Spectrum of the Charmed Baryons in 2+1-flavor Lattice QCD

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We extract the spectrum of charmed baryons on $32^3 \times 64$, $2 + 1$-flavor gauge ensembles. Calculations are performed with almost physical light quarks, $m_\pi \sim 156$ MeV, and physical strange and charm quarks. A relativistic heavy-quark action is used for valance charm quarks to suppress the systematic errors. We employ a two-fold variational analysis in order to access the excited states by varying the interpolating operators and smearing parameters independently. In this contribution, we report the status of our on-going calculations and present the preliminary results for positive and negative parity, spin-1/2 and spin-3/2 states.

1. Introduction

In this contribution, we report on our on-going calculations of the spectrum of the charmed baryons. Recent experimental results from the LHCb Collaboration on the Ω_c states and the doubly charmed Ξ_{cc} state have put further emphasis on the relevance of the hadron spectroscopy. Charmed baryons provide a unique laboratory for QCD interactions and confinement dynamics due to their composition of light and charm quarks. Studying the excited states of charmed baryons has the potential to reveal their internal dynamics and the nature of the excitation mechanisms.

Ground states of the singly charmed baryons are already established by experimental observations and lattice QCD results agree well with those observations. Ξ_{cc} is the only observed doubly-charmed baryon for the time being. It was first observed by the SELEX Collaboration [1, 2] but its results were not confirmed by other experiments until the LHCb Collaboration has reported the same particle with a different mass [3]. Lattice QCD predictions for the mass of the Ξ_{cc} lie above the SELEX reported value but agree very well with the LHCb value. Ground state masses of the other, yet-unobserved, doubly and triply charmed baryons are predicted by several lattice QCD calculations and they are in agreement with each other (see M. Padmanath's LATTICE'18 review). Extracting the excited states, however, is a challenge compared to calculating the ground states. There are just a few groups that have extracted the excited states of the charmed baryons, most notable being the Hadron Spectrum Collaboration's works [4–6]. One other work is by the RQCD group [7], in which they use a conventional approach to extract the first excited states.

We employ a conventional approach as well and, as an improvement compared to previous works,

work on gauge configurations with almost physical light quarks. In addition, charm quarks are treated relativistically to suppress the $O(am_q)$ discretization errors.

2. Theoretical framework and simulation setup

For a given interpolator, χ_i, the two-point correlation function contains the contributions from all the states that have the corresponding quantum number,

$$C_{ij}^{\pm}(t) = P^{\pm}\langle\chi_i(t)\bar{\chi}_j(0)\rangle = \sum_{\mathcal{B}}\langle0|\chi_i|\mathcal{B}\rangle\langle\mathcal{B}|\bar{\chi}_j|0\rangle e^{-E_{\mathcal{B}}t}, \tag{1}$$

where $P^{\pm} = \frac{1}{2}(1 \pm \gamma_4)$ is the parity projection operator.

In order to to extract the spin-1/2 and the spin-3/2 charmed baryons, we use the interpolating fields given in Table I. Desired parity is selected by applying the parity projection operator, $P^{\pm}$. N-like operators are employed for the Σ_c, Ξ_{cc}, Ω_c, and Ω_{cc} baryons with the quark contents $(q_1, q_2, q_3) = (u/d, c, u/d)$, $(c, u/d, c)$, (s, c, s), and (c, s, c) respectively. Λ_c and Ξ_c are studied by employing the Λ-like operators with $(q_1, q_2, q_3) = (u, d, c)$, and $(s, u/d, c)$. Δ-like operators are used for the spin-3/2 Σ_c^*, Ξ_c^*, Ω_c^*, Ξ_{cc}^*, Ω_{cc}^*, and Ω_{ccc} baryons with the quark contents $(q_1, q_2, q_3) = (u/d, u/d, c)$, $(u/d, s, c)$, (s, s, c), $(u/d, c, c)$, (s, c, c), and (c, c, c) respectively. Note that we do not distinguish between u and d quarks since they are degenerate in our lattice setup.

Table I. Interpolating operators with generic Dirac structures for spin-1/2 and spin-3/2 baryons. $C = \gamma_2\gamma_4$ is the charge conjugation operator. $[\Gamma_1, \Gamma_2]$ choices and the quark contents are given in the text. l denotes either a u quark or a d quark.

Baryon	Operator
N - like	$\varepsilon^{abc}\left[q_1^{Ta}(x)C\Gamma_1 q_2^b(x)\right]\Gamma_2 q_3^c(x)$
Λ - like	$\frac{1}{\sqrt{6}}\varepsilon^{abc}\left(2\left[q_1^{Ta}(x)C\Gamma_1 q_2^b(x)\right]\Gamma_2 q_3^c(x) + \left[q_1^{Ta}(x)C\Gamma_1 q_3^b(x)\right]\Gamma_2 q_2^c(x) - \left[q_2^{Ta}(x)C\Gamma_1 q_3^b(x)\right]\Gamma_2 q_1^c(x)\right)$
Ξ_c'	$\frac{1}{\sqrt{2}}\varepsilon^{abc}\left(\left[l^{Ta}(x)C\Gamma_1 c^b(x)\right]\Gamma_2 s^c(x) + \left[s^{Ta}(x)C\Gamma_1 c^b(x)\right]\Gamma_2 l^c(x)\right)$
Δ - like	$\frac{1}{\sqrt{3}}\varepsilon^{abc}\left(2\left[q_1^{Ta}(x)C\gamma_\mu q_2^b(x)\right]q_3^c(x) + \left[q_1^{Ta}(x)C\gamma_\mu q_3^b(x)\right]q_2^c(x)\right)$

We calculate the two-point correlation functions on the $m_\pi = 156(9)$ MeV, $32^3 \times 64$, 2 + 1-flavor configurations that are generated by the PACS-CS Collaboration [8]. These configurations are generated with the Iwasaki gauge action ($\beta = 1.9$) and the non-perturbatively $O(a)$-improved Wilson (Clover) action ($c_{sw} = 1.715$). The strange quark mass is fixed to its physical value. Lattice spacing is determined to be $a = 0.0907(13)$ fm ($a^{-1} = 2.176$ GeV). We use the Clover action for the valance u/d and s quarks as well but use a re-tuned strange quark mass to match the physical Ω mass on these configurations. We employ a relativistic heavy quark action for the charm quark with parameters tuned non-perturbatively to match the 1S spin-averaged mass of charmonium. Further details of the mass tuning and the charm quark action are discussed in Ref. [9].

Interpolating fields of the two-point correlation functions are Gaussian smeared in a gauge-invariant manner at the source ($t = 16a$) and at the sink. Smearing parameters are chosen so that the rms radius of the quark wave-function corresponds to $\sim 0.2, 0.4$ and 0.7 fm. Using a set of operators that couple to the same quantum numbers, one can utilize a variational approach to extract the ground and excited states reliably. We choose two of the three combinations of Dirac structures, $[\Gamma_1, \Gamma_2] = [\gamma_5, 1]$, $[1, \gamma_5]$, and $[\gamma_5\gamma_4, 1]$, for the spin-1/2 baryons to form a 2×2 correlation function matrix, $C(t)$, where each element, $C_{ij}(t)$, is the function given in Equation 1 with the appropriate interpolating field. For the spin-3/2 baryons, on the other hand, we construct the operator basis via

the smeared Δ-like operators with two of the above smearing parameters and form a 2×2 correlation matrix.

By solving the generalized eigenvalue problem [10, 11],

$$C(t)\psi^\alpha(t) = \lambda^\alpha(t, t_0)C(t_0)\psi^\alpha(t), \qquad \phi^\alpha(t)C(t) = \lambda^\alpha(t, t_0)\phi^\alpha(t)C(t_0), \qquad (2)$$

we extract the left and right eigenvectors, ϕ^α and ψ^α, and use them to diagonalize the correlation function matrix,

$$\phi^\alpha(t')C(t)\psi^\beta(t') \equiv C^\alpha(t) = \delta_{\alpha\beta}Z^\alpha\bar{Z}^\beta e^{-E_\alpha t}\left(1 + O(e^{-\Delta E_\alpha t})\right), \qquad (3)$$

to access the energies of the states, E_α. Note that t' may or may not be chosen equal to t. We choose a combination of the normalization time-slice t_0 and the time slice of the eigenvectors, t', which optimizes the signal. Once we diagonalize the correlation function matrix, we perform an effective mass analysis for each state, α,
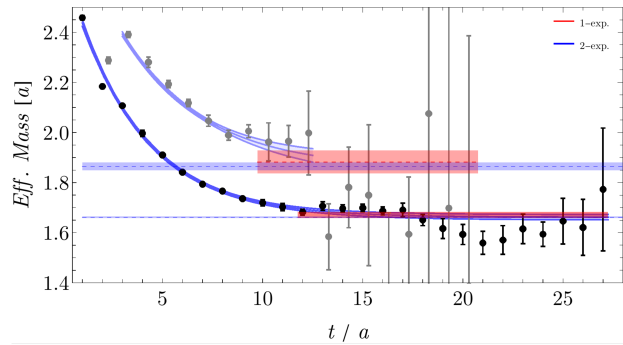
$$m_{\text{eff}}^\alpha(t) = \ln\frac{C^\alpha(t)}{C^\alpha(t + 1)}, \qquad (4)$$

to estimate a suitable fit window for one-exponential fits.

3.   Results

We extract the states from the diagonalized correlation functions via fitting the data to the form given in Equation 3. We consider adding extra exponential terms as well, in order to stabilize the fits against excited-state contributions. In most of the cases, where the signal forms a plateau in the effective mass plots, masses of the lowest states extracted from the one-exponential fits agrees with the multi-exponential results within their error bars. Yet, a two-exponential form stabilizes the fits and improves the accuracy of the results. An illustrative case is shown in Fig. 1.

Fig. 1.   Effective mass plot for a $J^P = \frac{1}{2}^+$ Ξ_{cc} baryon from a 2×2 variational analysis. Black data points are associated with the first state and the higher gray ones are with the second. The red regions mark the fit windows and the fit results of a one-exponential fit, while the blue curves and the regions show the two-exponential fits and results, respectively.

Note that the masses of some of the negative parity states lie close to two-particle thresholds, therefore it is possible that negative parity states contain scattering states. This is true for all the first excited states as well. We present and compare our extracted masses to the other lattice results and experimental values in Fig. 2. Overall, our ground states are in agreement with experimental results and the predictions of the other lattice groups. First excited states also mostly agree with the predictions of the HSC [4] and the RQCD [7]. Finally, a remark on the negative-parity Ω_c baryons: the masses of the Ω_c baryons that we extract with the $J^P = 1/2^-$ and the $J^P = 3/2^-$ operators are in the vicinity of the LHCb reported values. Although an indication, it is unconvincing to claim these quantum numbers at this stage before a through scattering state analysis.
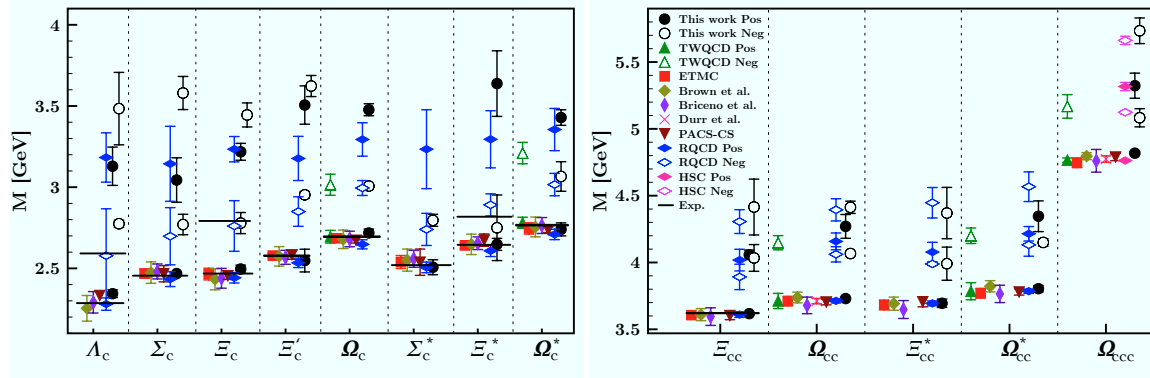
Fig. 2. Our results and a comparison to the determinations of HSC [4], RQCD [7], TWQCD [12], ETMC [13], Brown et al. [14], Briceno et al. [15], Durr et al. [16], and PACS-CS [17].

4. Summary and outlook

We have reported the ground and the first excited state masses of the charmed baryons from our on-going analysis. We have used a subset of our operator basis constructed from three different Dirac structures and three different quark smearings to perform a variational analysis. The masses we have extracted agree with the other lattice predictions and the experimental results where available. An analysis with the full operator set is on-going. Full details of the simulation setup and analyses will be presented in a future paper.

Acknowledgements

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