

The Λ_c^+ mass value, as predicted by the first-order model, is given by Eq. 1. The first order methodology ^[3, 4] leads to a predicted mass of 2462.6 MeV/ c^2 . This value is about 8% larger than the experimental value ^[19]. These results are consistent with the accuracy of previous calculations ^[5-17].

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 ^[18] are not definitive. Interactions are not rigorously modeled, and this 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 ^[5-17]. The coupling strength will likely depend on the physical properties of the interacting systems.

In addition, the interaction strength is likely much smaller than the quark masses. This consideration also justifies the weak coupling approximation. In spite of these uncertainties, the model continues to provide reasonably credible results ^[5-17] for candidate baryon systems.

5. QCD Justification for the Weak Coupling Assumption

The weak coupling assumption is based upon basic quantum chromodynamics (QCD) formulation ^[20, 21]. 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 ^[20, 21].

A key assumption of the first-order mass formula of Eq. 1 is weak coupling between the quark 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 $1/N_c$ ^[22, 23]. 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 ^[22, 23] is well accepted in elementary particle physics and leads to the Okubo-Zweig-Iizuka (OZI) rule ^[24-26] and the Skyrme model ^[27, 28]. 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 ^[22, 23]. This situation is also a characteristic of Eq. 1.

6. Conclusions

The existence of the Λ_c^+ baryon was recently investigated by the ALICE Collaboration. This baryons is investigated as a weakly coupled udc structure. The baryon mass and its spin and parity assignment 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 8% of the experimental value.

7. References

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