Spin-parity quantum numbers of $\Xi_c(2882)$ via relativistic flux tube model

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Introduction

The Ξ_c and Ξ_c' baryons offer an ideal structure to investigate the dynamics of an up/down quark and a strange quark in the presence of a charm quark. Recently, a tremendous amount of work has gone into measuring the characteristics of these charmed baryons.

The Ξ_c baryon has established states in $1S$- and $1P$-waves. But only the $1S$-wave states for the Ξ_c' baryon have been identified. Additionally, the experiment has observed a number of excited states, denoted as $\Xi_c(2923)$, $\Xi_c(2930)$, $\Xi_c(2939)$, $\Xi_c(2965)$, $\Xi_c(2970)$, $\Xi_c(3055)$, $\Xi_c(3080)$, and $\Xi_c(3123)$ [1]. These observations have driven various theoretical approaches, including the quark model [2–6], Regge phenomenology [7], lattice QCD [8], QCD sum rules [9], and relativistic flux tube model [10, 11]. In 2023, the LHCb discovered the initial evidence of a $\Xi_c(2882)$ state. This recent discovery has prompted us to determine its spin and parity in order to establish their mass spectrum [12].

The relativistic flux tube (RFT) model with a quark-diquark representation of a baryon is used to figure out the mass of the first orbitally excited states of the Ξ_c' baryons. We have incorporated the j-j coupling scheme to account for spin-dependent interactions. The objective is to determine the spin-parity quantum numbers of the $\Xi_c(2882)$ state based on the computed masses in this study.

Theoretical Framework

The Ξ_c' baryon consists of one charm quark (c), one strange quark (s), and one light quark (u or d). Under the RFT model, a diquark is linked to a charm quark by means of a thin string-like structure of string tension $\mathcal{T}$. The complete system, comprising a charm quark, diquark, and flux tube, undergoes constant relativistic rotation around its centre of mass. In this theoretical framework, the relation between mass ($\bar{M}$) and angular momentum quantum number (L) can be derived as [10, 11, 13–16]

$$(\bar{M} - m_c)^2 = \frac{\sigma}{2}L + (m_{\mathcal{D}} + m_c v_c^2)^2. \quad (1)$$

Here, masses of charm quark and diquark are denoted as m_c and $m_{\mathcal{D}}$, respectively. We denote a charm quark's velocity as v_c. Let $\sigma = 2\pi T$.

Within this model, the distance between the charm quark and the diquark is defined as[11]

$$r = (v_1 + v_2)\sqrt{\frac{8L}{\sigma}}, \quad (2)$$

where v_1 represents the speed of a diquark.

Given the assumption of spinless quarks in the RFT model, it is necessary to consider the effect of spin-dependent interactions on mass from the QCD-motivated quark potential model, as

$$\Delta M = H_{so} + H_t + H_{ss}. \quad (3)$$

The spin-orbit interaction H_{so} is formed by the short-range one-gluon exchange contribution and the long-range Thomas-precession term, as [17]

$$H_{so} = [(\frac{2\alpha}{3r^3} - \frac{b}{2r})\frac{1}{m_{\mathcal{D}}^2} + \frac{4\alpha}{3r^3}\frac{1}{m_c m_{\mathcal{D}}}]\mathbf{L}.\mathbf{S}_{\mathcal{D}} + [(\frac{2\alpha}{3r^3} - \frac{b}{2r})\frac{1}{m_c^2} + \frac{4\alpha}{3r^3}\frac{1}{m_c m_{\mathcal{D}}}]\mathbf{L}.\mathbf{S_c}. \quad (4)$$

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Moreover, the tensor interaction is

$$H_t = \frac{4\alpha}{3r^3}\frac{1}{m_c m_{\mathcal{D}}}[\frac{3(\mathbf{S}_{\mathcal{D}}.\mathbf{r})(\mathbf{S_c}.\mathbf{r})}{r^2} - \mathbf{S}_{\mathcal{D}}.\mathbf{S_c}], \tag{5}$$

and the spin-spin interaction is expressed as

$$H_{ss} = \frac{32\alpha\sigma_0^3}{9\sqrt{\pi}m_c m_{\mathcal{D}}} e^{-\sigma_0^2 r^2}\mathbf{S}_{\mathcal{D}}.\mathbf{S_c}. \tag{6}$$

Here, α, b, and σ_0 are the model parameters. $\mathbf{S_c}$ and $\mathbf{S}_{\mathcal{D}}$ correspond to the spins of the charm quark and diquark, respectively. An orbital angular momentum of the system is denoted as $\mathbf{L}$.

For single charmed baryons, the $j-j$ coupling scheme is preferable because it favours heavy quark symmetry. In this method, the total angular momentum of the diquark, or $\mathbf{j}$, is obtained by first coupling $\mathbf{S_d}$ with $\mathbf{L}$. Afterwards, coupling $\mathbf{j}$ with $\mathbf{S_c}$ yields the total angular momentum, or $\mathbf{J}$. The experimentally observable states of singly charmed baryons are used to derive the model's parameters [11]. We first use Eq. (1) to determine the spin average mass of the $1P$-wave of the $\Xi_c^{'}$ baryon using these known parameters. Next, we incorporate spin-dependent splitting to determine the masses of five possible 1P-wave states.

Results and Discussion

The calculated masses of the five $1P$-wave states of the $\Xi_c^{'}$ baryon in the quark-diquark picture are shown in Tables I. The masses of experimentally observed states, as listed in PDG[1], are then compared to these calculated masses. For comparison, we also display the mass predictions from other theoretical model [2]. We note that our calculated mass of the $|1P, \frac{1}{2}^-\rangle_{j=0}$ state in our model is extremely close to the experimentally measured mass of $\Xi_c(2882)$ by LHCb. This strongly suggests that $\Xi_c(2882)$ could be a $1P$-wave candidate with spin-parity $J^P = \frac{1}{2}^-$.

TABLE I: Masses of $1P$-wave states of $\Xi_c^{'}$ baryons (in MeV)

States $\|nL, J^P\rangle_j$	Present	PDG [1]	[2]
$\|1P, 1/2^-\rangle_{j=0}$	2873.3	2882.00±9.0	2854
$\|1P, 1/2^-\rangle_{j=1}$	2886.4	2923.20±0.4	2936
$\|1P, 3/2^-\rangle_{j=1}$	2937.9	2938.55±0.3	2912
$\|1P, 3/2^-\rangle_{j=2}$	2992.9		2935
$\|1P, 5/2^-\rangle_{j=2}$	3030.5		2929

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References

[1] S. Navas *et al.* [Particle Data Group], Phys. Rev. D **110** 030001 (2024).
[2] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Rev. D **84**, 014025 (2011).
[3] Z. Shah, K. Thakkar, and A. K. Rai, Eur. Phys. J. A **52**, 313 (2016).
[4] B. Chen *et al.*, Eur. Phys. J. C **77**, 154 (2017).
[5] K. Gandhi and A. K. Rai, Eur. Phys. J. Plus **135**, 213 (2020).
[6] Z.-Y. Li *et al.*, *Chin. Phys. C* **47**, 073105 (2023).
[7] J. Oudichhya and A K Rai *Eur.Phys.J.A*, **59**, 123 (2023).
[8] P. Perez-Rubio, S. Collins, and G. S. Bali, Phys. Rev. D **92**,034504(2015).
[9] Z. G. Wang, Eur. Phys. J. A **47**, 81(2011).
[10] B. Chen, K. W. Wei, and A. Zhang, Eur. Phys. J. A **51**, 82 (2015).
[11] P. Jakhad *et al.*, *Phys. Rev. D* **108**, 014011 (2023).
[12] R. Aaij *et al.* [LHCb],Phys. Rev. D **108**, 012020 (2023).
[13] P. Jakhad, J. Oudichhya and A. K. Rai, [arXiv:2407.01655 [hep-ph]].
[14] P. Jakhad, J. Oudichhya and A. K. Rai, DAE Symp. Nucl. Phys. **67**, 935-936 (2024).
[15] P. Jakhad, J. Oudichhya and A. K. Rai, PoS **HQL2023** 091 (2023).
[16] P. Jakhad, J. Oudichhya and A. K. Rai, [arXiv:2409.07789 [hep-ph]].
[17] B. Chen *et al.*, Phys. Rev. D **105**, 074014 (2023).