Spectroscopic exploration of the $1D$-wave Σ_c baryon

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Introduction

Singly charmed baryons, with one heavy and two light quarks, are the basis for examining the ideas of heavy quark symmetry and the chiral symmetry of light quarks. Many states of singly charmed baryons have been detected experimentally in the last few years by Belle, BaBar, CLEO, and LHCb [1]. But only states associated with the $1S$-wave with $J^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$ have been established for Σ_c baryons. Merely one excited state of Σ_c beryon, called $\Sigma_c(2800)$, has been observed until now by Belle and BaBar collaborations in the $\Lambda_c^+\pi$ channel, but its spin and parity are still unknown [2, 3]. A number of theoretical approaches have been used in recent years to investigate the mass spectrum of excited Σ_c baryons, such as a Reggie phenomenology [4], the QCD-motivated relativistic quark model [5], the hyper-central constituent quark model [6–8], heavy hadron chiral perturbation theory [9], lattice QCD [10], light cone QCD sum rules [11], and QCD sum rules [12].

In our previous work, we used the relativistic flux tube model to obtain the masses of the first orbital and radial excitations of Σ_c baryon in a quark-diquark picture. The charm quark and the diquark were assumed to have orbital or radial excitations relative to each other. The spin-dependent interactions are included in the j-j coupling scheme to find spin-dependent splitting, and we generated the complete mass spectra. The mass of an experimentally observed state $\Sigma_c(2800)$ is successfully generated.So, in the present work, by extending this model, we try to obtain the masses of the second orbital excitation, i.e., the $1D$-wave of the Σ_c baryon.

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Theoretical Framework

The Σ_c baryon is made of a charm quark and two light quarks. According to heavy quark symmetry, the strong correlation between two light quarks permits the formation of a diquark. In the relativistic flux tube (RFT) model, the Σ_c baryon can be pictured as a system of heavy charm quark connected to light diquark with a gluonic flux tube, and the whole system is rotating about its center of mass. The Regge-like relation between mass ($\bar{M}$) and anguler momentum quantum number (L) can be obtained using the RFT model as [13],

$$(\bar{M} - m_c)^2 = \frac{\sigma}{2}L + (m_d + m_c v_2^2), \quad (1)$$

where m_c and m_d are masses of charm quark and diquark, respectively. v_2 is the speed of a charm quark. $\sigma = 2\pi T$, where T is string tension.

The distance between a diquark and a charm quark is

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

where v_1 is the speed of a diquark.

As the RFT model considers quarks to be spinless, we now incorporate spin-dependent interactions in order to obtain the complete mass spectrum. The total contribution of spin-dependent interactions, (ΔM), can be given as

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

where H_{so} is the spin-orbit interaction with the form

$$H_{so} = [(\frac{2\alpha}{3r^3} - \frac{b'}{2r})\frac{1}{m_d^2} + \frac{4\alpha}{3r^3}\frac{1}{m_c m_d}]\mathbf{L}.\mathbf{S_d} + [(\frac{2\alpha}{3r^3} - \frac{b'}{2r})\frac{1}{m_c^2} + \frac{4\alpha}{3r^3}\frac{1}{m_c m_d}]\mathbf{L}.\mathbf{S_c}, \quad (4)$$

the tensor interaction term is

$$H_t = \frac{4\alpha}{3r^3}\frac{1}{m_c m_d}[\frac{3(\mathbf{S_d}.\mathbf{r})(\mathbf{S_c}.\mathbf{r})}{r^2} - \mathbf{S_d}.\mathbf{S_c}], \tag{5}$$

and the spin-spin contact hyperfine interaction is given by

$$H_{ss} = \frac{32\alpha\sigma_0^3}{9\sqrt{\pi}m_c m_d}e^{-\sigma_0^2 r^2}\mathbf{S_d}.\mathbf{S_c}. \tag{6}$$

Here, α is the coupling constant. b' and σ_0 can be fixed using experimental data. $\mathbf{S_c}$ and $\mathbf{S_d}$ represent the spins of the charm quark and diquark, respectively.

Since the charm quark has a much larger mass than the diquark, we can apply the heavy quark symmetry. This lets us describe the baryonic states as j-j coupling states. Now, in the j-j coupling scheme, $\mathbf{S_d}$ first couples with $\mathbf{L}$ to give total angular momentum of the diquark, i.e., $\mathbf{j}$, and then coupling of $\mathbf{j}$ with $\mathbf{S_c}$ results in total angular momentum, i.e., $\mathbf{J}$. A detailed calculation of operators involved in spin-dependent interaction in the j-j coupling scheme for $1D$-wave is given in ref.[13]. The parameters involved in this model are already calculated using the experimentally available states of singly charmed baryons in ref. [13]. With the help of these known parameters, we first calculate the spin average mass of the $1D$-wave of the Σ_c baryon using Eq.(1). Then, we include spin-dependent splitting to find masses of six possible states of the $1D$-wave.

Results and Discussion

The obtained results about the masses of six possible states of $1D$-wave of Σ_c baryon in quark-diquark picture is shown in Table I. The first column gives quantum numbers of given state $|nL, J^P\rangle$. We compare our results with that of ref. [5] and observe that they are in good agreement with our results. These predictions can provide valuable insight to ongoing experimental search in the field of heavy baryon spectroscopy to establish the mass spectra of Σ_c baryon.

TABLE I: Predicted Masses of $1D$-wave of Σ_c baryon (in MeV)

(n, L, J, j)	States $\|nL, J^P\rangle$	Present	[5]
(1, 2, 1/2, 1)	$\|1D, 1/2^+\rangle$	3007.2	3041
(1, 2, 3/2, 1)	$\|1D, 3/2^+\rangle$	3038.9	3040
(1, 2, 3/2, 2)	$\|1D, 3/2^+\rangle$	3066.5	3043
(1, 2, 5/2, 3)	$\|1D, 5/2^+\rangle$	3095.2	3023
(1, 2, 5/2, 2)	$\|1D, 5/2^+\rangle$	3152.8	3038
(1, 2, 7/2, 3)	$\|1D, 7/2^+\rangle$	3177.4	3013

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