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Excited-state spectroscopy of singly, doubly and triply-charmed baryons from lattice QCD

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ON BEHALF OF HADRON SPECTRUM COLLABORATION

We present the ground and excited state spectra of singly, doubly and triply-charmed baryons by using dynamical lattice QCD. A large set of baryonic operators that respect the symmetries of the lattice and are obtained after subduction from their continuum analogues are utilized. These operators transform as irreducible representations of $SU(3)_F$ symmetry for flavour, $SU(4)$ symmetry for Dirac spins of quarks and $O(3)$ symmetry for orbital angular momenta. Using novel computational techniques correlation functions of these operators are generated and the variational method is exploited to extract excited states. The lattice spectra that we obtain have baryonic states with well-defined total spins up to $7/2$ and the low lying states remarkably resemble the expectations of quantum numbers from $SU(6) \otimes O(3)$ symmetry.

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1 Introduction

Heavy hadron spectroscopy finds itself in a rejuvenated phase following the discovery of numerous heavy hadrons in the past decade at various particle colliders, like Belle, BaBar, CDF, LHCb, BECIII, etc. However, in contrast to heavy quarkonia which have been studied comprehensively, heavy baryons have not been explored in much greater detail, both theoretically and experimentally, though the later can also provide similar information about the quark confinement mechanism as well as elucidating our knowledge about the nature of strong force by providing a clean probe of the interplay between the perturbative and the non-perturbative QCD. Experimentally only a handful of singly charmed baryons have been discovered, the discovery of doubly charm baryon is controversial, whereas no triply heavy baryon has been observed yet [1]. Moreover most of the observed charmed baryons do not have assigned quantum numbers yet. However it is expected that the large data set that will be collected in experiments at BES-III, the LHCb, and the planned PANDA experiment at GS/FAIR may provide significant information for baryons with heavy quarks. In light of these existing and future experimental prospects on charm baryon studies, it is desirable to have model independent predictions from first principles calculations, such as from lattice QCD. Results from such calculations will naturally provide crucial inputs to the future experimental discovery and can be compared with those obtained from potential models which have been very successful in the case of charmonia. Details of various potential model calculations for charm baryons can be found in Refs. [2, 3, 4]. However, lattice QCD results on charmed baryons include only the ground states with spin up to $\frac{3}{2}$ [5, 6, 7, 8] until very recently where the comprehensive spectra of doubly and triply charmed baryons have been presented [9, 10]. Here, along with doubly and triply charmed baryon spectra, we also present the preliminary results on singly charmed baryon spectra.

2 Numerical details

We utilized the ensembles of dynamical anisotropic gauge-field configurations generated by the Hadron Spectrum Collaboration (HSC) to extract highly excited hadron spectra. Adopting a large anisotropy co-efficient $\xi = a_s/a_t = 3.5$, with $a_t m_c \ll 1$, we could use the standard relativistic formulation of fermions for all the quark flavors from *light* to *charm*. Along with an $O(a)$ -improved gauge action, we used the $O(a)$ -improved Shekholeslami-Wohlert action with tree-level tadpole improvement and stout-smearred spatial links for the $N_f = 2 + 1$ dynamical flavours fermionic fields and the valence fermionic fields. The temporal lattice spacing, $a_t^{-1} = 5.67\text{GeV}$, was determined by equating the m_Ω to its physical value, resulting in a lattice spatial extension of 1.9 fm, which presumably be sufficiently large for a study of charmed baryons. We used an ensemble of 96 sample configurations with a temporal extension equal to 128. The pion masses in these lattices were equal to 391 MeV. More details of

the formulation of actions as well as the techniques used to determine the anisotropy parameters can be found in Refs. [11, 12].

3 Operator construction and spin identification

We use a large basis of operators, constructed employing derivative-based operator construction formalism [13], including non-local operators constructed using up to two derivatives. This enables us to extract states confidently with spins up to $J = 7/2$ for both the parities. The two derivative operators also include operators that contains the field strength tensor appearing in it. A state with strong overlap to such operators indicate the strong intrinsic gluonic content in it, and so are called ‘hybrid states’[13]. Lattice operators are obtained by subducing these continuum operators on to various irreps of the symmetry of the lattice [13]. For each of these irreps, we compute $N \times N$ matrix of correlation functions, where N is the number of lattice operators used in each irreps. A subset of operators that are formed just by considering only the upper two components of the four component Dirac-spinors are called non-relativistic as they form the whole set of creation operators (with $SU(6) \otimes O(3)$ symmetry) in a leading order velocity expansion.

Lattice computations of hadron masses proceed through the calculations of the Euclidean two point correlation functions, between creation operators at time t_i and annihilation operators at time t_f ,

$$C_{ij}(t_f - t_i) = \langle 0 | O_j(t_f) \bar{O}_i(t_i) | 0 \rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2m_n} e^{-m_n(t_f - t_i)}. \quad (1)$$

The RHS is the spectral decomposition of such two point functions where the sum is over a discrete set of states. $Z^n = \langle 0 | O_i^\dagger | n \rangle$ is the vacuum state matrix element, also called as overlap factor. We employ a variational method [14] to extract the spectrum of baryon states from the matrix of correlation functions constructed using a large basis of interpolating operators. The method proceeds by solving a generalized eigenvalue problem of the form

$$C_{ij}(t) v_j^{(n)}(t, t_0) = \lambda^{(n)}(t, t_0) C_{ij}(t_0) v_j^{(n)}(t, t_0), \quad (2)$$

where the eigenvalues, $\lambda^{(n)}(t, t_0)$ form the principal correlators and the eigenvectors are related to the overlap factors as $Z_i^{(n)} = \langle 0 | O_i | n \rangle = \sqrt{2E_n} \exp^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$. The energies are determined by fitting the principal correlators, while the spin identification of the states are made by using these overlap factors as discussed in ref.[14].

4 Results

In Figure 1 we show the spin identified spectra of the triply charmed baryons where $3/2$ times the mass of η_c is subtracted to account for the difference in the charm quark content [9]. It is preferable to compare the energy splittings between the

states, as it reduces the systematic uncertainty in the determination of the charm quark mass parameter in the lattice action and to lessen the effect of ambiguity in the scale setting procedure. Boxes with thicker borders correspond to those states with a greater overlap onto the operators that are proportional to the field strength tensor, which might consequently be hybrid states. The states inside the pink ellipses have relatively large overlap with non-relativistic operators. One remarkable feature one can observe is that though we use a large set of operators including many relativistic ones, the number of low lying states in the non-relativistic bands exactly agree with expectations from models with an $SU(6) \otimes O(3)$ symmetry.

Figure 2 shows the spin identified spectra of the doubly charmed baryons [10]. Here the spectra is shown with the mass of η_c subtracted from them

so as to account for the charm quark content as previously. The boxes and the pink ellipses represent the similar quantities as in Figure 1. Here again one can see the agreement between the number of states in the lower non-relativistic bands and the expectations as per a model with $SU(6) \otimes O(3)$ symmetry.

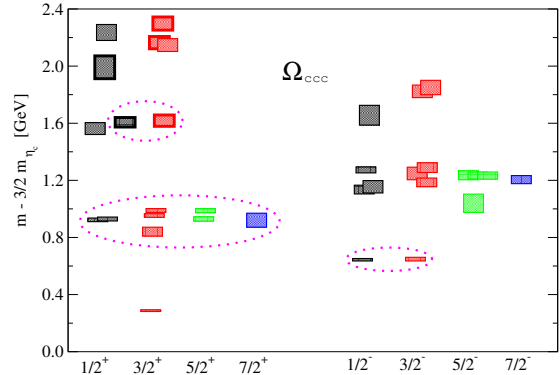


Figure 1: Spin identified spectra of triply-charmed baryons with respect to $\frac{3}{2}m_{\eta_c}$. The boxes with thick borders corresponds to the states with strong overlap with hybrid operators. The states inside the pink ellipses are those with relatively large overlap to non-relativistic operators.

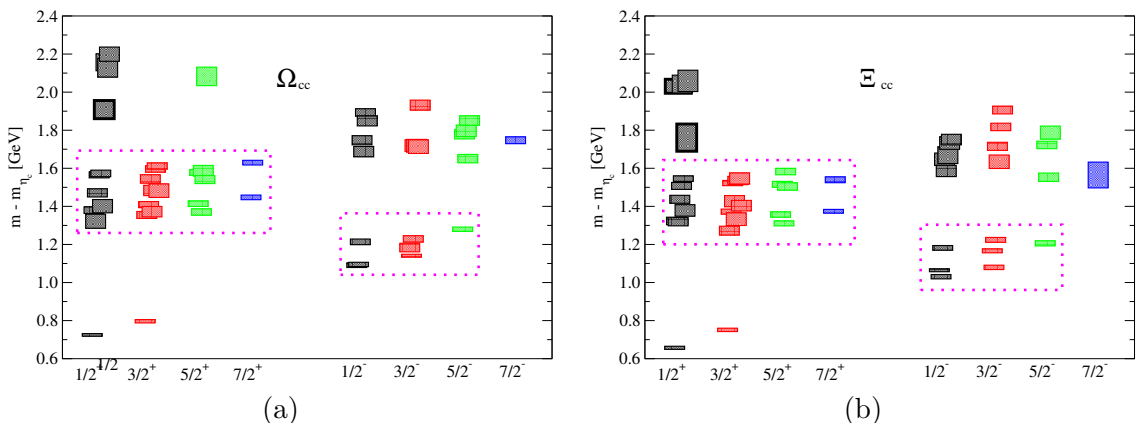


Figure 2: Spin identified spectra of (a) Ω_{cc} and (b) Ξ_{cc} baryon for both parities and with spins up to $\frac{7}{2}$ w.r.t. m_{η_c} . The keys are same as in Figure 1.

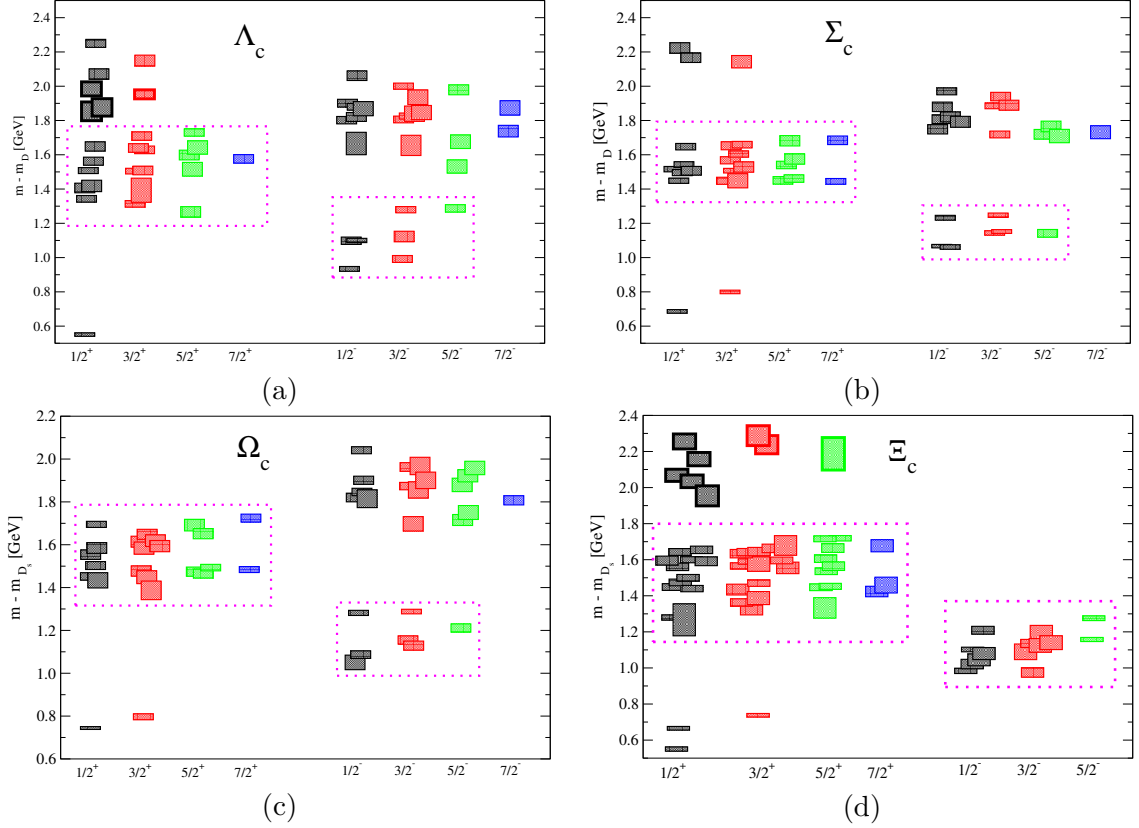


Figure 3: Preliminary results on the spin identified spectra of (a) Λ_c , (b) Σ_c , (c) Ω_c and (d) Ξ_c baryons for both parities *w.r.t.* D (upper two) and D_s (lower two) mesons. The keys are same as in Figure 1.

Figure 3 shows the spin identified spectra of the singly charmed baryons, which include Λ_c , Σ_c , Ξ_c and Ω_c . Here for Λ_c and Σ_c the spectra are shown with m_D subtracted, while for Ξ_c and Ω_c we plot the difference of the baryon mass from m_{D_s} in order to account for the heavy flavor content. Here also there is good agreement between the number of states in the lower non-relativistic bands and the expectations as per a model with $SU(6) \otimes O(3)$ symmetry.

5 Conclusions

In this work we present a comprehensive calculation on the ground and excited state spectra of singly, doubly and triply-charmed baryons by using dynamical lattice QCD. Preliminary results on singly charmed baryons are shown first time here. The spectra that we obtain have states with well-defined total spins up to $7/2$ and the low lying states remarkably resemble the expectations of quantum numbers from $SU(6) \otimes O(3)$ symmetry. However, it is to be noted that we only mentioned statistical error in this work and the systematics from other sources like chiral extrapolation, lattice spacing

are not addressed here. Also we have not incorporated multi-hadron operators which may effect some of the above conclusions, though to a lesser extent than their influence in the light hadron spectra. One other caveat in this work, particularly for singly charmed baryons, is that pseudoscalar mass used is unphysical ($m_\pi = 391$ MeV).

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