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Strong decay widths and mass spectra of charmed baryons

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The total decay widths of charmed baryons, including all the possible open-flavor decay channels, are calculated by means of the $^3P_0$ model. Our calculations consider in the final states: the charmed baryon-(vector/pseudoscalar) meson pairs and the (octet/decuplet) baryon-(pseudoscalar/vector) charmed meson pairs, within a constituent quark model. Furthermore, we calculate the masses of the charmed baryon ground states and their excitations up to the D-wave in a constituent quark model both in the three-quark and in quark-diquark schemes. To do so, we utilize a Hamiltonian model based on a harmonic oscillator potential plus a mass splitting term that encodes the spin, spin-orbit, isospin, and flavor interactions. The parameters of the Hamiltonian model are fitted to experimental data of charmed baryon masses and decay widths. As the experimental uncertainties of the data affect the fitted model parameters, we have thoroughly propagated these uncertainties into our predicted charmed baryon masses and decay widths via a Monte Carlo bootstrap approach. Our quantum number assignments and predictions of mass and strong partial decay widths are in reasonable agreement with the available data. Thus, our results show the ability to guide future measurements in LHCb, Belle and Belle II experiments.

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1. Introduction

The theoretical understanding of charmed baryons has recently improved thanks to the application of non-relativistic quark models, QCD sum rules, and lattice QCD [1]. Nevertheless, the success of these studies is only partial since no model is capable of describing the complete baryon spectrum, decay widths and internal quantum structure. On the experimental side, the LHCb and Belle experiments have consistently observed charmed baryons. LHCb and Belle reported the states $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, $\Omega_c(3119)$ (only seen by LHCb) and $\Omega_c(3188)$ [2, 3]. Moreover, the $\Sigma_c(2455)$, $\Sigma_c(2520)$ and $\Sigma_c(2800)$ states are reported in Ref. [4]. Lastly, LHCb observed the $\Xi_c^0(2923)$, $\Xi_c^0(2939)$ and $\Xi_c^0(2965)$ states [5]. Both theory and experimental results motivate further studies on charmed baryons.

In this work we use the models of Ref. [6] to predict the charmed baryon mass spectra and decay widths in all the possible open decay channels, as explained in Sec. 2. In Sec. 3 we outline the construction of the considered states up to the D-wave shell. In Sec. 4 we describe our fit procedure and error propagation via the Monte Carlo method. Sec. 5 contains our results and discussion.

2. Mass spectra and decay widths of charmed baryons

The masses of the charmed baryon states are calculated as the eigenvalues of their Hamiltonian defined in the formalism of Ref.[6]. The charmed baryon system is modeled with a three-dimensional harmonic oscillator (h.o.) Hamiltonian, $H_{\text{h.o}}$, plus a perturbation term for the spin, spin-orbit, isospin and flavor dependences mass splittings:

$$H = H_{\text{h.o.}} + P_s\,\mathbf{S}^2 + P_{sl}\,\mathbf{S}\cdot\mathbf{L} + P_I\,\mathbf{I}^2 + P_f\,\text{C}_2(\text{SU(3)}_\text{f}), \tag{1}$$

where $\mathbf{S}, \mathbf{L}, \mathbf{I}$ and $\text{C}_2(\text{SU(3)}_\text{f})$ are the spin, orbital momentum, isospin and Casimir operators, respectively. For the three-quark system, the h.o. Hamiltonian reads as,

$$H_{\text{h.o.}} = \sum_{i=1}^{3} m_i + \frac{\mathbf{p}_\rho^2}{2m_\rho} + \frac{\mathbf{p}_\lambda^2}{2m_\lambda} + \frac{1}{2}m_\rho\omega_\rho^2\boldsymbol{\rho}^2 + \frac{1}{2}m_\lambda\omega_\lambda^2\boldsymbol{\lambda}^2, \tag{2}$$

where $\boldsymbol{\rho}$ and $\boldsymbol{\lambda}$ are the Jacobi coordinates, $\mathbf{p}_\rho$ and $\mathbf{p}_\lambda$ their momenta. The $H_{\text{h.o.}}$ eigenvalues are $\sum_{i=1}^{3} m_i + \omega_\rho n_\rho + \omega_\lambda n_\lambda$. Here, $\omega_{\rho(\lambda)} = \sqrt{\frac{3K_c}{m_{\rho(\lambda)}}}$, m_i are the constituent quark masses, m_1 and m_2 correspond to the light quarks and m_3 to the charm quark; m_ρ is defined as $m_\rho = (m_1 + m_2)/2$, and $m_\lambda = 3m_\rho m_3/(2m_\rho + m_3)$. We use $n_{\rho(\lambda)} = 2k_{\rho(\lambda)} + l_{\rho(\lambda)}$; $l_{\rho(\lambda)}$ are the orbital angular momenta and $k_{\rho(\lambda)}$ are nodes of the $\rho(\lambda)$ oscillators. K_c is the spring constant. Additionally, we consider a model for the charmed baryon where the two light quarks behave as a single diquark object. The quark-diquark $H_{\text{h.o.}}$ and its eigenvalues have a similar form to Eq. 2, with only one relative coordinate $\boldsymbol{r}$ and momentum $\mathbf{p}_r$ and eigenvalues $m_D + m_c + \omega_r n_r$; here m_D is the diquark mass, m_c is the charm quark mass and ω_r is the h.o. frequency.

The open-flavor strong decays of a charmed baryon A to another baryon B plus a meson C, $A \to BC$, are studied by means of the $^3P_0$ model. A $q\bar{q}$ pair is created from the vacuum when a qqc baryon decays and regroups into an outgoing meson and a baryon via a quark rearrangement. The decay of a charmed baryon A to both a charmed baryon B plus a light meson C and a light baryon B plus a charmed meson C are considered. The total decay width Γ is the sum of the partial widths of all the open channels BC, $\Gamma = \sum_{BC} \Gamma_{A \to BC}$ and is calculated as

$$\Gamma_{A\to BC} = \frac{2\pi\gamma_0^2}{2J_A+1}\,\Phi_{A\to BC}(q_0) \times \sum_{M_{J_A},M_{J_B}} \left|\mathcal{M}^{M_{J_A},M_{J_B}}\right|^2, \quad (3)$$

where γ_0 is a dimensionless free parameter related to the strength of the $q\bar{q}$ pair. $\mathcal{M} = \langle BC|T^\dagger|A\rangle$ is the $^3P_0$ amplitude in terms of hadron h.o. wave functions and the sum runs over the projections M_{J_A,J_B} of the total angular momenta $J_{A,B}$ of A and B. The quantity q_0 is the relative momentum between B and C, and the coefficient $\Phi_{A\to BC}(q_0) = q_0 E_B(q_0) E_C(q_0)/m_A$ is the relativistic phase space factor, with $E_{B,C} = \sqrt{m_{B,C}^2 + q_0^2}$, m_A is the initial charmed baryon mass and the masses m_B and m_C and energies E_B and E_C correspond to the final baryon and meson, respectively.

3. Charmed baryon states

A three-quark (quark-diquark) quantum charmed baryon state, written as $\left|l_\lambda(l_r), l_\rho, k_\lambda(k_r), k_\rho\right\rangle$, is defined by its total angular momentum $\mathbf{J}_{\rm tot} = \mathbf{L}_{\rm tot} + \mathbf{S}_{\rm tot}$, where $\mathbf{L}_{\rm tot} = \mathbf{l}_\rho + \mathbf{l}_\lambda$ ($\mathbf{L}_{\rm tot} = \mathbf{l}_r$) and $\mathbf{S}_{\rm tot} = \mathbf{S}_{\rm lt} + \frac{1}{2}$, $\mathbf{S}_{\rm lt}$ is the coupled spin of the light quarks and the number of nodes is $k_{\lambda,\rho}(k_r)$. We assign them the flavor $\mathcal{F}$ and spectroscopy $^{2S+1}L_J$ representations. The states are constructed for the two different flavor representations available for the charmed baryons. We consider the energy bands $N = n_\rho + n_\lambda$ ($N = n_r$) and $N = 0, 1, 2$ in order to find the S-, P-, D-wave configurations.

4. Parameter determination

We fitted Ω_c, Σ_c, Λ_c, Ξ'_c, and Ξ_c experimental data to the masses predicted by Eq. 2, to obtain the constituent quark and diquark masses and the model parameters (P_s, P_{sl}, P_I, P_f and K_c) and to the decays predicted by Eq. 3 to obtain γ_0. To integrate the model uncertainties in the fit, we sampled the experimental masses from a Gaussian distribution with a mean equal to the mass value and a width equal to the squared sum of the uncertainties, then and we repeated the fit 10^4 times. In this manner, we obtained a Gaussian distribution for each model parameter.

5. Results and discussion

Our results for the Σ_c resonances are shown in Fig. 1 and Tab. 1. The identifications of our calculations to the experimental data, consider as a first criterion, the mass spectrum; the second criterion is the decay width. The λ-type excitations for the quark-diquark model are equivalent to that of the three-quark. The ρ-type excitations are exclusive of the three-quark model. The $\Sigma_c(2455)$ observed state is identified as the ground state $J^P = 1/2^+$. The $\Sigma_c(2520)$ state is identified as a ground state with a spin excitation $J^P = 3/2^+$. Finally, the $\Sigma_c(2800)$ resonance is identified as the first P_λ-wave excitation, with the assignment $J^P = 1/2^-$. The quantum numbers for the Σ_c resonances have not yet been measured. Our predicted masses(widths) are in excellent(reasonably) agreement with the experimental data reported in PDG [4].

In the light baryon sector, the two oscillators ρ and λ have the same frequency, $\omega_\rho \simeq \omega_\lambda$, meaning that the λ and ρ states are degenerated in mass. In the charm sector, we obtain for the Σ_c

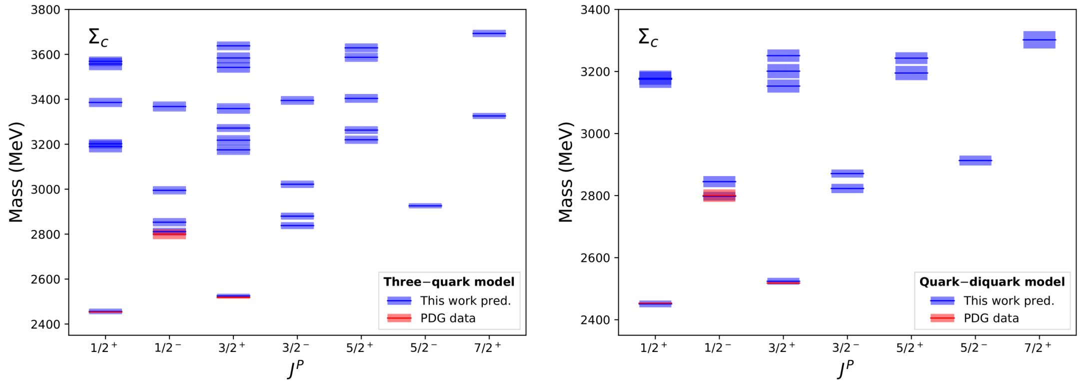

Figure 1: Adapted from Figs.4 and 9 of Ref. [7], APS copyright. Σ_c mass spectra and tentative quantum number assignments on using the three-quark model (left) and quark-diquark model (right). The theoretical predictions and their uncertainties (blue lines and bands) are compared with PDG data (red lines and bands).

$\Sigma_c(nnc)$ $\mathcal{F} = \mathbf{6}_{\rm f}$	${}^{2S+1}L_J$	Three-Quark Mass Pred.	Quark-diquark Mass Pred.	Mass Exp.	Γ Pred.	Γ Exp.
$N = 0$						
$\vert l_\lambda{=}0, l_\rho{=}0, k_\lambda{=}0, k_\rho{=}0\rangle$	${}^2S_{1/2}$	2456^{+11}_{-11}	2451^{+11}_{-11}	2453.5 ± 0.9	$1.7^{+1.1}_{-1.2}$	2.3 ± 0.3
$\vert l_\lambda{=}0, l_\rho{=}0, k_\lambda{=}0, k_\rho{=}0\rangle$	${}^4S_{3/2}$	2525^{+11}_{-11}	2524^{+11}_{-11}	2518.1 ± 2.8	$14.9^{+7.8}_{-7.9}$	17.2 ± 3.6
$N = 1$						
$\vert l_\lambda{=}1, l_\rho{=}0, k_\lambda{=}0, k_\rho{=}0\rangle$	${}^2P_{1/2}$	2811^{+12}_{-12}	2798^{+14}_{-14}	2800.0 ± 20.0	$30.5^{+17.5}_{-17.1}$	75 ± 60

Table 1: Masses and decay widths of the $\Sigma_c(nnc)$ states obtained in accordance with Sec. 2-4. Only the first states are shown here, for a complete list of states and the remaining baryons, see Ref. [7].

baryons, $\omega_\lambda - \omega_\rho \simeq 183$ MeV, hence the ρ and λ states are well separated. In Fig. 1, the higher number of states in the three-quark, arises from the ρ excitations. Therefore, given that the ρ states have not been observed yet, the charmed baryons may correspond to quark-diquark configurations.

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