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Decay properties of singly charmed baryons

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Abstract. The magnetic moments, transition magnetic moments and the radiative decay widths of singly charmed baryons are calculated with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ in the constitute quark model. Further, the strong decay rates for S, P and D wave transitions are also presented. The singly charmed baryon masses used in the calculations were obtained from the hypercentral Constitute Quark Model (hCQM) without and with first-order relativistic correction. Obtained results are compared with experimental observation as well as with the other theoretical predictions.

1 Introduction

The ground state masses of singly charmed baryons are well established and many of their radially and orbitally excited states masses are well known experimentally [1] as well as theoretically in our previous work [2]. In order to understand the structural properties of the singly charmed baryons, it is necessary to analyze the decay modes from theoretical study. Experimental observations for the radiative decay of singly charmed baryons are rare, whereas their strong decay rates, widths and lifetimes are measured by various experimental groups [3–12] till date. The various properties of heavy baryons are nicely presented in the review articles [13–16].

In order to improve the structural understanding of baryons (made of both light and heavy quarks) the magnetic moment is an important tool. There are many theoretical approaches which study the individual contribution of quarks in the magnetic moments of baryons; such as heavy chiral perturbation theory [17, 18], effective quark mass scheme [19], bag model [20], QCD sum rule model [21], lattice QCD [22–24], relativistic quark model [25, 26], non-relativistic quark model [27, 28], chiral constitute quark model [29], etc. For the radiative decay, there is no phase space and isospin conservation constraint for the transitions of mass-less photon among the charmed baryons. There are many phenomenological approaches: relativistic quark model [30], bag model [20], QCD sum rule model [31, 32], non-relativistic constitute quark model [33–35], heavy hadron chiral perturbation theory [36–39], etc.; these have calculated the contribution of radiative interaction in the decay of singly charmed baryons. The future experiments at J-PARC, $\bar{\text{P}}$ANDA [40–44] and LHCb are expected to give further information on charmed baryons.

The fundamental theory of the strong interactions, Quantum Chromodynamics (QCD), simplifies enormously in the presence of a system containing one heavy quark (c or b) and two light quarks (u, d or s). It will provide the understanding of the $SU(4)$ spin-flavor symmetry of heavy quark and the $SU(3)$ symmetry of light quarks. Such a heavy quark symmetry arises when the mass of the heavy quark is much larger than the QCD limit $\Lambda_{\text{QCD}} \simeq 0.2\,\text{GeV}$ [45]. In this heavy quark limit the dynamics of heavy and light quarks are decouple and providing a number of model-independent relations between various decay mode of the heavy baryons. The chiral Lagrangian corresponding to the heavy baryon coupling to the pseudoscalar mesons were first introduced in ref. [46] in 1992. Theoretically, the relativistic constitute quark model [30], the non-relativistic quark model with various QCD inspired potentials [13, 47, 48], light-front quark model [49, 50], Heavy Hadron Chiral Perturbation Theory (HHCPT) [39, 46, 51], and the QCD sum rules on the light cone [52], etc., are used for studying the strong decays of singly charmed baryons by an exchange of a single pion.

This paper is organized as follows: The basic methodology adopted for generating the mass spectra of singly charmed baryons is described in sect. 2. The magnetic moments and the electromagnetic radiative decays from their transition magnetic moments of ground state with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ are presented in sect. 3. The details of hadronic strong decays of singly charmed baryon are presented in sect. 4. In the last section, we draw our discussion and conclusion.

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Table 1. The masses of singly charm baryons [2] (in MeV); $M_A \rightarrow$ without first-order correction masses; $M_B \rightarrow$ with first-order correction masses.

Baryon	State $n\ ^{2S+1}L_J$	M_A	M_B	PDG [1]
Λ_c^+	$1^2S_{\frac{1}{2}}$	2286	2286	2286.46 ± 0.14
Σ_c^{++}	$1^2S_{\frac{1}{2}}$	2449	2454	2453.97 ± 0.14
Σ_c^+	$1^2S_{\frac{1}{2}}$	2444	2452	2452.9 ± 0.4
Σ_c^0	$1^2S_{\frac{1}{2}}$	2444	2453	2453.75 ± 0.14
Ξ_c^+	$1^2S_{\frac{1}{2}}$	2467	2467	2467.87 ± 0.30
Ξ_c^0	$1^2S_{\frac{1}{2}}$	2470	2470	$2470.87^{+0.28}_{-0.31}$
Ω_c^0	$1^2S_{\frac{1}{2}}$	2695	2695	2695.2 ± 1.7
Σ_c^{*++}	$1^4S_{\frac{3}{2}}$	2505	2530	$2518.41^{+0.21}_{-0.19}$
Σ_c^{*+}	$1^4S_{\frac{3}{2}}$	2506	2501	2517.5 ± 2.3
Σ_c^{*0}	$1^4S_{\frac{3}{2}}$	2506	2529	2518.48 ± 0.20
Ξ_c^{*+}	$1^4S_{\frac{3}{2}}$	2625	2619	2645.53 ± 0.31
Ξ_c^{*0}	$1^4S_{\frac{3}{2}}$	2584	2610	2646.32 ± 0.31
Ω_c^{*0}	$1^4S_{\frac{3}{2}}$	2740	2745	2765.9 ± 2.0
Λ_c^+	$1^2P_{\frac{1}{2}}$	2607	2692	2592.25 ± 0.28
Σ_c^{++}	$1^2P_{\frac{1}{2}}$	2842	2890	2801^{+4}_{-6}
Σ_c^+	$1^2P_{\frac{1}{2}}$	2831	2849	2792^{+14}_{-5}
Σ_c^0	$1^2P_{\frac{1}{2}}$	2824	2873	2806^{+5}_{-7}
Λ_c^+	$1^2P_{\frac{3}{2}}$	2592	2612	2628.11 ± 0.19
Σ_c^{++}	$1^2P_{\frac{3}{2}}$	2814	2860	–
Σ_c^{++}	$1^4P_{\frac{5}{2}}$	2791	2835	–

2 Methodology

The mass spectra of singly charmed baryons [2, 53–55] are generated by the Hamiltonian

$$H = \frac{P_x^2}{2m} + V(x), \tag{1}$$

in the hypercentral Constitute Quark Model (hCQM). Here, $m = \frac{m_\rho m_\lambda}{m_\rho + m_\lambda}$ is the reduced mass and x is the six-dimensional radial hypercentral coordinate of the three-body system. In this case, we consider the hypercentral potential $V(x)$ as the color Coulomb plus power potential with first-order correction as

$$V(x) = V^0(x) + \left(\frac{1}{m_\rho} + \frac{1}{m_\lambda}\right) V^1(x) + V_{SD}(x), \tag{2}$$

where $V_{SD}(x)$ represents the spin-dependent potential, $V^0(x)$ is the sum of hyper Coulomb (hC) interaction and a confinement term,

$$V^0(x) = \frac{\tau}{x} + \beta x, \tag{3}$$

and the first-order correction is employed by Koma *et al.* [56]:

$$V^1(x) = -C_F C_A \frac{\alpha_s^2}{4x^2}\,. \tag{4}$$

We have used this correction not only for baryons but mesons as well [57–59]. Here, the hyper-Coulomb strength $\tau = -\frac{2}{3}\alpha_s$; where $\frac{2}{3}$ is the baryon color factor and α_s represents the strong running coupling constant and is ≈ 0.6 considered in the present study. β is the string tension of the confinement; and C_F and C_A are the Casimir charges of the fundamental and adjoint representation. The details of all the constants can be found from ref. [2].

For the u, d, s and c quarks, we set the constituent quark masses $m_u = 338\,\text{MeV}$, $m_d = 350\,\text{MeV}$, $m_s = 500\,\text{MeV}$ and $m_c = 1275\,\text{MeV}$. The 1S and 1P state masses of singly charmed baryons are tabulated in table 1 with PDG masses [1]. M_A and M_B are the masses of without and with first-order relativistic correction to the potential energy term, respectively. We will use these masses in the calculation of magnetic moments, the radiative decays and the strong decays in next sections.

Table 2. Magnetic moments of the singly charmed baryons with $J^P = \frac{1}{2}^+$ (in μ_N).

Baryon	Expression	A	B	[18]	[22–24]	[20]	[19]	[60]	[29]	[25]
Λ_c^+	μ_c	0.421	0.421	0.21		0.411	0.370	0.385	0.39	0.42
Σ_c^{++}	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_c$	1.835	1.831	1.50	1.499(202)	1.679	2.09	2.279	2.540	1.76
Σ_c^0	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_c$	−1.095	−1.091	−1.25	−0.875(103)	−1.043	−1.230	−1.015	−1.46	−1.04
Σ_c^+	$\frac{2}{3}\mu_u + \frac{2}{3}\mu_d - \frac{1}{3}\mu_c$	0.381	0.380	0.12		0.318	0.550	0.500	0.540	0.36
Ξ_c^0	$\frac{2}{3}\mu_d + \frac{2}{3}\mu_s - \frac{1}{3}\mu_c$	−1.012	−1.012	0.19	0.192(17)	−0.914	−0.940	−0.966	−1.23	
Ξ_c^+	$\frac{2}{3}\mu_u + \frac{2}{3}\mu_s - \frac{1}{3}\mu_c$	0.523	0.523	0.24	0.235(25)	0.591	0.75	0.711	0.770	0.41
Ω_c^0	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_c$	−1.127	−1.179	−0.67	−0.667(96)	−0.774	−0.890	−0.960	−0.900	−0.85

Table 3. Magnetic moments of the singly charmed baryons with $J^P = \frac{3}{2}^+$ (in μ_N).

Baryon	Expression	A	B	[20]	[19]	[60]	[29]	[27]	[21]
Σ_c^{*++}	$2\mu_u + \mu_c$	3.264	3.232	3.127	3.630	3.844	4.390		4.81 ± 1.22
Σ_c^{*+}	$\mu_u + \mu_d + \mu_c$	1.134	1.136	1.085	1.180	1.256	1.390		2.00 ± 0.46
Σ_c^{*0}	$2\mu_d + \mu_c$	−1.054	−1.044	−0.958	−1.180	−0.850	−1.610	−1.99	-0.81 ± 0.20
Ξ_c^{*0}	$\mu_d + \mu_s + \mu_c$	−0.846	−0.837	−0.746	−1.020	−0.690	−1.260	−1.49	
Ξ_c^{*+}	$\mu_u + \mu_s + \mu_c$	1.330	1.333	1.270	−1.390	1.517	1.740		1.68 ± 0.24
Ω_c^{*0}	$2\mu_s + \mu_c$	−1.127	−1.129	−0.547	−0.840	−0.867	−0.910	−0.860	-0.62 ± 0.18

3 Magnetic moments and radiative decays

The magnetic moments and the radiative decays are computed using spin-flavour wave functions of the participating baryons. The magnetic moments are obtained in terms of spin, charge and effective mass of the bound quarks of baryons. In radiative decay, there is an exchange of massless photon among the singly charmed baryons. Such a decay does not contain phase space restriction. Therefore, some of the radiative decay mode of heavy baryons contribute significantly to the total decay rate.

3.1 The magnetic moments

The magnetic moment is the fundamental property of baryons in both light and heavy quark sector and purely depends upon the masses and spin of their internal constitutions. The magnetic moment of the baryon (μ_B) is given by the expectation value [28,33] as

$$\mu_B = \sum_q \langle \Phi_{sf} | \mu_{q_z} | \Phi_{sf} \rangle ; \quad q = u, d, s, c, \tag{5}$$

where Φ_{sf} represents the spin-flavour wave function of a participating baryon and μ_q is the magnetic moment of the individual quark given by

$$\mu_q = \frac{e_q}{2m_q^{\text{eff}}} \cdot \sigma_q, \tag{6}$$

with e_q the charge and σ_q the spin of the constitute quark of the particular baryonic state, and the effective mass of each constituting quark (m_q^{eff}) can be defined in terms of the constituting quark mass (m_q) as

$$m_q^{\text{eff}} = m_q \left(1 + \frac{\langle H \rangle}{\sum_q m_q} \right), \tag{7}$$

where the Hamiltonian is given in the form of the measured or predicted baryon mass (M) as $\langle H \rangle = M - \sum_q m_q$. Here, the m_q^{eff} represents the mass of the bound quark inside the baryons by taking into account its binding interactions with other two quarks described in eq. (1) in the case of hCQM.

Using these equations and taking the constituent quark mass of [2], we determine the ground state magnetic moment of the singly charmed baryons with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ without and with first-order relativistic correction as set A and set B, respectively. We present our results in tables 2 and 3 in the unit of nuclear magnetons ($\mu_N = \frac{e\hbar}{2m_p}$).

Table 4. The transition magnetic moments $|\mu_{B_c \to B'_c}|$ of singly charmed baryons (in μ_N).

Transition	Expression	A	B	[19]			[34]	[31]
				(nqm)	(ems)	(ses)		
$\mu_{\Sigma_c^+ \to \Lambda_c^+}$	$\frac{-1}{\sqrt{3}}(\mu_u - \mu_d)$	1.2722	1.2680	2.28	2.28	2.15	1.347	1.48 ± 0.55
$\mu_{\Sigma_c^{*++} \to \Sigma_c^{++}}$	$\frac{2\sqrt{2}}{3}(\mu_u - \mu_c)$	0.9984	0.9885	1.41	1.19	1.23	1.080	1.06 ± 0.38
$\mu_{\Sigma_c^{*+} \to \Sigma_c^{+}}$	$\frac{\sqrt{2}}{3}(\mu_u + \mu_d - 2\mu_c)$	0.0089	0.0089	0.09	0.04	0.08	0.008	0.45 ± 0.11
$\mu_{\Sigma_c^{*0} \to \Sigma_c^{0}}$	$\frac{2\sqrt{2}}{3}(\mu_d - \mu_c)$	1.0220	1.0127	1.22	1.11	1.07	1.064	0.19 ± 0.08
$\mu_{\Sigma_c^{*+} \to \Lambda_c^{+}}$	$\sqrt{\frac{2}{3}}(\mu_u - \mu_d)$	1.7546	1.7582				1.857	
$\mu_{\Xi_c^{*+} \to \Xi_c^{+}}$	$\sqrt{\frac{2}{3}}(\mu_u - \mu_s)$	0.9832	0.9852	2.02	1.96	1.94	0.991	1.47 ± 0.66
$\mu_{\Xi_c^{*0} \to \Xi_c^{0}}$	$\sqrt{\frac{2}{3}}(\mu_d - \mu_s)$	0.2552	0.2527	0.26	0.25	0.18	0.120	0.16 ± 0.07
$\mu_{\Omega_c^{*0} \to \Omega_c^{0}}$	$\frac{2\sqrt{2}}{3}(\mu_s - \mu_c)$	0.8734	0.8719	0.92	0.88	0.90	0.908	

3.2 The radiative decays

The electromagnetic radiative decay width is mainly the function of radiative transition magnetic moment $\mu_{B'_C \to B_c}$ (in μ_N) and photon energy (k) [33,34,60] as

$$\Gamma_\gamma = \frac{k^3}{4\pi}\frac{2}{2J+1}\frac{e}{m_p^2}\mu^2_{B_c \to B'_c}, \tag{8}$$

where m_p is the mass of proton, J is the total angular momentum of the initial baryon (B_c). Such transition magnetic moments ($\mu_{B_c \to B'_c}$) are determine in the same manner by sandwiching eq. (7) between the appropriate initial ($\Phi_{sf_{B_c}}$) and final state ($\Phi_{sf_{B'_c}}$) singly charm baryon spin-flavour wave functions as

$$\mu_{B_c \to B'_c} = \left\langle \Phi_{sf_{B_c}} \right| \mu_{B_{c'_z}} \left| \Phi_{sf_{B'_c}} \right\rangle. \tag{9}$$

To determine the radiative decay of the channel $\Sigma_c^{*+} \to \Lambda_c^+ \gamma$, we first need to calculate the transition magnetic moment given as

$$\mu_{\Sigma_c^{*+} \to \Lambda_c^+} = \left\langle \Phi_{sf_{\Sigma_c^{*+}}} \right| \mu_{\Lambda_{c_z^+}} \left| \Phi_{sf_{\Lambda_c^+}} \right\rangle; \tag{10}$$

the spin-flavour wave functions (Φ_{sf}) of Σ_c^{*+} and Λ_c^+ baryons are expressed as

$$\left|\Phi_{sf_{\Sigma_c^{*+}}}\right\rangle = \left(\frac{1}{\sqrt{2}}(ud+du)c\right)\cdot\left(\frac{1}{\sqrt{3}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow)\right), \tag{11}$$

$$\left|\Phi_{sf_{\Lambda_c^{+}}}\right\rangle = \left(\frac{1}{\sqrt{2}}(ud-du)c\right)\cdot\left(\frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)\uparrow\right). \tag{12}$$

Following the orthogonality condition of quark flavour and the spin states, for example, $\langle u\uparrow d\uparrow c\downarrow | u\uparrow d\downarrow c\uparrow\rangle = 0$, we will get the expression of transition magnetic moment as

$$\mu_{\Sigma_c^{*+} \to \Lambda_c^+} = \sqrt{\frac{2}{3}}\,(\mu_u - \mu_d)\,. \tag{13}$$

The transition magnetic moments are given in table 4. Using the masses and transition magnetic moment of the participating baryons, we compute its radiative decay width. The obtained results are listed in table 5 for both set A and set B with other theoretical predictions.

Table 5. The radiative decay widths (Γ_γ) of singly charmed baryons (in keV).

Decay Mode	A	B	[35]	[36]	[32]	[34]	[61]	[20]	[37]	[30]	[31]
$\Sigma_c^+\ (1^2S_{\frac{1}{2}}) \to \Lambda_c^+\gamma$	58.131	66.660	80.6	164		60.55	120	46.1	88	60.7 ± 1.5	
$\Sigma_c^{*++}\ (1^4S_{\frac{3}{2}}) \to \Sigma_c^{++}\gamma$	0.8504	2.0597	3.94	11.6	3.567	1.15	1.6	0.826	1.4		2.65 ± 1.60
$\Sigma_c^{*+}\ (1^4S_{\frac{3}{2}}) \to \Sigma_c^{+}\gamma$	9×10^{-5}	4×10^{-5}	0.004	0.85	0.187	0.00006	0.0001	0.004	0.002	0.14 ± 0.004	0.40 ± 0.22
$\Sigma_c^{*0}\ (1^4S_{\frac{3}{2}}) \to \Sigma_c^{0}\gamma$	1.2049	2.1615	3.43	2.92	1.049	1.12	1.2	1.08	1.2		0.08 ± 0.042
$\Sigma_c^{*+}\ (1^4S_{\frac{3}{2}}) \to \Lambda_c^{+}\gamma$	143.97	135.30	373	893	409.3	154.48	310	126	147	151 ± 4	130 ± 65
$\Xi_c^{*+}\ (1^4S_{\frac{3}{2}}) \to \Xi_c^{+}\gamma$	17.479	15.686	139	502	152.4	63.32	71	44.3	54	54 ± 3	52 ± 32
$\Xi_c^{*0}\ (1^4S_{\frac{3}{2}}) \to \Xi_c^{0}\gamma$	0.4535	0.8114	0.0	0.36	1.318	0.30	1.7	0.908	1.1	0.68 ± 0.04	0.66 ± 0.41
$\Omega_c^{*0}\ (1^4S_{\frac{3}{2}}) \to \Omega_c^{0}\gamma$	0.3408	0.4645	0.89	4.82	1.439	2.02	0.71	1.07			

4 The strong decays

The effective coupling constant of the heavy baryons is small, which leads to their strong interactions perturbatively and makes it easier to understand the systems containing only light quarks. Such a theory describes strong interactions in the low-energy regime by an exchange of light Goldstone boson, which is developed well by the co-ordination of chiral perturbation theory and heavy quark effective theory, called Heavy Hadron Chiral Perturbation Theory (HHCPT). This hybrid effective theory has been applied to study the strong and the electromagnetic decays of ground and excited states in the both charm and bottom sector [46,62,63]. By using the Langrangian in ref. [51], we calculated a strong P-wave couplings among the s-wave baryons, S-wave couplings between the s-wave and p-wave baryons, and the strong couplings of D-wave from p-wave to s-wave baryons in this section. Such a chiral Lagrangian gives the expressions of typical decay rate of single pion transitions between singly charmed baryons mentiond in eqs. (15)–(20) [13]. The pion momentum for the two-body decay $x \to y + \pi$ is

$$p_\pi = \frac{1}{2m_x}\sqrt{[m_x^2 - (m_y + m_\pi)^2][m_x^2 - (m_y - m_\pi)^2]}\,. \tag{14}$$

P-wave transitions

The decay rates corresponding to the P-wave transitions from the isospin partners of $\Sigma_c(1^2S_{\frac{1}{2}})$ and $\Sigma_c^*(1^4S_{\frac{3}{2}})$ to the state $\Lambda_c^+(1^2S_{\frac{1}{2}})$ by an exchange of single pion are

$$\Gamma_{\Sigma_c^+/\Sigma_c^* \to \Lambda_c^+\pi} = \frac{a_1^2}{2\pi f_\pi^2}\frac{M_{\Lambda_c^+}}{M_{\Sigma_c^+/\Sigma_c^*}}p_\pi^3\,, \tag{15}$$

where p_π^3 represents the momentum corresponding to the P-wave transition. The pion decay constant $f_\pi = 132\,\text{MeV}$ [46] and the strong coupling constant $a_1 = 0.612$ as in ref. [51] are obtained from quark model calculations.

S-wave transitions

S-wave transitions of $\Lambda_c^+(1^2P_{\frac{1}{2}})$ into the isospin partners of $\Sigma_c(1^2S_{\frac{1}{2}})$ by an exchange of single pion are

$$\Gamma_{\Lambda_c^+ \to \Sigma_c\pi} = \frac{b_1^2}{2\pi f_\pi^2}\frac{M_{\Sigma_c}}{M_{\Lambda_c^+(1^2P_{\frac{1}{2}})}}E_\pi^2 p_\pi, \tag{16}$$

where p_π represents the S-wave transitions and, when the single pion is at rest, $E_\pi \approx m_\pi$. The coupling constants $b_1 = 0.572$ and $b_2 = \sqrt{3}\cdot b_1$ are taken from ref. [51]. The decay rates for the decay of isospin triplets $\Sigma_c(1^2P_{\frac{1}{2}})$ into $\Lambda_c^+(1^2S_{\frac{1}{2}})\pi$ are

$$\Gamma_{\Sigma_c \to \Lambda_c^+\pi} = \frac{b_2^2}{2\pi f_\pi^2}\frac{M_{\Lambda_c^+}}{M_{\Sigma_c}}E_\pi^2 p_\pi. \tag{17}$$

Table 6. Strong one-pion decay rates (in MeV).

Decay mode	A	B	PDG [1]	[13]	[30]	[49]	[48]	[47]	[51]	Others
P-wave transitions										
$\Sigma_c^{++}(1^2S_{\frac{1}{2}}) \rightarrow \Lambda_c^+\pi^+$	1.72	2.34	$1.89^{+0.09}_{-0.18}$		2.85 ± 0.19	1.64	2.5	2.41 ± 0.07	2.025	$1.96^{+0.07}_{-0.14}$ [64]
$\Sigma_c^{+}(1^2S_{\frac{1}{2}}) \rightarrow \Lambda_c^+\pi^0$	1.60	2.59	< 4.6	$2.3^{+0.1}_{-0.2}$	3.63 ± 0.27	1.70	3.2	2.79 ± 0.08		$2.28^{+0.09}_{-0.17}$ [64]
$\Sigma_c^{0}(1^2S_{\frac{1}{2}}) \rightarrow \Lambda_c^+\pi^-$	1.17	2.21	$1.83^{+0.11}_{-0.19}$	$1.9^{+0.1}_{-0.2}$	2.65 ± 0.19	1.57	2.4	2.37 ± 0.07	1.94	$1.94^{+0.07}_{-0.14}$ [64]
$\Sigma_c^{*++}(1^4S_{\frac{3}{2}}) \rightarrow \Lambda_c^+\pi^+$	13.11	21.34	$14.78^{+0.30}_{-0.40}$	$14.5^{+0.5}_{-0.8}$	21.99 ± 0.87	12.84		17.52 ± 0.75	17.9	$14.7^{+0.6}_{-1.1}$ [64]
$\Sigma_c^{*+}(1^4S_{\frac{3}{2}}) \rightarrow \Lambda_c^+\pi^0$	14.28	12.83	< 17	$15.2^{+0.6}_{-1.3}$			25	15.31 ± 0.74		$15.3^{+0.6}_{-1.1}$ [64]
$\Sigma_c^{*0}(1^4S_{\frac{3}{2}}) \rightarrow \Lambda_c^+\pi^-$	13.40	20.97	$15.3^{+0.4}_{-0.5}$	$14.7^{+0.6}_{-1.2}$	21.21 ± 0.81	12.40		16.90 ± 0.72	13.0	$14.7^{+0.6}_{-1.1}$ [64]
S-wave transitions										
$\Lambda_c^+(1^2P_{\frac{1}{2}}) \rightarrow \Sigma_c^{++}\pi^-$	3.92	5.54		$0.72^{+0.43}_{-0.30}$	0.79 ± 0.09	2.15	$0.55^{+1.3}_{-0.55}$			0.64 [65]
$\Lambda_c^+(1^2P_{\frac{1}{2}}) \rightarrow \Sigma_c^{0}\pi^+$	4.45	5.63	2.6 ± 0.6	$0.77^{+0.46}_{-0.32}$	0.83 ± 0.09	2.61	1.7 ± 0.49			1.2 [65]
$\Lambda_c^+(1^2P_{\frac{1}{2}}) \rightarrow \Sigma_c^{+}\pi^0$	4.52	5.62		$1.57^{+0.93}_{-0.65}$	0.98 ± 0.12	1.73	0.89 ± 0.86			0.84 [65]
$\Sigma_c^{++}(1^2P_{\frac{1}{2}}) \rightarrow \Lambda_c^+\pi^+$	68.19	72.67	75^{+22}_{-17}							75^{+18+12}_{-13-11} [66]
$\Sigma_c^{+}(1^2P_{\frac{1}{2}}) \rightarrow \Lambda_c^+\pi^0$	62.92	64.54	62^{+60}_{-40}							62^{+37+52}_{-23-38} [66]
$\Sigma_c^{0}(1^2P_{\frac{1}{2}}) \rightarrow \Lambda_c^+\pi^-$	66.44	71.11	72^{+22}_{-15}							61^{+18+22}_{-13-13} [66]
D-wave transitions										
$\Lambda_c^+(1^2P_{\frac{3}{2}}) \rightarrow \Sigma_c^{++}\pi^-$	0.001	0.0012		0.029	0.076 ± 0.009	2.15	0.013			0.011 [65]
$\Lambda_c^+(1^2P_{\frac{3}{2}}) \rightarrow \Sigma_c^{0}\pi^+$	0.011	0.0013	< 0.97	0.029	0.080 ± 0.009	2.61	0.013			0.011 [65]
$\Lambda_c^+(1^2P_{\frac{3}{2}}) \rightarrow \Sigma_c^{+}\pi^0$	0.033	0.0025		0.041	0.095 ± 0.012	1.73	0.013			0.011 [65]
$\Sigma_c^{++}(1^2P_{\frac{3}{2}}) \rightarrow \Lambda_c^+\pi^+$	13.22	19.61							~ 12	
$\Sigma_c^{++}(1^4P_{\frac{5}{2}}) \rightarrow \Lambda_c^+\pi^+$	10.68	15.91							~ 12	
$\Sigma_c^{++}(1^2P_{\frac{3}{2}}) \rightarrow \Sigma_c^+\pi^+$	1.70	2.86								
$\Sigma_c^{++}(1^2P_{\frac{3}{2}}) \rightarrow \Sigma_c^{*+}\pi^+$	0.61	1.46								
$\Sigma_c^{++}(1^2P_{\frac{3}{2}}) \rightarrow \Sigma_c^{*++}\pi^0$	0.65	0.95								

D-wave transitions

The decay of $\Lambda_c(1^2P_{\frac{3}{2}})$ into the isospin partners of $\Sigma_c(1^2P_{\frac{1}{2}})$ are considered as D-wave transitions. For that the decay rates are

$$\Gamma_{\Lambda_c^+(1^2P_{\frac{3}{2}})\rightarrow\Sigma_c\pi} = \frac{2b_3^2}{9\pi f_\pi^2}\frac{M_{\Sigma_c}}{M_{\Lambda_c^+}}p_\pi^5\,, \tag{18}$$

where p_π^5 represents the D-wave transitions and the coupling constant $b_3 = 3.50 \times 10^{-3}\,\text{MeV}^{-1}$ ref. [51]. The Σ_c^{++} with $(1^2P_{\frac{3}{2}})$ and $\Sigma_c(1^4P_{\frac{5}{2}})$ are expected to decay into $\Lambda_c^+(1^2S_{\frac{1}{2}})\pi^+$ through D-wave couplings as

$$\Gamma_{\Sigma_c^{++}\rightarrow\Lambda_c^+\pi^+} = \frac{4b_4^2}{15\pi f_\pi^2}\frac{M_{\Lambda_c^+}}{M_{\Sigma_c^{++}}}p_\pi^5; \tag{19}$$

here, the coupling constant $b_4 = 0.4 \times 10^{-3}\,\text{MeV}^{-1}$ ref. [51]. According to the quark model relation, $b_5 = \sqrt{2 \cdot b_4}$. Using this, we obtained the decay rates for the decay of $\Sigma_c^{++}(1^2P_{\frac{3}{2}})$ into $\Sigma_c^+(1^2S_{\frac{1}{2}})\pi^+$, $\Sigma_c^{*+}(1^4S_{\frac{3}{2}})\pi^+$ and $\Sigma_c^{*++}(1^4S_{\frac{3}{2}})\pi^0$ are determined as

$$\Gamma_{\Sigma_c^{++}\rightarrow\Sigma_c^+\pi^+/\Sigma_c^*\pi} = \frac{b_5^2}{10\pi f_\pi^2}\frac{M_{\Sigma_c^+/\Sigma_c^*}}{M_{\Sigma_c^{++}}}p_\pi^5. \tag{20}$$

Summing up, the decay rates of these three decay modes of $\Sigma_c^{++}(1^2P_{\frac{3}{2}})$ will be 2.97 MeV and 5.27 MeV for set A and for set B, respectively, and the value of set A is closer to $\simeq 3.16$ MeV of ref. [51]. The obtained results for these three, S-, P- and D-wave transitions are listed in table 6.

5 Discussion and conclusion

The electromagnetic radiative decays of singly charmed baryons by an exchange of massless photon are determined by using the parameters obtaining in the framework of hypercentral Constitute Quark Model (hCQM).

There are no experimental information available about the magnetic moments of singly charmed baryons. Our predictions for the ground state magnetic moment of singly charmed baryons, with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, see table 2 and table 3, respectively, for set A and set B, are comparable to the results obtained from bag model [20], effective quark mass scheme [19], non-relativistic quark model [60], chiral constitute quark model [29] and relativistic quark model [25]. For $J^P = \frac{3}{2}^+$, our results are smaller than the results based on the QCD sum rule model [21]. The recent paper of Wang *et al.* [18] based on heavy chiral perturbation theory and those by Can *et al.* [22], Bahtiyar *et al.* [23,24] are based on lattice QCD; their calculated magnetic moments for $J^P = \frac{1}{2}^+$ are less than our predictions.

The expression of electromagnetic radiative decay rate contains a term transition magnetic moment ($\mu_{B'_c \to B_c}$) of the participating singly charmed baryons by which the decay takes place. Our calculated transition magnetic moments and radiative decay rates are smaller than the other theoretical predictions. For Ξ_c^{*+}, Ξ_c^{*0} and Ω_c^{*0}, our predictions are much smaller than the others and, for Σ_c^{*+}, the radiative decay rate is of the order of 10^{-1} to 10^{-5} keV; in our case it is 10^{-5} keV. Our results for the transition magnetic moment and radiative decay of Σ_c^+, Σ_c^{*++}, Σ_c^{*+} and Σ_c^{*0} are smaller but reasonably close to other theoretical predictions, see tables 4 and 5, respectively.

The strong P-wave transitions of isospin partners $\Sigma_c(1^2S_{\frac{1}{2}})$ and $\Sigma_c^*(1^4S_{\frac{3}{2}})$ are calculated and found to be in accordance with other model predictions and experimental measurements. In our case, the ratio of $\frac{\Gamma(\Sigma_c^{*++})}{\Gamma(\Sigma_c^{++})}$ is 7.62 for the set A and 9.12 for the set B, and from the PDG [1] it is 7.82 consistent with set A. For the strong decay channel $\Sigma_c^*(1^4S_{\frac{3}{2}}) \to \Sigma_c(1^2S_{\frac{1}{2}})\pi$, the mass difference $\Delta M(m\Sigma_c^* - m\Sigma_c)$ is smaller than the mass of the single pion. Therefore, there is no sufficient phase space for this respective decay. Such decay is kinematically forbidden.

For the S-wave transitions of $\Lambda_c^+(1^2P_{\frac{1}{2}})$ that decay into isopartners of $\Sigma_c(1^2S_{\frac{1}{2}})$, values are overestimated compared to others because, here, the mass of $\Lambda_c^+(1^2P_{\frac{1}{2}})$ is higher than that of the PDG [1] value (table 1). Also, as for the decay of the isotriplet $\Sigma_c(1^2P_{\frac{1}{2}})$ into $\Lambda_c^+\pi$, their decay widths are consistent with PDG [1] and ref. [66]. The D-wave transitions of Σ_c^{++} with $(1^2P_{\frac{3}{2}})$ decay into the various decay mode shown in table 6. The decay rates of $\Sigma_c^{++}(1^4P_{\frac{5}{2}})$ decaying into $\Lambda_c^+(1^2P_{\frac{1}{2}})\pi^+$ are also determined. Experimentally, both states are not confirmed yet and only few theoretical results are available, whereas the D-wave transitions of $\Lambda_c^+(1^2P_{\frac{3}{2}})$ into the isospin partners of $\Sigma_c(1^2P_{\frac{1}{2}})$ are kinematically barely allowed to have an extremely small width and this study will be useful for the experimental determination of their decay widths < 0.97 [1].

From these calculations we noted that the decay of $\Sigma_c^+(1^2S_{\frac{1}{2}})$ and $\Sigma_c^{*+}(1^4S_{\frac{3}{2}})$ into $\Lambda_c^+(1^2S_{\frac{1}{2}})$ are common in both strong and radiative decays. So we are interested in calculating their total decay width and branching fractions.

The total decay rate is simply the sum of the decay rates of each individual decay. The branching fraction for particular decay mode is the ratio of the decay rate of a particular decay rate to the relatively total decay rate. For example, the total decay widths of $\Sigma_c^+(1^2S_{\frac{1}{2}})$,

$$\Gamma_{\mathrm{tot}(\Sigma_c^+)} = \Gamma_{\Sigma_c^+(1^2S_{\frac{1}{2}})\to\Lambda_c^+\pi^0} + \Gamma_{\Sigma_c^+(1^2S_{\frac{1}{2}})\to\Lambda_c^+\gamma}, \tag{21}$$

are ~ 1.66 MeV and ~ 2.66 MeV for set A and set B, respectively, and the branching fractions of $\Sigma_c^+(1^2S_{\frac{1}{2}})$ for the strong decay,

$$\mathcal{B}_{\Sigma_c^+(1^2S_{\frac{1}{2}})\to\Lambda_c^+\pi^0} = \frac{\Gamma_{\Sigma_c^+(1^2S_{\frac{1}{2}})\to\Lambda_c^+\pi^0}}{\Gamma_{\mathrm{tot}(\Sigma_c^+)}}, \tag{22}$$

are $\sim 96.49\%$ and $\sim 97.49\%$ for set A and set B, respectively. Similarly, the branching fractions of $\Sigma_c^+(1^2S_{\frac{1}{2}})$ for the radiative decay,

$$\mathcal{B}_{\Sigma_c^+(1^2S_{\frac{1}{2}})\to\Lambda_c^+\gamma} = \frac{\Gamma_{\Sigma_c^+(1^2S_{\frac{1}{2}})\to\Lambda_c^+\gamma}}{\Gamma_{\mathrm{tot}(\Sigma_c^+)}}, \tag{23}$$

are $\sim 3.50\%$ and $\sim 2.50\%$ for set A and set B, respectively.

In the same manner we determine the total decay rate of $\Sigma_c^{*+}(1^4S_{\frac{3}{2}})$, and they are ~ 14.42 MeV and ~ 12.96 MeV for set A and set B, respectively. For their strong decay, the branching fractions are $\sim 99.00\%$ and $\sim 98.96\%$ for set A and set B, respectively, and, for the radiative decay, they are $\sim 1.00\%$ and $\sim 1.04\%$ for set A and set B, respectively.

So we conclude that such singly charmed baryons, $\Sigma_c^+(1^2S_{\frac{1}{2}})$ and $\Sigma_c^{*+}(1^4S_{\frac{3}{2}})$, are purely decaying through strong interaction and this is consistent with the PDG [1] value, $\sim 100\%$. We see that the contribution of the radiative decay is small to their total decay. Therefore, our results are in accordance with the present theoretical and experimental status of singly charmed baryons; the strong decays are dominant over the electromagnetic radiative decays. We hope that future experiments, like $\bar{\text{P}}$ANDA, will be in a unique position for providing contribution to the radiative decay of the charm sector.

For the success of a particular model, it is required to produce not only the mass spectra but also the decay properties of these baryons. The masses obtained from the hypercentral Constitute Quark Model (hCQM) are used to calculate the radiative and the strong decay widths. Such calculated widths are reasonably close to other model predictions and experimental observations (where available). This model has been successful in determining these properties, thus, we would like to use this scheme to calculate the decay rates of singly bottom baryons.

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