Quantum numbers of Ω_c states and other charmed baryons

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Possible spin-parity quantum numbers for excited charmed baryon resonances are discussed in this work. Our main results are as follows. (i) Among the five newly observed Ω_c states, we have identified $\Omega_c(3090)$ and $\Omega_c(3119)$ with radially excited $\frac{1}{2}^+(2S)$ and $\frac{3}{2}^+(2S)$ states, respectively, and $\Omega_c(3000)$ with $\frac{1}{2}^-(1P)$. The two states $\Omega_c(3050)$ and $\Omega_c(3066)$ form a P-wave $(\frac{3}{2}^-, \frac{5}{2}^-)$ doublet. (ii) The widths of $\Omega_c(3066)$ and $\Xi_c'(2930)$ are calculable within the framework of heavy hadron chiral perturbation theory. (iii) Since the width of $\Omega_{c0}(\frac{1}{2}^-)$ is of order 410 MeV, not all observed narrow Ω_c baryons can be identified with $1P$ states. (iv) For the antitriplet Λ_c and Ξ_c states, their Regge trajectories for the orbital excitations of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ are parallel to each other. Based on this nice property of parallelism, we see that the highest state $\Lambda_c(2940)$ does not fit if its quantum numbers are $\frac{3}{2}^-$ as found by LHCb. We suggest that $\Lambda_c(2940)^+$ is most likely the $\frac{1}{2}^-(2P)$ state. (v) The charmed baryon $\Sigma_c(2800)$ cannot be a $\frac{1}{2}^-$ state; otherwise, its width will be over 400 MeV, too large compared to the measured one. (vi) In the study of Regge trajectories of Ξ_c' states, we find a missing state. It should have quantum numbers $\frac{5}{2}^-$ with a mass around 2920 MeV. (vii) Antitriplet and sextet states are classified according to their $J^P(nL)$ quantum numbers. The mass differences between Ξ_c and Λ_c in the antitriplet states clearly lie between 180 and 200 MeV. Moreover, the mass splitting between Ω_c and Ξ_c' is found to be very close to the one between Ξ_c' and Σ_c for five different sets of sextet multiplets. This lends a strong support to the quantum number assignment to the sextet states in this work.

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I. INTRODUCTION

Charmed baryon spectroscopy provides an ideal place for studying the dynamics of the light quarks in the environment of a heavy quark. The observed mass spectra and decay widths of singly charmed baryons are summarized in Table I. By now, the $J^P = \frac{1}{2}^+, \frac{1}{2}^-, \frac{3}{2}^+, \frac{3}{2}^-$ and $\frac{5}{2}^+$ antitriplet states Λ_c, Ξ_c and $J^P = \frac{1}{2}^+, \frac{3}{2}^+$ sextet states $\Omega_c, \Xi_c', \Sigma_c$ are established (see Table IV below for details). Notice that except for the parity of the lightest Λ_c^+ and the heavier ones $\Lambda_c(2880)^+$ [1,2] and $\Lambda_c(2860)^+$ [1], none of the other J^P quantum numbers given in Table I have been measured. One has to rely on the quark model to determine the J^P assignments.

For a long time, only two ground states had been observed thus far for the Ω_c baryons: $\frac{1}{2}^+$ Ω_c^0 and $\frac{3}{2}^+$ $\Omega_c(2770)^0$. The latter was seen by *BABAR* in the electromagnetic decay $\Omega_c(2770) \to \Omega_c \gamma$ [7]. The mass difference between Ω_c^* and Ω_c is too small for any strong decay to occur. Very recently, LHCb has explored this sector and observed five new, narrow excited Ω_c states decaying into $\Xi_c^+ K^-$: $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$ and $\Omega_c(3119)$ [6]. This has triggered a lot of interest in attempting to identify their spin-parity quantum numbers [8–21].

In this work we shall use the predictions of the heavy quark–light diquark model and the Regge trajectories in conjunction with other model calculations to study the spin-parity quantum numbers of sextet and antitriplet charmed baryons, especially the newly discovered Ω_c resonances.

II. SPECTROSCOPY

The charmed baryon spectroscopy has been studied extensively in various models. It appears that the spectroscopy is well described by the model based on the relativistic heavy quark–light diquark model advocated by Ebert, Faustov and Galkin (EFG) [22] (see also [23]). Indeed, the quantum numbers $J^P = \frac{5}{2}^+$ of $\Lambda_c(2880)$ have been correctly predicted in the model based on the diquark idea [24] even before its discovery in the Belle experiment [2]. Based on the heavy quark–light diquark model, EFG have constructed the Regge trajectories of heavy baryons for orbital and radial excitations; all available experimental data on heavy baryons fit nicely to linear Regge trajectories, namely, the trajectories in the (J, M^2) and (n_r, M^2) planes for orbitally and radially excited heavy baryons, respectively,

$$J = \alpha M^2 + \alpha_0, \qquad n_r = \beta M^2 + \beta_0, \qquad (2.1)$$

where J is the baryon spin, M is the baryon mass, n_r is the radial excitation quantum number, α, β are the slopes and α_0, β_0 are the intercepts. The Regge trajectories can be plotted for charmed baryons with natural $[P = (-1)^{J-1/2}]$ and unnatural $[P = (-1)^{J+1/2}]$ parities. We have proposed in

TABLE I. Mass spectra and widths (in units of MeV) of the observed charmed baryons. Experimental values are taken from the Particle Data Group [3]. For the masses and widths with a superscript † and *, we have taken into account the recent measurements of LHCb [1] or Belle [4], respectively, for a weighted average. For $\Xi_c(3055)^0$, we quote the result from Belle [5]. For the five new Ω_c states, we quote [6].

State	J^P	Mass	Width	Decay modes
Λ_c^+	$\frac{1}{2}^+$	2286.46 ± 0.14		Weak
$\Lambda_c(2595)^+$	$\frac{1}{2}^-$	2592.25 ± 0.28	2.6 ± 0.6	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2625)^+$	$\frac{3}{2}^-$	2628.11 ± 0.19	< 0.97	$\Lambda_c\pi\pi, \Sigma_c^{(*)}\pi$
$\Lambda_c(2765)^+$	$?^?$	2766.6 ± 2.4	50	$\Sigma_c\pi, \Lambda_c\pi\pi$
$\Lambda_c(2860)^+$	$\frac{3}{2}^+$	$2856.1^{+2.3\dagger}_{-5.9}$	$67.6^{+11.8\dagger}_{-21.6}$	$\Sigma_c^{(*)}\pi, D^0p, D^+n$
$\Lambda_c(2880)^+$	$\frac{5}{2}^+$	$2881.64 \pm 0.25^\dagger$	$5.6 \pm 0.7^\dagger$	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Lambda_c(2940)^+$	$?^?$	$2939.8 \pm 1.4^\dagger$	$20 \pm 6^\dagger$	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p, D^+n$
$\Sigma_c(2455)^{++}$	$\frac{1}{2}^+$	2453.97 ± 0.14	$1.89^{+0.09}_{-0.18}$	$\Lambda_c\pi$
$\Sigma_c(2455)^+$	$\frac{1}{2}^+$	2452.9 ± 0.4	< 4.6	$\Lambda_c\pi$
$\Sigma_c(2455)^0$	$\frac{1}{2}^+$	2453.75 ± 0.14	$1.83^{+0.11}_{-0.19}$	$\Lambda_c\pi$
$\Sigma_c(2520)^{++}$	$\frac{3}{2}^+$	$2518.41^{+0.21}_{-0.19}$	$14.78^{+0.30}_{-0.40}$	$\Lambda_c\pi$
$\Sigma_c(2520)^+$	$\frac{3}{2}^+$	2517.5 ± 2.3	< 17	$\Lambda_c\pi$
$\Sigma_c(2520)^0$	$\frac{3}{2}^+$	2518.48 ± 0.20	$15.3^{+0.4}_{-0.5}$	$\Lambda_c\pi$
$\Sigma_c(2800)^{++}$	$?^?$	2801^{+4}_{-6}	75^{+22}_{-17}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^+$	$?^?$	2792^{+14}_{-5}	62^{+64}_{-44}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^0$	$?^?$	2806^{+5}_{-7}	72^{+22}_{-15}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
Ξ_c^+	$\frac{1}{2}^+$	$2467.93^{+0.28}_{-0.40}$		Weak
Ξ_c^0	$\frac{1}{2}^+$	$2470.85^{+0.28}_{-0.40}$		Weak
$\Xi_c'^+$	$\frac{1}{2}^+$	$2578.3 \pm 0.5^*$		$\Xi_c\gamma$
$\Xi_c'^0$	$\frac{1}{2}^+$	$2579.2 \pm 0.5^*$		$\Xi_c\gamma$
$\Xi_c(2645)^+$	$\frac{3}{2}^+$	$2645.7 \pm 0.3^*$	$2.1 \pm 0.2^*$	$\Xi_c\pi$
$\Xi_c(2645)^0$	$\frac{3}{2}^+$	$2646.3 \pm 0.3^*$	$2.35 \pm 0.22^*$	$\Xi_c\pi$
$\Xi_c(2790)^+$	$\frac{1}{2}^-$	$2791.5 \pm 0.6^*$	$8.9 \pm 1.0^*$	$\Xi_c'\pi, \Xi_c\pi, \Lambda_c\bar{K}$
$\Xi_c(2790)^0$	$\frac{1}{2}^-$	$2794.8 \pm 0.6^*$	$10.0 \pm 1.1^*$	$\Xi_c'\pi, \Xi_c\pi, \Lambda_c\bar{K}$
$\Xi_c(2815)^+$	$\frac{3}{2}^-$	$2816.7 \pm 0.3^*$	$2.43 \pm 0.26^*$	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2815)^0$	$\frac{3}{2}^-$	$2820.2 \pm 0.3^*$	$2.54 \pm 0.25^*$	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2930)^0$	$?^?$	2931 ± 6	36 ± 13	$\Lambda_c\bar{K}, \Sigma_c\bar{K}, \Xi_c\pi, \Xi_c'\pi$
$\Xi_c(2970)^+$	$?^?$	$2966.7 \pm 0.8^*$	$24.6 \pm 2.0^*$	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(2970)^0$	$?^?$	$2970.6 \pm 0.8^*$	$29 \pm 3^*$	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(3055)^+$	$?^?$	3055.1 ± 1.7	11 ± 4	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3055)^0$	$?^?$	3059.0 ± 0.8	6.4 ± 2.4	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^+$	$?^?$	3076.94 ± 0.28	4.3 ± 1.5	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^0$	$?^?$	3079.9 ± 1.4	5.6 ± 2.2	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3123)^+$	$?^?$	3122.9 ± 1.3	4.4 ± 3.8	$\Sigma_c^*\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
Ω_c^0	$\frac{1}{2}^+$	2695.2 ± 1.7		Weak
$\Omega_c(2770)^0$	$\frac{3}{2}^+$	2765.9 ± 2.0		$\Omega_c\gamma$
$\Omega_c(3000)^0$	$?^?$	$3000.4^{+0.4}_{-0.5}$	4.5 ± 0.7	$\Xi_c\bar{K}$
$\Omega_c(3050)^0$	$?^?$	$3050.2^{+0.3}_{-0.5}$	0.8 ± 0.2	$\Xi_c\bar{K}$
$\Omega_c(3066)^0$	$?^?$	$3065.6^{+0.4}_{-0.6}$	3.5 ± 0.4	$\Xi_c\bar{K}$
$\Omega_c(3090)^0$	$?^?$	$3090.2^{+0.7}_{-0.8}$	8.7 ± 1.3	$\Xi_c^{(\prime)}\bar{K}$
$\Omega_c(3119)^0$	$?^?$	$3119.1^{+1.0}_{-1.1}$	1.1 ± 0.9	$\Xi_c^{(\prime)}\bar{K}$

[25] to employ the predictions of the spin-parity quantum numbers of charmed baryons and their masses in [22] as a theoretical benchmark, where the linearity, parallelism and equidistance of the Regge trajectories were verified in their calculations.

A. Ω_c states

Some recent calculations of the Ω_c spectrum based on the quark model, QCD sum rules and lattice QCD are summarized in Table II. (See also Table 6 of [26] for a complete compilation of other model predictions.) Among the five

TABLE II. Mass spectrum of the Ω_c states. Numbers inside the parentheses are our suggested assignments for the masses of the newly observed Ω_c states. The subscripts l and h denote light and heavy states, respectively, as explained in the text.

State nL, J^P	Ebert *et al.* [22]	Shah *et al.* [26]	Chen *et al.* [27]	Agaev *et al.* [8]	Expt. [6]
$1S, 1/2^+$	2698	2695	$2695 \pm 24 \pm 15$	2685 ± 123	2695.2 ± 2.0
$2S, 1/2^+$	3088	3100		3066 ± 138	(3090)
$1S, 3/2^+$	2768	2767	$2781 \pm 12 \pm 22$	2769 ± 89	2765.9 ± 2.0
$2S, 3/2^+$	3123	3126		3119 ± 114	(3119)
$(1P, 1/2^-)_l$	2966	3011	$3015 \pm 29 \pm 34$		(3000)
$(1P, 1/2^-)_h$	3055	3028			
$(1P, 3/2^-)_l$	3029	2976			
$(1P, 3/2^-)_h$	3054	2993			(3050)
$1P, 5/2^-$	3051	2947			(3066)

narrow resonances, we can identify the $\frac{3}{2}^+(2S)$ state with $\Omega_c(3119)$, $(1P, \frac{1}{2}^-)_l$ with $\Omega_c(3000)$ and $\frac{1}{2}^+(2S)$ with $\Omega_c(3090)$ from the quark model predictions of [22,26]. This is further supported by the lattice QCD calculation for $\Omega_c(3000)$[1] and QCD sum rules for $\Omega_c(3119)$. Having identified radially excited states of Ω_c and Ω_c^*, the remaining two resonances $\Omega_c(3050)$ and $\Omega_c(3066)$ should be the orbitally excited states with $J^P = \frac{3}{2}^-$ and $\frac{5}{2}^-$. We propose to assign the quantum numbers $\frac{3}{2}^-$ to $\Omega_c(3050)$ and $\frac{5}{2}^-$ to $\Omega_c(3066)$. Such a quantum number assignment is supported by the nearly parallel Regge trajectories of Ω_c shown in Fig. 1 and the roughly equal distances between $\Omega_c(2695)$ and $\Omega_c(3050)$ with natural parities and between $\Omega_c(2770)$ and $\Omega_c(3066)$ with unnatural parities (see Fig. 2).

Since many authors [10,13,14,16,17] claim that the newly observed five Ω_c resonances can be assigned to the five orbitally excited $1P(1/2^-, 3/2^-, 5/2^-)$ states, we will go through the details and show that not all the observed Ω_c baryons can be interpreted as the P-wave orbitally excited states.

In the quark model, there are seven first P-wave orbitally excited Ω_c states given in Table III. Assuming that the spin of the two light quarks S_ℓ is 1, a common assumption for the sextet baryons, we are left with five states $\Omega_{c0}(\frac{1}{2}^-)$, $\Omega_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ and $\Omega_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ in the notation of $\mathcal{B}_{cJ_\ell}(J^P)$ with J_ℓ being the total angular momentum of the two light quarks [28,29]. The orbital angular momentum of the light diquark can be decomposed into $\mathbf{L}_\ell = \mathbf{L}_\rho + \mathbf{L}_\lambda$, where $\mathbf{L}_\rho$ is the orbital angular momentum between the two light quarks, and $\mathbf{L}_\lambda$ is the orbital angular momentum between the diquark and the charmed quark. Denoting the eigenvalues of $\mathbf{L}_\rho^2$ and $\mathbf{L}_\lambda^2$ with L_ρ and L_λ, respectively, we see that all $\frac{1}{2}^-(1P)$ Ω_c states carry $L_\lambda = 1$ and $L_\rho = 0$. In the presence of the spin-orbit interaction $\mathbf{S}_c \cdot \mathbf{L}$ and the tensor interaction, states with the same J^P but different J_ℓ will mix together [22]. Following [17,30], we write

$$\begin{pmatrix} (1P, 1/2^-)_l \\ (1P, 1/2^-)_h \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 \\ \sin\theta_1 & \cos\theta_1 \end{pmatrix} \begin{pmatrix} \Omega_{c0}(1/2^-) \\ \Omega_{c1}(1/2^-) \end{pmatrix}, \tag{2.2}$$

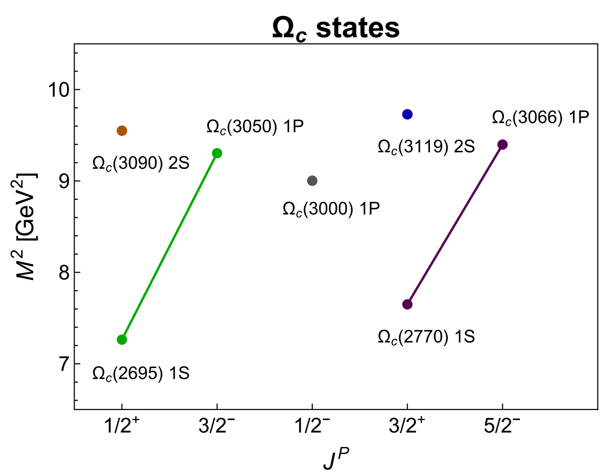

FIG. 1. Regge trajectories of the Ω_c states in the (J^P, M^2) plane with natural $(1/2^+, 3/2^-)$ and unnatural $(1/2^-, 3/2^+, 5/2^-)$ parities.

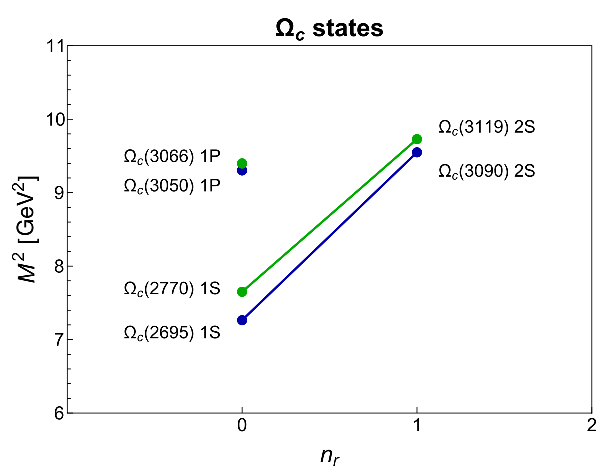

FIG. 2. Regge trajectories of the Ω_c states in the (n_r, M^2) plane with natural (blue) and unnatural (green) parities.

[1]A recent lattice calculation with $N_f = 2 + 1 + 1$ optimal domain-wall fermions [27] yields a mass of $2317 \pm 15 \pm 5$ MeV for D_{s0}^* and $2463 \pm 13 \pm 9$ MeV for $D_{s1}'(2460)$, in excellent agreement with experiment. It also gives a first lattice result on the mass of the $\frac{1}{2}^-$ Ω_c state.

TABLE III. The P-wave Ω_c baryons denoted by $\Omega_{cJ_\ell}(J^P)$ and $\tilde{\Omega}_{cJ_\ell}(J^P)$ with J_ℓ being the total angular momentum of the two light quarks [28,29].

State	SU(3)	S_ℓ	$L_\ell(L_\rho, L_\lambda)$	$J_\ell^{P_\ell}$
$\Omega_{c0}(\frac{1}{2}^-)$	**6**	1	1 (0,1)	0^-
$\Omega_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	**6**	1	1 (0,1)	1^-
$\Omega_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$	**6**	1	1 (0,1)	2^-
$\tilde{\Omega}_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	**6**	0	1 (1,0)	1^-

and

$$\begin{pmatrix} (1P,3/2^-)_h \\ (1P,3/2^-)_l \end{pmatrix} = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 \\ \sin\theta_2 & \cos\theta_2 \end{pmatrix} \begin{pmatrix} \Omega_{c1}(3/2^-) \\ \Omega_{c2}(3/2^-) \end{pmatrix}. \tag{2.3}$$

We shall see below that the $(\frac{3}{2}^-, \frac{5}{2}^-)$ doublets also exist in Σ_c and Ξ_c' sextet states. The mass splitting in the doublet is small and the $3/2^-$ one is slightly heavier than the $5/2^-$ one for Σ_c and Ξ_c' sextets.

The strong decays of charmed baryons are most conveniently described by heavy hadron chiral perturbation theory (HHChPT), into which heavy-quark symmetry and chiral symmetry are incorporated [31,32]. In this approach, the partial widths read[2]

$$\Gamma(\Omega_{c0}(1/2^-) \to \Xi_c \bar{K}) = \frac{h_3^2}{2\pi f_\pi^2} \frac{m_{\Xi_c}}{m_{\Omega_{c0}}} E_K^2 p_K,$$
$$\Gamma(\Omega_{c1}(1/2^-) \to \Xi_c' \bar{K}) = \frac{h_4^2}{4\pi f_\pi^2} \frac{m_{\Xi_c'}}{m_{\Omega_{c1}}} E_K^2 p_K,$$
$$\Gamma(\Omega_{c1}(3/2^-) \to \Xi_c' \bar{K}) = \frac{h_9^2}{9\pi f_\pi^2} \frac{m_{\Xi_c'}}{m_{\Omega_{c1}}} p_K^5,$$
$$\Gamma(\Omega_{c2}(3/2^-, 5/2^-) \to \Xi_c \bar{K}) = \frac{4h_{10}^2}{15\pi f_\pi^2} \frac{m_{\Xi_c}}{m_{\Omega_{c2}}} p_K^5,$$
$$\Gamma(\Omega_{c2}(3/2^-) \to \Xi_c' \bar{K}) = \frac{h_{11}^2}{10\pi f_\pi^2} \frac{m_{\Xi_c'}}{m_{\Omega_{c2}}} p_K^5,$$
$$\Gamma(\Omega_{c2}(5/2^-) \to \Xi_c' \bar{K}) = \frac{2h_{11}^2}{45\pi f_\pi^2} \frac{m_{\Xi_c'}}{m_{\Omega_{c2}}} p_K^5, \tag{2.4}$$

where p_K is the center-of-mass (c.m.) momentum of the kaon and $f_\pi = 132$ MeV. In the above equations, $h_{3,4}$ are the couplings responsible for the s-wave transition between S- and P-wave baryons and $h_{9,10,11}$ are the couplings for the d-wave transition between S- and P-wave baryons. Using the quark-model relation $|h_3| = \sqrt{3}|h_2|$ from [33] and the coupling h_2 extracted from $\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$, it is found that $\Gamma(\Omega_{c0} \to \Xi_c\bar{K}) \approx 410$ MeV for $h_2 = 0.437$ [28] and 852 MeV for $h_2 = 0.63$ [34].[3] Hence, $\Omega_c(3000)$ cannot be a pure $\Omega_{c0}(\frac{1}{2}^-)$ state due to a very broad width expected for the s-wave transition. Nevertheless, it can be identified with $\Omega_{c1}(\frac{1}{2}^-)$ since its decay into $\Xi_c K$ is prohibited in the heavy-quark limit but could be allowed when heavy-quark symmetry is broken. This means that the mixing angle θ_1 in Eq. (2.2) must be close to 90° if $\Omega_c(3000)$ is to be identified with the $(1P, 1/2^-)_l$ state. From the data $\Gamma(\Omega_c(3000)) = 4.5 \pm 0.7$ MeV [6], we find that $\theta_1 \approx 96°$ or 84° where we have neglected the contributions from $\Omega_{c1}(\frac{1}{2}^-) \to \Xi_c\bar{K}$. The other state $(1P, 1/2^-)_h$ will be too broad to be observed. For example, if we identify $\Omega_c(3090)$ with $(1P, 1/2^-)_h$, we will obtain $\Gamma(\Omega_c(3090) \to \Xi_c\bar{K} + \Xi_c'\bar{K}) = \sin^2\theta_1(1006\text{ MeV}) + \cos^2\theta_1(173\text{ MeV}) = 997$ MeV for $\theta_1 = 96°$, where use of $|h_4| = 2|h_2|$ [33] has been made. Hence, we conclude that only one of the $(1P, 1/2^-)$ states can be identified with the observed narrow Ω_c baryon. We see that $\Omega_c(3000)$ is narrow because it is primarily a $\Omega_{c1}(\frac{1}{2}^-)$ state with a very small component of $\Omega_{c0}(\frac{1}{2}^-)$.

We next turn to the widths of $\Omega_c(3050)$ and $\Omega_c(3066)$. It is clear from Eq. (2.4) that their widths are governed by the coupling h_{10}, which can be determined from the measured widths of $\Sigma_c(2800)^{++,+,0}$ to be [34]

$$|h_{10}| = (0.85^{+0.11}_{-0.08}) \times 10^{-3}\ \text{MeV}^{-1}. \tag{2.5}$$

We then obtain $\Gamma(\Omega_c(3050)) = \sin^2\theta_2(8.6^{+2.2}_{-1.6})$ MeV and $\Gamma(\Omega_c(3066)) = (13.3^{+3.4}_{-2.5})$ MeV where we have neglected the contribution from $\Omega_{c1}(3/2^-)$ as it does not decay into $\Xi_c K$ in the heavy-quark limit. The experimental width of $(0.8 \pm 0.2 \pm 0.1) < 1.2$ MeV for $\Omega_c(3050)$ [6] is well accommodated for $\theta_2 \approx 160°$, but our prediction for $\Omega_c(3066)$ is too large by a factor of 4 compared to the data $3.5 \pm 0.4 \pm 0.2$ MeV [6]. It is not clear to us what is the underlying reason for this discrepancy. For example, lowering the estimate of background events in the data may bring the observed widths closer to our calculations.

There are two recent papers claiming reasonable model results for the Ω_c widths: [12,17]. Using the decay formula proposed by Eichten, Hill and Quigg and the $^3P_0$ model in conjunction with the simple harmonic oscillator wave functions for the transition form factors, Chen and Liu [17] calculated partial and total widths for the $1P$ and $2S$ Ω_c states. They obtained $\Gamma(\Omega_{c0}) = 35$ MeV (see Fig. 1 of

[2]Equation (2.4) is derived from the Lagrangian terms [33]

$$\mathcal{L} = ih_{10}\epsilon_{ijk}\bar{\mathcal{T}}_i(\mathcal{D}_\mu A_\nu + \mathcal{D}_\nu A_\mu)_{jl}\mathcal{X}^{\mu\nu}_{kl} + h_{11}\epsilon_{\mu\nu\sigma\lambda}\text{Tr}\{\bar{\mathcal{S}}^\mu(\mathcal{D}^\nu A_\alpha + \mathcal{D}_\alpha A^\nu)\mathcal{X}^{\alpha\sigma}\}v^\lambda,$$

where $\mathcal{T}_i$ and $\mathcal{S}^{ij}_\mu$ are superfields for S-wave baryons and $\mathcal{X}^{ij}_{\mu\nu}$ for spin-$\frac{5}{2}$ and spin-$\frac{3}{2}$ $J_\ell^{P_\ell} = 2^-$ multiplet (see [33] for details).

[3]The coupling h_2 used to be of order 0.42 . It became large, of order 0.60, after a more sophisticated treatment of the mass line shape of $\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$ by the CDF Collaboration [35]. However, this latest value of h_2 will lead to the predictions of $\Gamma(\Xi_c^+(2790))$ and $\Gamma(\Xi_c^0(2790))$ too large by a factor of 2 compared to the recent measurements by Belle [4]. Therefore, we should use $h_2 = 0.437^{+0.114}_{-0.102}$ [28] in the ensuing discussions.

[17]), which was smaller than our model-independent result by 1 order of magnitude. For comparison, we notice that a very broad width of 1400 MeV for Ω_{c0} is predicted in [18], while the QCD sum rule result of 420 MeV [9] is very close to ours. As noticed in passing, if the width of Ω_{c0} is indeed of order 400 MeV, $(1P, 1/2^-)_l$ and $(1P, 1/2^-)_h$ cannot both be identified with the observed narrow Ω_c states. Wang *et al.* computed the strong and radiative decays of Ω_c states using the chiral quark model [12] and obtained narrow widths for all ${}^{2S+1}L_{J^P}$ states for $L = 1$, $J^P = 1/2^-, 3/2^-$ and $5/2^-$. In this work, the authors did not consider the mixing effects of the states with the same J but different J_ℓ or S. We suspect that at least some widths calculated in [12,17] are underestimated.

B. Λ_c states

$\Lambda_c(2765)^+$ is a broad state first seen in the $\Lambda_c^+\pi^+\pi^-$ decay by CLEO [36]. However, it is still not known whether it is Λ_c^+ or Σ_c^+ and whether the large width might be due to overlapping states. In the quark-diquark model, it has also been proposed to be either the first radial $(2S)$ excitation of the Λ_c with $J^P = \frac{1}{2}^-$ containing the light scalar diquark or the first orbital excitation $(1P)$ of the Σ_c with $J^P = \frac{3}{2}^-$ containing the light axial-vector diquark [37]. In this work we shall consider the former case.

The state $\Lambda_c(2880)^+$, first observed by CLEO [36] in the $\Lambda_c^+\pi^+\pi^-$ decay, was also seen by *BABAR* in the D^0p spectrum [38]. Belle studied the experimental constraint on the J^P quantum numbers of $\Lambda_c(2880)^+$ [2] and found that $J^P = \frac{5}{2}^+$ was favored by the angular analysis of $\Lambda_c(2880)^+ \to \Sigma_c^{0,++}\pi^\pm$ decays. The mass, width and quantum numbers of $\Lambda_c(2880)$ were recently confirmed by LHCb [1]. The $\frac{1}{2}^+(1S)$ Λ_c, $\frac{3}{2}^-(1P)$ $\Lambda_c(2625)$ and $\frac{5}{2}^+(1D)$ $\Lambda_c(2880)$ states form a Regge trajectory. The new resonance $\Lambda_c(2860)^+$ observed by LHCb, as manifested in the near-threshold enhancement in the D^0p amplitude through an amplitude analysis of the $\Lambda_b^0 \to D^0p\pi^-$ decay, has $J^P = \frac{3}{2}^+$ with mass and width shown in Table I [1]. It forms another Regge trajectory with $\frac{1}{2}^-(1P)$ $\Lambda_c(2595)$. It is worth mentioning that the existence of this new state $\Lambda_c(2860)^+$ was noticed before the LHCb experiment [30,39,40]. We see from Fig. 3 that both trajectories are nicely parallel to each other.

The highest state $\Lambda_c(2940)^+$ was first discovered by *BABAR* in the D^0p decay mode [38] and confirmed by Belle in the $\Sigma_c^0\pi^+, \Sigma_c^{++}\pi^-$ decays, which subsequently decayed into $\Lambda_c^+\pi^+\pi^-$ [2]. Its spin-parity assignment is quite diverse (see [25] for a review). The constraints on its spin and parity were recently studied by LHCb [1]. The most likely assignment was found to be $J^P = \frac{3}{2}^-$ with

$$m(\Lambda_c(2940)) = 2944.8^{+3.5}_{-2.5} \pm 0.4^{+0.1}_{-4.6}\ \text{MeV},$$
$$\Gamma(\Lambda_c(2940)) = 27.7^{+8.2}_{-6.0} \pm 0.9^{+5.2}_{-10.4}\ \text{MeV}, \qquad (2.6)$$

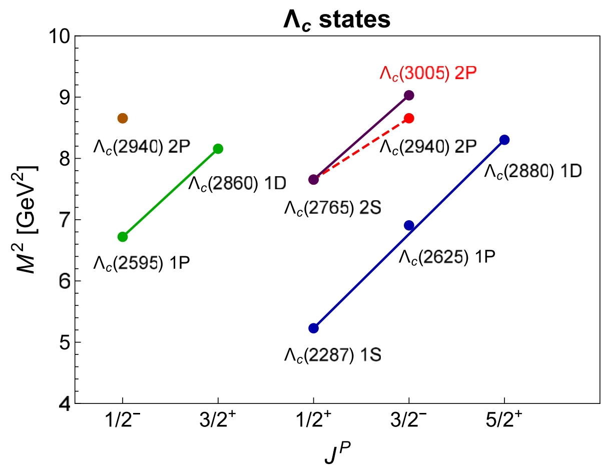

FIG. 3. Regge trajectories of the Λ_c states in the (J^P, M^2) plane with natural $(1/2^+, 3/2^-, 5/2^+)$ and unnatural $(1/2^-, 3/2^+)$ parities. The yet detected state is labeled in red. The red dashed line shows a discordant identification of $\Lambda_c(2940)$ as a $3/2^-(2P)$ state.

to be compared with $m = 2939.3^{+1.4}_{-1.5}$ MeV and $\Gamma = 17^{+8}_{-6}$ MeV quoted in PDG [3]. We have averaged them in Table I. If we draw a Regge trajectory connecting $\Lambda_c(2940)$ and $\Lambda_c(2765)$ with $\frac{1}{2}^+(2S)$, we see that this Regge line is not parallel to the other two Regge trajectories. If we use the quark-diquark model prediction of $\Lambda_c(3005)$ for the $\frac{3}{2}^-(2P)$ state [22], the trajectories satisfy the parallelism nicely. Hence, we suggest that the quantum numbers of $\Lambda_c(2940)^+$ are most likely $\frac{1}{2}^-(2P)$. Indeed, LHCb [1] has cautiously stated that "the most likely spin-parity assignment for $\Lambda_c(2940)$ is $J^P = \frac{3}{2}^-$ but the other solutions with spin 1/2 to 7/2 cannot be excluded." In order to clarify this issue, it is thus important to search for the Λ_c^+ state with a mass of order 3005 MeV and verify its quantum numbers as $\frac{3}{2}^-(2P)$.

C. Ξ_c states

Another example showing the usefulness of the Regge phenomenology in the J^P assignment of charmed baryons is the Ξ_c states. The Regge analysis suggests $3/2^+(1D)$ for $\Xi_c(3055)$ and $5/2^+(1D)$ for $\Xi_c(3080)$ [22] (see also discussions in [41]). The $\Xi_c(2470)$, $\Xi_c(2815)$ and $\Xi_c(3080)$ states form a $\frac{1}{2}^+$ Regge trajectory, while $\Xi_c(2790)$ and $\Xi_c(3055)$ form a $\frac{1}{2}^-$ one (see Fig. 4). They are parallel to each other nicely. Recently, the discovery of the neutral $\Xi_c(3055)^0$, observed by its decay into the final-state ΛD^0, and the first observation and evidence of the decays of $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ into ΛD^+ were presented by Belle [5].

D. Ξ_c' states

A state $\Xi_c(2930)^0$, which is omitted from the PDG summary table, has been seen only by *BABAR* in the

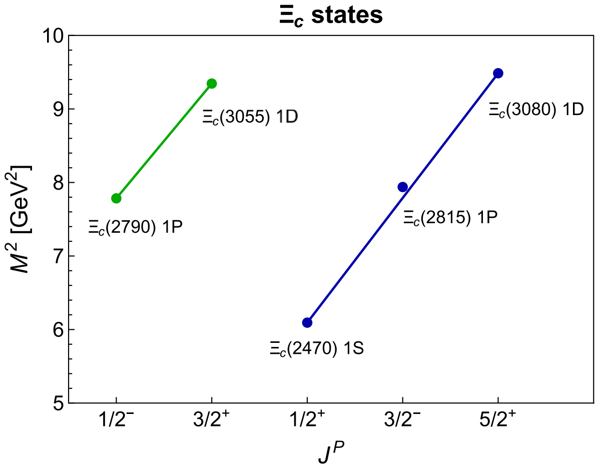

FIG. 4. Regge trajectories of the Ξ_c states in the (J^P, M^2) plane with natural $(1/2^+, 3/2^-, 5/2^+)$ and unnatural $(1/2^-, 3/2^+)$ parities.

$\Lambda_c^+ K^-$ mass projection of $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ [42]. According to the quark-diquark model of [22] (see also [30]), its J^P quantum numbers could be $\frac{3}{2}^-$ or $\frac{5}{2}^-$. Quark-model calculations suggest that $\frac{3}{2}^-(1P)$ is slightly heavier than $\frac{5}{2}^-(1P)$ (see Table 3 of [30]). The $\Xi_c'(2645)$ state with $\frac{3}{2}^+(1S)$ and $\Xi_c'(3123)$ with $\frac{7}{2}^+(1D)$ form a Regge trajectory. It is clear from Fig. 5 that the unknown $\frac{5}{2}^-$ state has a mass of order 2890 MeV. We shall designate this state to $\Xi_c'(2921)$, which carries the correct spin-parity quantum numbers, and its mass is not far from 2890 MeV [37]. Hence, we should assign $\frac{3}{2}^-$ to $\Xi_c'(2930)$. Now $\Xi_c'(2930)$ and $\Xi_c'(2921)$ form a P-wave doublet denoted by $\Xi_{c2}'(\frac{3}{2}^-, \frac{5}{2}^-)$. Just as the Ω_{c2} doublet, the partial widths of $\Xi_{c2}'(3/2^-)$ read

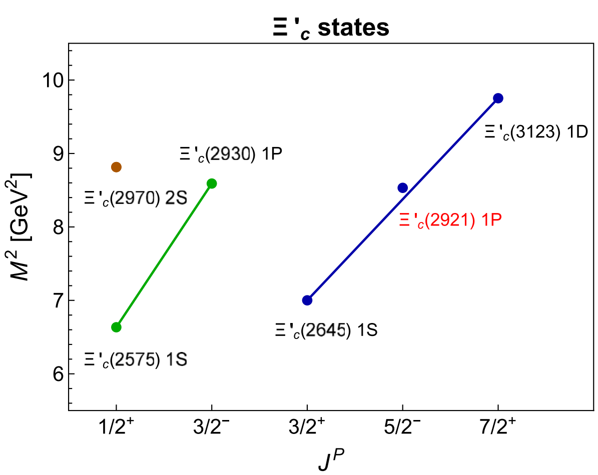

FIG. 5. Regge trajectories of the Ξ_c' states in the (J^P, M^2) plane with natural $(1/2^+, 3/2^-)$ and unnatural $(3/2^+, 5/2^-, 7/2^+)$ parities. The yet detected state is labeled in red.

$$\Gamma(\Xi_{c2}'(3/2^-) \to \Lambda_c \bar{K}) = \frac{4h_{10}^2}{15\pi f_\pi^2} \frac{m_{\Lambda_c}}{m_{\Xi_{2c}'}} p_K^5,$$

$$\Gamma(\Xi_{c2}'(3/2^-) \to \Xi_c \pi) = \frac{4h_{10}^2}{15\pi f_\pi^2} \frac{m_{\Xi_c}}{m_{\Xi_{2c}'}} p_\pi^5,$$

$$\Gamma(\Xi_{c2}'(3/2^-) \to \Sigma_c \bar{K}) = \frac{h_{11}^2}{10\pi f_\pi^2} \frac{m_{\Sigma_c}}{m_{\Xi_{c2}'}} p_K^5,$$

$$\Gamma(\Xi_{c2}'(3/2^-) \to \Xi_c' \pi) = \frac{h_{11}^2}{10\pi f_\pi^2} \frac{m_{\Xi_c'}}{m_{\Xi_{c2}'}} p_\pi^5. \quad (2.7)$$

If the state $\Xi_{c2}'(3/2^-)$ is identified with $\Xi_c'(2930)$, its decay into $\Sigma_c \bar{K}$ will be kinematically prohibited. Although $\Xi_c'(2930)$ has been observed only in the $\Lambda_c K$ decay mode, we need to sum over the $\Lambda_c \bar{K}, \Xi_c \pi, \Xi_c' \pi$ channels in order to estimate its total width. Using the quark-model relation $h_{11}^2 = 2h_{10}^2$ [33] and Eq. (2.5), we obtain

$$\Gamma(\Xi_c'(2930)^0) = 77^{+20}_{-14}\ \text{MeV}, \quad (2.8)$$

which deviates from the measurement of 36 ± 13 MeV [42] by 2.1σ. One possibility for the discrepancy is ascribed to the SU(3) breaking in the quark-model relation $h_{11}^2 = 2h_{10}^2$. In view of theoretical difficulties in estimating decay widths, we regard the above HHChPT result as a good support for the $\frac{3}{2}^-(1P)$ assignment to $\Xi_c'(2930)$.

E. Σ_c states

The highest isotriplet charmed baryons, $\Sigma_c(2800)^{++,+,0}$, decaying to $\Lambda_c^+ \pi$, were first measured by Belle [43] with widths of order 70 MeV. We have advocated in [28] that they are $\Sigma_{c2}(\frac{3}{2}^-)$ states. Their quantum numbers are sometimes assigned to be $\frac{1}{2}^-$ in the literature. Here we repeat our argument again. The possible quark states are $\Sigma_{c0}(\frac{1}{2}^-)$, $\Sigma_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$, $\tilde{\Sigma}_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ and $\Sigma_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ in the notation of $\mathcal{B}_{cJ_\ell}(J^P)$ [28,29], or $[\mathbf{6}_F, 0, 1, \lambda]$, $[\mathbf{6}_F, 1, 1, \lambda]$, $[\mathbf{6}_F, 1, 0, \rho]$ and $[\mathbf{6}_F, 2, 1, \lambda]$ in terms of the notation $[\mathbf{6}_F, J_\ell, S_\ell, \rho/\lambda]$. The states Σ_{c1} and $\tilde{\Sigma}_{c1}$ are ruled out because their decays to $\Lambda_c^+ \pi$ are prohibited in the heavy-quark limit, recalling that only the $\Sigma_c(2800) \to \Lambda_c \pi$ decay mode has been observed. Now the $\Sigma_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ baryons decay primarily into the $\Lambda_c \pi$ system in a d-wave, whereas $\Sigma_{c0}(\frac{1}{2}^-)$ decays into $\Lambda_c \pi$ in an s-wave. In the framework of HHChPT, we have [33]

$$\Gamma(\Sigma_{c0}(1/2^-) \to \Lambda_c \pi) = \frac{h_3^2}{2\pi f_\pi^2} \frac{m_{\Lambda_c}}{m_{\Sigma_{c0}}} E_\pi^2 p_\pi, \quad (2.9)$$

where h_3 is one of the couplings responsible for the s-wave transition between S- and P-wave baryons, and p_π is the c.m. momentum of the pion. Using the quark-model relation $|h_3| = \sqrt{3}|h_2|$ from [33] and the coupling h_2 extracted from $\Lambda_c(2595)^+ \to \Lambda_c^+ \pi^+ \pi^-$, it is found that

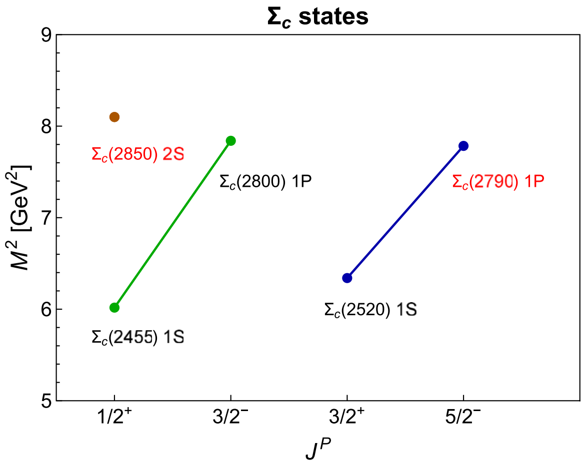

FIG. 6. Regge trajectories of the Σ_c states in the (J^P, M^2) plane with natural $(1/2^+, 3/2^-)$ and unnatural $(3/2^+, 5/2^-)$ parities. The yet-detected states are labeled in red.

$\Gamma(\Sigma_{c0}^{++} \to \Lambda_c^+\pi^+) \approx 425$ MeV for $h_2 = 0.437$ [28] and 885 MeV for $h_2 = 0.63$ [34]. In either case, the predicted width is too large by 1 order of magnitude compared to the measured one of order 75 MeV. Hence, this very broad Σ_{c0} cannot be identified with $\Sigma_c(2800)$. Therefore, $\Sigma_c(2800)^{++,+,0}$ are likely to be either $\Sigma_{c2}(\frac{3}{2}^-)$ or $\Sigma_{c2}(\frac{5}{2}^-)$ or a mixture of the two. In the quark-diquark model [22], both of them have very close masses compatible with experiment. Given the fact that for light strange baryons, the first orbital excitation of the light Σ has the quantum numbers $J^P = \frac{3}{2}^-$, we thus advocate a $\Sigma_{c2}(\frac{3}{2}^-)$ state for $\Sigma_c(2800)$. The $\frac{5}{2}^-$ $\Sigma_c(2790)$ state has a mass in the vicinity of 2790 MeV [22,30].

Using QCD sum rules, the authors of [9] obtained the widths of 200, 7.9 and 300 MeV, respectively, for the $\Sigma_{c0}(\frac{1}{2}^-) \to \Lambda_c\pi$, $\Sigma_{c1}(\frac{1}{2}^-) \to \Sigma_c\pi$ and $\tilde{\Sigma}_{c1}(\frac{1}{2}^-) \to \Sigma_c\pi$ decays, and proposed that $\Sigma_c(2800)$ might be a $\frac{1}{2}^-$ state belonging to Σ_{c0} or as a $\frac{1}{2}^-$ state containing both Σ_{c0} and Σ_{c1}.

Among the sextet states, both Ω_c and Ξ_c' have $\frac{1}{2}^+(2S)$ states: $\Omega_c(3090)$ and $\Xi_c'(2970)$. In the Σ_c sector, we also have a possible $\frac{1}{2}^+(2S)$ candidate. *BABAR* observed an excited Σ_c^0 state [denoted as $\Sigma_c^0(2850)$ in [30]] in the decay $B^- \to \Sigma_c(2850)^0\bar{p} \to \Lambda_c^+\pi^-\bar{p}$ with a mass of $2846 \pm 8 \pm 10$ MeV and a width of 86^{+33}_{-22} MeV [44]. We shall follow [30] to designate this new state with $\frac{1}{2}^+(2S)$. Regge trajectories for the Σ_c states are plotted in Fig. 6.

F. Antitriplet and sextet states

Many observed charmed baryons form antitriplet and sextet states. They are classified according to the quantum numbers $J^P(nL)$ in Table IV. The mass difference $\Delta m_{\Xi_c\Lambda_c} \equiv m_{\Xi_c} - m_{\Lambda_c}$ in the antitriplet states clearly lies between about 180 and 200 MeV. This means that the quantum numbers of the listed $\bar{\mathbf{3}}$ states are now established. Also shown in Table IV are five different sets of sextet states associated with the Ω_c, Ξ_c' and Σ_c baryons. The states labeled in red are yet to be measured and have been discussed in previous subsections. The mass splittings $\Delta m_{\Omega_c\Xi_c'} \equiv m_{\Omega_c} - m_{\Xi_c'}$ between Ω_c and Ξ_c' and $\Delta m_{\Xi_c'\Sigma_c} \equiv m_{\Xi_c'} - m_{\Sigma_c}$ between Ξ_c' and Σ_c ought to be about the same. Numerically, we find that $\Delta m_{\Omega_c\Xi_c'}$ and $\Delta m_{\Xi_c'\Sigma_c}$ are indeed close to each other, between about 120 and 130 MeV. This lends a further strong support for the quantum number assignment to the sextet states in this work.

It is clear from Table IV that various doublets are observed. In the antitriplet sector, $(\Lambda_c(2595), \Lambda_c(2625))$ and $(\Xi_c(2790), \Xi_c(2815))$ belong to the P-wave doublets $(\frac{1}{2}^-, \frac{3}{2}^-)$ while $(\Lambda_c(2860), \Lambda_c(2880))$ and $(\Xi_c(3055),$

TABLE IV. Antitriplet and sextet states of charmed baryons. Mass differences $\Delta m_{\Xi_c\Lambda_c} \equiv m_{\Xi_c} - m_{\Lambda_c}$, $\Delta m_{\Xi_c'\Sigma_c} \equiv m_{\Xi_c'} - m_{\Sigma_c}$ and $\Delta m_{\Omega_c\Xi_c'} \equiv m_{\Omega_c} - m_{\Xi_c'}$ are all in units of MeV. The yet-detected states are printed in bold face.

	$J^P(nL)$	States	Mass differences
$\bar{\mathbf{3}}$	$\frac{1}{2}^+(1S)$	$\Lambda_c(2287)^+, \Xi_c(2470)^+, \Xi_c(2470)^0$	$\Delta m_{\Xi_c\Lambda_c} = 183$
	$\frac{1}{2}^-(1P)$	$\Lambda_c(2595)^+, \Xi_c(2790)^+, \Xi_c(2790)^0$	$\Delta m_{\Xi_c\Lambda_c} = 198$
	$\frac{3}{2}^-(1P)$	$\Lambda_c(2625)^+, \Xi_c(2815)^+, \Xi_c(2815)^0$	$\Delta m_{\Xi_c\Lambda_c} = 190$
	$\frac{3}{2}^+(1D)$	$\Lambda_c(2860)^+, \Xi_c(3055)^+, \Xi_c(3055)^0$	$\Delta m_{\Xi_c\Lambda_c} = 201$
	$\frac{5}{2}^+(1D)$	$\Lambda_c(2880)^+, \Xi_c(3080)^+, \Xi_c(3080)^0$	$\Delta m_{\Xi_c\Lambda_c} = 196$
$\mathbf{6}$	$\frac{1}{2}^+(1S)$	$\Omega_c(2695)^0, \Xi_c'(2575)^{+,0}, \Sigma_c(2455)^{++,+,0}$	$\Delta m_{\Omega_c\Xi_c'} = 119$, $\Delta m_{\Xi_c'\Sigma_c} = 124$
	$\frac{3}{2}^+(1S)$	$\Omega_c(2770)^0, \Xi_c'(2645)^{+,0}, \Sigma_c(2520)^{++,+,0}$	$\Delta m_{\Omega_c\Xi_c'} = 120$, $\Delta m_{\Xi_c'\Sigma_c} = 128$
	$\frac{1}{2}^+(2S)$	$\Omega_c(3090)^0, \Xi_c'(2970)^{+,0}, \mathbf{\Sigma_c(2850)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi_c'} = 120$, $\Delta m_{\Xi_c'\Sigma_c} = 120$
	$\frac{3}{2}^-(1P)$	$\Omega_c(3050)^0, \Xi_c'(2930)^{+,0}, \Sigma_c(2800)^{++,+,0}$	$\Delta m_{\Omega_c\Xi_c'} = 120$, $\Delta m_{\Xi_c'\Sigma_c} = 130$
	$\frac{5}{2}^-(1P)$	$\Omega_c(3066)^0$, $\mathbf{\Xi_c'(2921)^{+,0}}$, $\mathbf{\Sigma_c(2790)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi_c'} = 145$, $\Delta m_{\Xi_c'\Sigma_c} = 131$

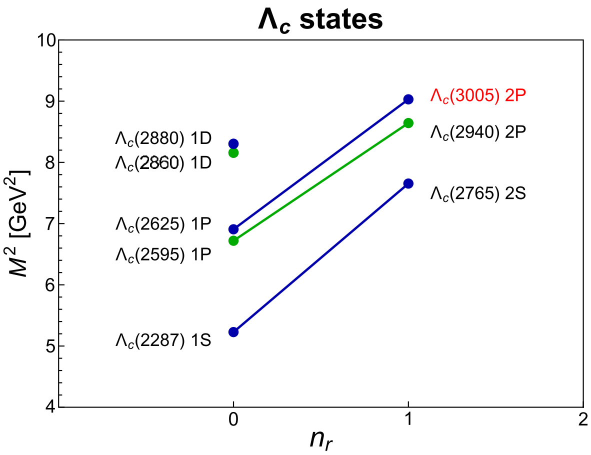

FIG. 7. Regge trajectories of the Λ_c states in the (n_r, M^2) plane with natural (blue) and unnatural (green) parities.

$\Xi_c(3080)$) form the D-wave doublets $(\frac{3}{2}^+, \frac{5}{2}^+)$. In the sextet sector, $(\Omega_c(2695), \Omega_c(2770))$, $(\Sigma_c(2455), \Sigma_c(2520))$ and $(\Xi'_c(2575), \Xi'_c(2645))$ belong to the S-wave doublets $(\frac{1}{2}^+, \frac{3}{2}^+)$ while $(\Omega_c(3050), \Omega_c(3066))$, $(\Sigma_c(2800), \Sigma_c(2790))$ and $(\Xi'_c(2930), \Xi'_c(2921))$ form the P-wave doublets $(\frac{3}{2}^-, \frac{5}{2}^-)$.

G. Regge trajectories

Various Regge trajectories in the (J^P, M^2) plane for $\Omega_c, \Lambda_c, \Xi_c, \Xi'_c$ and Σ_c states are depicted in Figs. 1–6. In the phenomenology of Regge trajectories, the Regge slopes are usually assumed to be the same for all the baryon multiplets. This ansatz leads to the parallelism among trajectories with natural or unnatural parities, and the parallelism between natural and unnatural parities. Empirically, this is nicely supported by the Regge trajectories of the antitriplet Λ_c and Ξ_c states. We see that their Regge trajectories for the orbital excitations of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ are parallel to each other, as shown in Figs. 3 and 4. Based on this nice property of parallelism, we have shown that the quantum numbers of $\Lambda_c(2940)^+$ are most likely $\frac{1}{2}^-(2P)$ rather than $\frac{3}{2}^-$ found by LHCb [1].

As for the sextet Ω_c, Ξ'_c and Σ_c states, the slope of the Regge trajectory for the orbital excitation of $\frac{1}{2}^+$ is slightly larger than that of the $\frac{3}{2}^+$ one for reasons not clear to us. The $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states $(\Omega_c(3050), \Omega_c(3066))$, $(\Xi'_c(2930), \Xi'_c(2921))$ and $(\Sigma_c(2800), \Sigma_c(2790))$ form P-wave doublets described by $[\mathbf{6}_F, 2, 1, \lambda]$ or $\Omega_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$, $\Xi'_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$, $\Sigma_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$, respectively. The mass splittings in the doublets are small and the $\frac{3}{2}^-$ states are slightly heavier than the $\frac{5}{2}^-$ ones.

For completeness, we also show the Regge trajectories in the (n_r, M^2) plane for Ω_c and Λ_c in Figs. 2 and 7, respectively. The parallelism and nearly equidistance of the Regge trajectories of Λ_c states with natural parities $(1/2^+, 3/2^-, 5/2^+)$ are obviously seen in Fig. 7.

III. CONCLUSIONS

Based mainly on the heavy quark–light diquark model and the Regge trajectories in conjunction with other model calculations, we have studied the spin-parity quantum numbers of charmed baryons. Our main results are as follows.

(i) Among the five newly observed Ω_c states, we have identified $\Omega_c(3090)$ and $\Omega_c(3119)$ with the radially excited $\frac{1}{2}^+(2S)$ and $\frac{3}{2}^+(2S)$ states, respectively, and $\Omega_c(3000)$ with $\frac{1}{2}^-(1P)$ and $S = \frac{3}{2}$. The two states $\Omega_c(3050)$ and $\Omega_c(3066)$ form a P-wave $(\frac{3}{2}^-, \frac{5}{2}^-)$ doublet.

(ii) Since the width of $\Omega_{c0}(\frac{1}{2}^-)$ is estimated to be of order 410 MeV using heavy hadron chiral perturbation theory, not all observed narrow Ω_c baryons can be identified with $1P$ states. The mixing angles θ_1 and θ_2 defined in Eqs. (2.2) and (2.3) are constrained to be around 96° and 160°, respectively.

(iii) In the sextet sector, $(\Sigma_c(2800), \Sigma_c(2790))$ and $(\Xi'_c(2930), \Xi'_c(2921))$ also belong to the P-wave $(\frac{3}{2}^-, \frac{5}{2}^-)$ doublet. Using the measured width of $\Sigma_c(2800)$ as an input, the widths of $\Omega_c(3066)$ and $\Xi'_c(2930)$ are calculable within the framework of heavy hadron chiral perturbation theory. The predicted width of $\Xi'_c(2930)$ deviates from experiment by 2.1σ. While $\Omega_c(3066)$ is broader than $\Omega_c(3050)$, it is narrower than $\Sigma_c(2880)$ and $\Xi'_c(2930)$ by 1 order of magnitude due to the smaller c.m. momentum p_K appearing in the D-wave suppression factor proportional to p_K^5.

(iv) For the Λ_c and Ξ_c antitriplet states, their Regge trajectories for the orbital excitations of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ are parallel to each other. Based on this nice property of parallelism, we see that although the newly detected $\Lambda_c(2860)^+$ fits nicely to the Regge trajectory, the highest state $\Lambda_c(2940)^+$ does not fit if its quantum numbers are $\frac{3}{2}^-$ as preferred by LHCb. We suggest that $\Lambda_c(2940)^+$ is most likely the $\frac{1}{2}^-(2P)$ state. Experimentally, it is thus important to search for the Λ_c baryon with a mass of order 3005 MeV and verify its quantum numbers as $\frac{3}{2}^-(2P)$.

(v) The charmed baryon $\Sigma_c(2800)$ cannot be a $\frac{1}{2}^-$ state. Otherwise, its width will be over 400 MeV, too large compared to the measured one.

(vi) In the study of Regge trajectories of Ξ'_c states, we find a missing state. It should have quantum numbers $\frac{5}{2}^-$ with a mass around 2920 MeV.

(vii) Antitriplet and sextet states classified according to their $J^P(nL)$ quantum numbers are shown in Table IV. The mass difference between Ξ_c and Λ_c

in the antitriplet states clearly lies between 180 and 200 MeV. Moreover, the mass splitting between Ω_c and Ξ'_c is found to be very close to the one between Ξ'_c and Σ_c for five different sets of sextet multiplets. This lends a strong support for the quantum number assignment to the sextet states in this work.

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