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Exploring higher excitations of Σ_c baryons in the relativistic flux tube approach

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Motivated by recent experimental advancements to explore and identify the new singly charmed baryons at particle accelerators like the LHCb, we perform a study on Σ_c baryons by applying the quark-diquark structure of baryons. The Regge relation, derived in the framework of the relativistic flux tube model, is used to find the spin average mass of the different orbital excitations. Further, we include spin-dependent interactions in the j-j coupling scheme to find the spin-dependent splitting. Our mass predictions for states belonging to the $1F$- and $1G$-waves can help future experimental studies detect these unobserved states of the Σ_c baryonic family.

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1. Introduction

Investigating the way the charm quark interacts with the light quarks in a singly charmed baryon can help us gain a better understanding of the dynamics of the strong force within a baryon. Experimental discoveries and theoretical ideas have led to the identification of over forty singly charmed baryons [1]. Particle detectors at the LHC, Belle, BaBar, etc., have an essential role in capturing these short-lived particles.

The first experimental detection of the Σ_c baryons commenced with the identification of its ground state $\Sigma_c(2455)$ at Brookhaven National Laboratory in 1975 [2]. Subsequently, in the year 1993, $\Sigma_c(2520)$ was detected at the Gargamelle bubble chamber [3]. Currently, the $\Sigma_c(2455)$ and $\Sigma_c(2520)$ states are recognized as well-established states in the $1S$-wave, with spin-parity values of $J^P = 1/2^+$ and $3/2^+$, respectively. To this point, only one excited state of the Σ_c baryon, named $\Sigma_c(2800)$, has been detected in the $\Lambda_c^+\pi$ channel through the collaborative efforts of Belle and *BABAR* [4, 5]. However, the spin and parity of this state remain undetermined.

To further explore the mass spectrum of excited Σ_c baryons, several theoretical approaches have been employed in the last few years. Some of these studied include the relativistic quark potential model [6], the Godfrey-Isgur relativized quark model [7], the hyper central constituent quark model [8, 9], Regge phenomenology [10], and non-relativistic potential model [11]. In our prior study, we employed a relativistic flux tube model to compute the mass spectra of Σ_c baryons up to the $1D$-wave [12, 13]. The mass predictions we made were highly consistent with the masses of the experimentally observed states. Therefore, in this article, we extend the existing model with the same set of parameters to compute the masses of the states in the $1F$- and $1G$-waves that have not yet been observed in experiments.

The paper is organized in the following manner: Sec. 2 provides a theoretical overview of the relativistic flux tube model and the spin-dependent interactions used in this work. We tabulate the results in Sec. 3. Finally, in Sec. 4, we provide our conclusion.

2. Theoretical framework

In the relativistic flux tube (RFT) model, we study the Σ_c baryon in a configuration where a gluonic field-filled flux tube having the string tension T connects a heavy charm quark (c) and a light diquark (qq, where q is either a u or d quark). Further, this configuration is rotating around its center of mass at a relativistic speed. The Regge relation between mass (M) and angular momentum quantum number (L) of the system can be derived within this framework as [12]

$$(M - m_c)^2 = \frac{\sigma}{2}L + (m_{qq} + m_c v_c^2), \tag{1}$$

where $\sigma = 2\pi T$. The effective masses of the charm quark and diquark are denoted as m_c and m_{qq}, respectively. v_c is the speed of a charm quark.

In the original version of the RFT model, the quarks are seen as a spinless particles. But due to the presence of spin in quarks, it is required to include the spin-dependent interactions derived from the QCD-inspired quark model as follows [14]:

$$H_{so} = [(\frac{2\alpha}{3r^3} - \frac{b}{2r})\frac{1}{m_{qq}^2} + \frac{4\alpha}{3r^3}\frac{1}{m_c m_{qq}}]\mathbf{L}.\mathbf{S_{qq}} + [(\frac{2\alpha}{3r^3} - \frac{b}{2r})\frac{1}{m_c^2} + \frac{4\alpha}{3r^3}\frac{1}{m_c m_{qq}}]\mathbf{L}.\mathbf{S_c}, \tag{2}$$

$$H_t = \frac{4\alpha}{3r^3}\frac{1}{m_c m_{qq}}[\frac{3(\mathbf{S_{qq}}.\mathbf{r})(\mathbf{S_c}.\mathbf{r})}{r^2} - \mathbf{S_{qq}}.\mathbf{S_c}], \text{ and } H_{ss} = \frac{32\alpha\sigma_0^3}{9\sqrt{\pi}m_c m_{qq}}e^{-\sigma_0^2 r^2}\mathbf{S_{qq}}.\mathbf{S_c}. \quad (3)$$

Here, H_{so}, H_t, and H_{ss} are the spin-orbit interaction energy, the tensor interaction energy, and the spin-spin contact hyperfine interaction energy, respectively. The spins of the charm quark and diquark are denoted by $\mathbf{S_c}$ and $\mathbf{S_{qq}}$, respectively. α represents the coupling constant. The values of parameters b and σ_0 can be determined by analysing experimental data. r is the distance of a diquark from a charm quark, and in the RFT model, it is related to the angular momentum quantum number by the relation, $r = (v_{qq} + v_c)\sqrt{8L/\sigma}$.

In the case of heavy-light baryons, the preferred coupling scheme is the j-j coupling scheme, where the initial coupling of the spin of the diquark, $\mathbf{S_{qq}}$, with the orbital angular momentum $\mathbf{L}$ results in the total angular momentum of the diquark, $\mathbf{j}$. Then, the coupling of $\mathbf{j}$ with the spin of the charm quark, $\mathbf{S_c}$, leads to the total angular momentum, $\mathbf{J}$. Hence, we calculate the expected values of the operators engaged in spin-dependent interactions in the j-j coupling scheme.

To calculate masses of the higher excited states of Σ_c baryon, eight parameters (v_{qq}, v_c, m_c, m_{qq}, σ, α, b, and σ_0) in Eq.1-3 should be determined. The light diquark's ultra-relativistic nature suggests that $v_{qq} \approx 1$. To find m_c in Eq. 1, we use experimentally well-defined states of the Λ_c baryons, such as Λ_c^+, $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2860)^+$, and $\Lambda_c(2880)^+$. Then, using the relation $m_c = m_{c0}/\sqrt{1 - v_c^2}$, we extract v_c, where the current quark mass of the charm quark is m_{c0}=1.27 ± 0.025 GeV [1]. To find α and b, we use the masses of $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2860)^+$, and $\Lambda_c(2880)^+$ as input in Eq.2. Then, using the masses of $\Sigma_c(2455)$ and $\Sigma_c(2520)$, the m_{qq} and σ_0 are calculated using Eq.1 and Eq.3, respectively. Finally, we find the σ for Σ_c baryon using the scaling relation $\sigma_{\Sigma_c}/\sigma_{\Lambda_c} = \left(m_{qq_{\Sigma_c}}/m_{qq_{\Lambda_c}}\right)^p$, where $m_{qq_{\Sigma_c}}$ and $m_{qq_{\Lambda_c}}$ are the masses of diquark present in Σ_c and Λ_c baryon, respectively, and p=0.661 [12]. For reader convenience, we presented values of parameters in Table 1.

Table 1: The values of parameters used in our calculation

v_{qq}	v_c	m_c(GeV)	m_{qq}(GeV)	σ(GeV^2)	α	b(GeV^2)	σ_0(GeV)
1	0.48	1.448	0.714	1.666	0.426	-0.076	0.373

3. Results and discussion

Within the specified theoretical framework, we calculate the masses of the states belonging to the $1F$- and $1G$-waves of Σ_c baryons and tabulate the results in Table 2. In Table 2, we represent the baryonic states as $nL(J^P)$ with the quantum numbers n, L, J, and j associated with each state. Here, n is the principle quantum number. In addition, we compare our findings with those of Refs. [6–8, 10, 11]. We observe that the mass splitting in the results of Refs. [6, 7, 11] is narrower compared to both our model and the Refs. [8, 10]. Furthermore, we find various model-dependent differences in the mass predictions from different theoretical models for such a high orbital excitation. Only extensive investigation in the future will allow us to identify which theoretical model is reasonable. **Our theoretical predictions for the masses of the higher-lying states can guide experimentalists to identify certain unobserved resonances in the spectrum of Σ_c baryon.**

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Table 2: Masses for $1F$- and $1G$-wave Σ_c resonances (in MeV).

n	L	J	j	States $nL(J^P)$	Present	[6]	[7]	[8]	[10]	[11]
1	3	3/2	2	$1F(3/2^-)$	3251.1	3288	3299	3654		3276
1	3	5/2	2	$1F(5/2^-)$	3278.4	3254	3304	3574	3198	3283
1	3	5/2	3	$1F(5/2^-)$	3311.8	3283	3299	3596	3259	3247
1	3	7/2	3	$1F(7/2^-)$	3391.7	3253	3305	3523	3332	3252
1	3	7/2	4	$1F(7/2^-)$	3336.5	3227	3299	3501	3139	3207
1	3	9/2	4	$1F(9/2^-)$	3413.8	3209	3305	3435	3408	3209
1	4	5/2	3	$1G(5/2^+)$	3461.3	3495	3501			
1	4	7/2	3	$1G(7/2^+)$	3486.9	3444	3502		3380	
1	4	7/2	4	$1G(7/2^+)$	3525.0	3483	3501		3500	
1	4	9/2	4	$1G(9/2^+)$	3603.9	3442	3502		3577	
1	4	9/2	5	$1G(9/2^+)$	3548.6	3410			3307	
1	4	11/2	5	$1G(11/2^+)$	3625.7	3386			3657	

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