# Charmed and Bottom Baryon spectrum from Lattice QCD

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## 1 Introduction

Experimental and theoretical studies of charmed and bottom hadrons have been the focus of vigorous research over the last several years [1, 2, 3, 4]. In particular, singly and doubly heavy baryon spectroscopy has received significant attention, mainly due to the recent experimental discoveries of both new charmed (SELEX) [5, 6] and bottom baryons by D0 [4] and CDF [7]. The bottom baryon spectrum has become somewhat controversial due to recent results from D0 and CDF. Last summer, D0[8] reported a first observation of the doubly strange bottom baryon $\Omega_b^-$ at 6.165(10)(13) GeV. However, a recent CDF work puts the $\Omega_b^-$ mass at 6.0544(68)(9) GeV, a difference of 111(12)(14) MeV. With a discrepancy of 6.2 standard deviations, it appears that the two collaborations cannot both be observing the $\Omega_b$. A theoretical understanding of the bottom baryon spectroscopy from first-principles QCD is crucial and can help disentangle such discrepancies in experiment. In addition to these discoveries, there are still many states of heavy and doubly heavy baryons remaining to be discovered. The new Beijing Spectrometer (BES-III), a detector at the recently upgraded Beijing Electron Positron Collider (BEPCII), has great potential for accumulating large numbers of events to help us understand more about charmed hadrons. The antiProton ANnihilation at DArmstadt (PANDA) experiment, a GSI future project, and the LHCb are also expected to provide new results to help experimentally map out the heavy-baryon sector. For these reasons, lattice quantum chromodynamic (QCD) calculations of the spectrum of heavy baryons are now very timely and will play a significant role in providing theoretical first-principles input to the experimental program.

Recent advances in theory and developments in computer hardware, are now making possible lattice QCD calculations capable of providing accurate results that can be directly compared to experiment. Calculations in the light-quark sector are well established and possible directly on the physical up and down quark mass. Although the study of heavy quarks requires careful treatment of discretization errors, significant advances have been made in this sector as well. Lattice heavy quarks have $\mathcal{O}((m_Q\, a)^n)$ errors, where $m_Q$ is the mass of the heavy quark and $a$ is the lattice spacing. Lattice spacings for typical, currently accessible dynamical ensembles are still too coarse ($a^{-1} \approx 2$ GeV) to make such systematic errors small. To assert better control over the discretization errors for heavy quarks on the lattice, several heavy-quark approaches have proven useful. For example, non-relativistic QCD (NRQCD) [9], which is an expansion of the lattice quark action in powers of $\frac{1}{am_Q}$, is commonly applied to bottom quarks. However, the charm-quark mass is not heavy enough to justify the use of NRQCD. Relativistic heavy-quark actions [10, 11, 12, 13] systematically remove $\mathcal{O}((m_Q a)^n)$ terms and are better suited to charm-quark calculations. Recent updates on the state of heavy-quark physics on the lattice can be found in several reviews [14, 15, 16, 17, 18, 19] and references therein.

Up to now, there have been a few lattice charmed-baryon calculations using the quenched approximation. In some cases an $\mathcal{O}(a)$-improved light-quark action is used on isotropic or anisotropic lattices with a single lattice spacing: Bowler et al. [20] used a tree-level clover action for both light and heavy quarks to calculate the singly charmed baryons spectrum of spin 1/2 and 3/2. Later, Flynn et al. [21] updated this project with nonperturbative clover action and extended the calculation to doubly charmed baryons. Chiu et al. [22] used a chiral fermion action for the charm quarks and calculated both the positive and negative parity spectrum for singly and doubly charmed baryons. Such calculations using light-quark actions to simulate heavy quarks introduce large systematic errors proportional to $(am_Q)^2$, which must be carefully addressed. One calculation has used a higher-order improved fermion action: Lewis et al. [23] performed a calculation on both doubly and singly charmed baryons using D234-type fermion action (which would leave a leading error of $\mathcal{O}(a^3)$) for both light and heavy quarks but on a coarse anisotropic ensemble (with anisotropy $\xi = 2$). Finally, heavy-quark effective theory was applied to charm calculation: Mathur et al. [24] continued to use anisotropic lattices, adding two more lattice spacings, but changed the heavy-quark action to NRQCD, which reduces the lattice-spacing discretization effects. For all of these calculations, the quenched approximation remains a significant source of systematic error that is difficult to estimate.

Given the progress on the experimental side, it is time to revisit these charmed baryon calculations using dynamical gauge ensembles and improve the calculations with the current available computational resources. Although more dynamical ensembles are available these days, not many charmed baryon calculations have been published so far, only a few proceedings [25, 26, 27].

Bottom baryons have not received much attention from lattice QCD either. Some pioneering works[20, 28, 24] were done using extrapolations with light-fermion actions or the NRQCD action in the quenched approximation, where the fermion loop degrees of freedom are absent. Since it is difficult to estimate the systematic error due to the quenched approximation, high-precision calculations cannot be achieved. Recently, more dynamical ensembles have become available due to the increase of the computer resources available for numerical research, and since the recent discovery of the double-$b$ baryon, more lattice calculations have emerged. Ref. [29] calculated single- and double-$b$ baryons with NRQCD action for the bottom quark on isotropic 2+1-flavor clover ensembles, having lightest pion mass around 600 MeV. Ref. [30] went to a lighter pion mass (275 MeV) using 2+1 flavors of domain-wall fermions but used static-quark action to simulate the bottom quarks. Since the static-quark action tends to result in noisy signals, one needs high statistics to yield numbers comparable with experimental results. A selection of single-$b$ baryons were calculated using static-quark action on 2-flavor chirally improved lattice Dirac operator at pion masses as light as 350 MeV in Ref. [31]. An ongoing work using staggered and Fermilab fermion actions[10] on MILC lattices with multiple lattice spacings was presented in Ref. [26].

In this talk I review results on both charmed and bottom baryons previously presented in [33, 27, 34]. We use the static quark action to simulate the bottom quark and the Fermilab action [10] for the charm quarks. For the light valence quarks we use domain-wall fermions. The gauge configurations were generated by MILC with 2+1-flavor Kogut-Susskind fermions and a range of quark masses resulting in pion masses as light as 290 MeV. We nonperturbatively tune the fermion anisotropy and two input bare masses for charm quarks, setting the remaining parameters to tree-level tadpole improved coefficients. Our results are extrapolated to the physical light-quark masses using both heavy-hadron chiral perturbation theory (HH$\chi$PT) as well as HH$\chi$PT-inspired polynomial extrapolations. For further details on the lattice calculation we refer the reader to [33, 27, 34].

# 2 Results and discussion

Our results from the charm sector are summarized in Figure 1. There results are obtained by extrapolating to the physical point the up/down quark masses as well as the charm mass. The physical point was defined by

$$\begin{aligned} \frac{M_{\eta_c}^{\rm phys} + 3M_{J/\Psi}^{\rm phys}}{4 f_\pi^{\rm phys}} &= 23.47\,, \\ \frac{m_\pi^{\rm phys}}{f_\pi^{\rm phys}} &= 1.056\,. \end{aligned} \tag{1}$$

We extrapolate to the physical point both the masses directly as well as the mass splittings. The discretization errors on the mass splittings scale as $\mathcal{O}(a^2(m_s - m_u))$ for members of the same $SU(3)$ multiplet or $\mathcal{O}(a^2/N_c) + \mathcal{O}(a^2(m_s - m_u))$ otherwise,

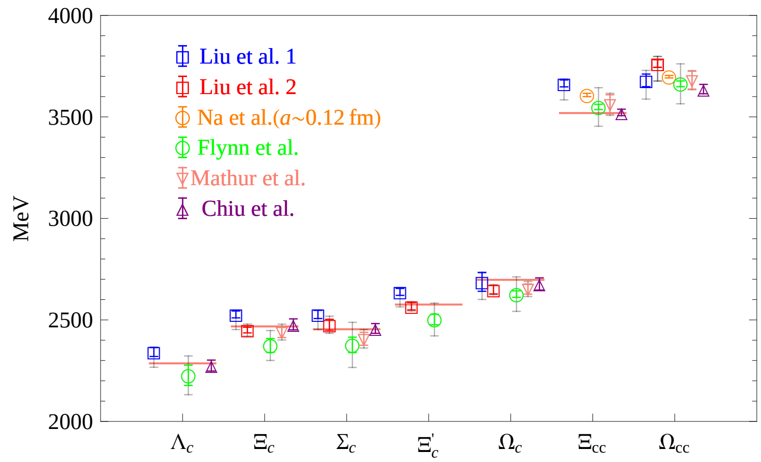


Figure 1: A summary of charmed baryon masses in MeV calculated using LQCD. We show both of our methods for obtaining the spectrum, the direct mass extrapolation (Liu et al. 1) and also using the extrapolated mass splittings, combined with $M_{\mathcal{L}_c}^{\rm exp}$ and $M_{\S_c}^{\rm exp}$ (Liu et al. 2).

hence these are the quantities obtained more accurately with a lattice calculation at one lattice spacing. For this reason we can compute more accurate results using the calculated mass splittings combined with the experimental value of $M_{\Lambda_c}^{\rm exp}$ and $M_{\Sigma_c}^{\rm exp}$ to determine the $J = 1/2$ baryon masses. Aside from the $\Xi_{cc}$ state,[1] the masses determined in this way are consistent with our direct mass extrapolation results, after including our estimated discretization errors. We used power counting arguments [38, 14] to estimate the size of these corrections and we compared our two methods of determining the baryon masses to determine the expected sign of the leading discretization corrections. In Fig. 1, we present our resulting mass calculations using the results from both the mass splitting method (Liu et al. 2) as well as the direct extrapolation of the masses (Liu et al. 1).

Although the SELEX Collaboration has reported the first observation of doubly charmed baryons, searches by the BaBar [35], Belle [36] and Focus [39] Collaborations have not confirmed their results. This makes it interesting to look back to the theory to see where the various predictions lie. We compute the mass of $\Xi_{cc}$ to be $3665 \pm 17 \pm 14\,^{+0}_{-78}$ MeV, which is higher than what SELEX observed, although less than two sigma with our estimated discretization errors; most theoretical results suggest

[1]Because the $\Xi_{cc}$ has not been verified by multiple experimental groups [5, 6, 35, 36, 37], we chose to use our extrapolated value of $M_{\Xi_{cc}}$, combined with our extrapolated value of $M_{\mathcal{O}_{cc}} - M_{\Xi_{cc}}$ to make a prediction for the $\mathcal{O}_{cc}$ mass.

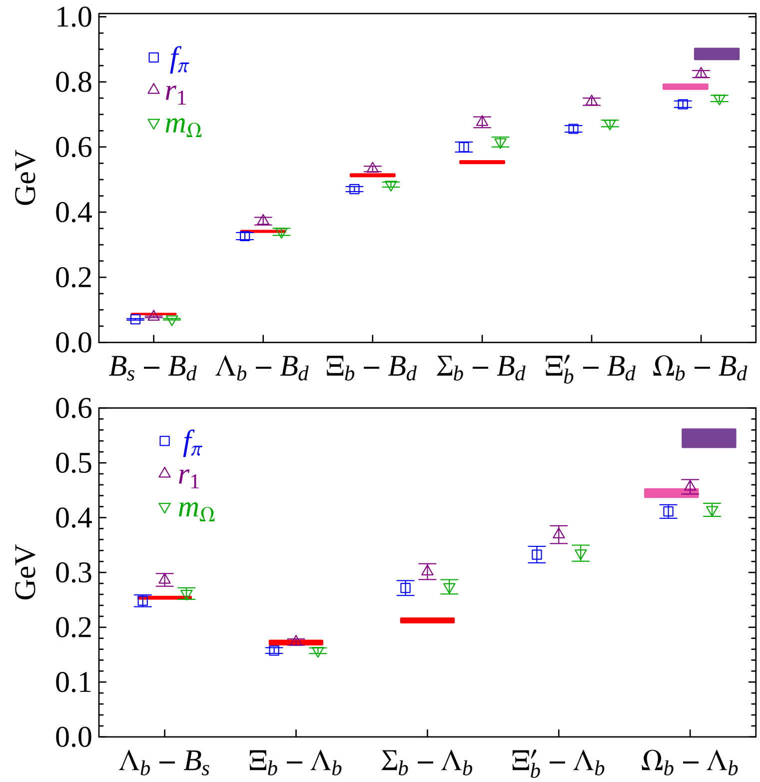


Figure 2: Comparison of mass-splitting extrapolated values using different reference scales. Splittings with respect to $B_d$ are on the left; those with respect to $\Lambda_b$ are on the right. The solid (red) bars indicate the experimental values given in the PDG, where available. For the $\Omega_b$, we show both the D0 result[8] (upper-right, purple) and the CDF result[32] (lower-left, magenta)

that the $\Xi_{cc}$ that is about 100–200 MeV higher than the SELEX experimental value. To improve this situation, we need results at multiple lattice spacings to reduce this systematic uncertainty. The $\Omega_{cc}$ has not been observed. Our calculation predicts its mass to be $3763 \pm 19 \pm 26\,^{+13}_{-79}$ MeV, and the overall theoretical expectation is for the $\Omega_{cc}$ to be 3650–3850 MeV. We hope that upcoming experiments will be able to resolve these mysteries of doubly charmed baryons.

In the bottom sector, we calculated only the mass splittings of bottom baryons because the static quark action was used for the bottom quark. This is a relatively high-statistics calculation resulting statistical error bars smaller than other recent lattice calculations of baryon mass splittings in the static limit. These results are presented in Figure 2. Our dominant errors are systematic. The most important systematic error is scale setting. We have used three options for converting to physical units and the spread of our final results is an indication of such errors. Such discrepancy is likely to be caused by a nonzero lattice-spacing systematic error in our calculation. A rough estimate of the lattice-spacing systematic error is 4% of the quoted numbers, assuming $O(a^2\Lambda_{QCD}^2)$ scaling violations caused by the light quarks; however, more generous systematic errors are assigned based on the discrepancy from setting the scale using different quantities. Extrapolations to the physical light-quark mass also introduce errors that should be of the same order of magnitude as typical lattice calculations with the same parameters as ours. Finally, $\Lambda_{\rm QCD}/m_b$ corrections (estimated to be 1%) have to be included for making direct comparison to experiment. Nonetheless, all the above systematic errors are small, and comparisons with experiment can provide useful conclusions. Our results agree well with experiment in the cases of known mass splittings. In the case of $\Omega_b$ our calculation is in agreement with the recent CDF result and several standard deviations away from the D0 result. Such conclusion holds for all other lattice calculations of the $\Omega_b$ mass. Our results for the $\Xi_b'$ mass splittings are a prediction since $\Xi_b'$ has not yet been observed. Using the splitting from the $\Lambda_b$ and summing with the experimental value of that baryon, we predict the mass of the $\Xi_b'$ to be 5955(27) MeV, where the error given combines in quadrature all our errors.

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