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Heavy baryon spectroscopy from lattice QCD

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Abstract. In this report, the most recent and precise estimates of masses of ground state baryons using lattice QCD are discussed. Considering the prospects in the heavy baryon sector, lattice estimates for these are emphasized. The first and only existing lattice determination of the highly excited Ω_c excitations in relation to the recent LHCb discovery is also discussed.

1 Introduction

Since its inception, heavy hadron physics continues to be in the limelight of scientific interests in understanding the nature of strong interactions. While heavy mesons have been studied extensively both experimentally and theoretically [1–3], studies on heavy baryons remained dormant. In this respect, the year 2017 featured two important landmarks in the heavy baryon physics. First of this is the unambiguous observation by LHCb collaboration of five new narrow Ω_c resonances in $\Xi_c^+ K^-$ invariant mass distribution in the energy range between $3000 - 3120$ MeV [4]. Four out of these five resonances were later confirmed by Belle collaboration [5]. Second landmark is the discovery of a doubly charmed baryon, $\Xi_{cc}^{+}(ccu)$ with a mass of 3621.40 ± 0.78 MeV by LHCb Collaboration [6]. Anticipating the discovery of many more hadrons (including baryons) from the huge data being collected at LHCb and Belle II, heavy hadron spectroscopy using *ab-initio* first principles methodology such as lattice QCD is of great importance.

Lattice QCD has been proven to be a novel non-perturbative technology in investigating the physics of low energy regime of QCD. Remarkable progress has been achieved over past ten years in making large volume simulations with physical quark masses, impressive statistical precision and good control over the systematic uncertainties [7–10]. In this report, a collection of lattice determinations of baryon masses that are well below allowed strong decay thresholds are summarized. A recent and only existing calculation of excited Ω_c baryons is discussed and a qualitative comparison with the experiment is made.

2 Lattice methodology

Hadron spectroscopy on the lattice proceeds through evaluation of Euclidean two point correlation functions,

$$C_{ij}(t_f - t_i) = \langle O_i(t_f) O_j^{\dagger}(t_i) \rangle = \sum_{n=1} \frac{Z_i^n Z_j^{n*}}{2E_n} e^{-E_n(t_f - t_i)}\,, \tag{1}$$

between different hadronic currents ($O_i(t)$) that are carefully built to respect the quantum numbers of interest. A generic baryon current or interpolator has a structure

$$O_i(\mathbf{x},t) = \epsilon_{abc} S_i^{\alpha\beta\delta}(\mathbf{x}) q^a_{1,\alpha}(\mathbf{x}) q^b_{2,\beta}(\mathbf{x}) q^c_{3,\delta}(\mathbf{x}), \tag{2}$$

where q_j are the quark fields, ϵ is the color space anti-symmetrizing Levi-Civita tensor and S carries all the flavor and spatial structure of the interpolator that determines the quantum information. $C_{ij}(t_f - t_i)$ are evaluated on lattice QCD ensembles that are generated via Monte Carlo techniques. A general practice is to compute matrices of correlation functions between a basis of carefully constructed interpolating currents $O_i(t)$ and solving the generalized eigenvalue problem (GEVP) [11–13]

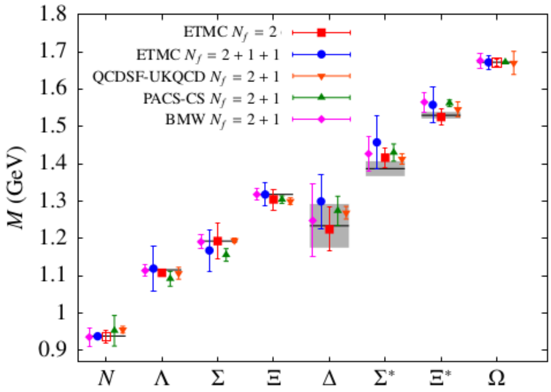
$$C_{ij}(t) v_j^n(t - t_0) = \lambda^n(t - t_0) C_{ij}(t_0) v_j^n(t - t_0). \tag{3}$$

Hadron energies (E_n) are extracted from non-linear fits to the large time behavior of the eigenvalues $\lambda^n(t - t_0)$. The eigenvectors ($v_j^n(t - t_0)$) are related to the operator state overlaps ($Z_i^n = \langle O_i | n \rangle$) that carry the quantum information of the propagating state. Basic principles remain the same as above, while details of the methodology differ between different groups in the lattice community. e.g. lattice ensembles being used in the study, lattice formulation of action for the fermion and the gauge fields, the hadron interpolators, different degree of control over the lattice systematics, etc. The success of lattice investigations are reflected in mutual agreement of the results they provide and their agreement with experiments.

All results presented in this report are estimated within the single hadron approximation, where only three quark interpolators (as in eqn. 2) are considered in the analysis and neglects effects of any nearby strong decay thresholds. This is a justifying assumption for most of the baryons discussed in this report, considering the fact that all of them are deeply below the respective lowest strong decay thresholds. Results for those baryons, which might be influenced by any nearby threshold effects will be alerted in the respective discussions.

3 Results

Light, strange and singly charm baryons : We begin our discussion with some benchmark calculations of baryon ground states that are experimentally well determined. In Fig. 1, a summary of lattice QCD estimates for the positive parity light baryon ground states (figure adapted from Ref. [10]) are presented at the top and for positive parity singly charm baryon ground states are shown at the bottom. Most of the baryons being discussed are deeply bound and stable to strong decays. Their masses as determined from the discrete energy spectrum on the lattice agree quite well with experiments. Agreement between all the lattice estimates with varying degree of control over the systematics involved in respective calculations and with the experiments demonstrate the power of lattice QCD techniques in making reliable predictions. However, lattice estimates for masses of baryon resonances, such as Δ, Σ^* and Ξ^* that can decay strongly, are less rigorous. They demand a computation of correlation matrices build out of baryon



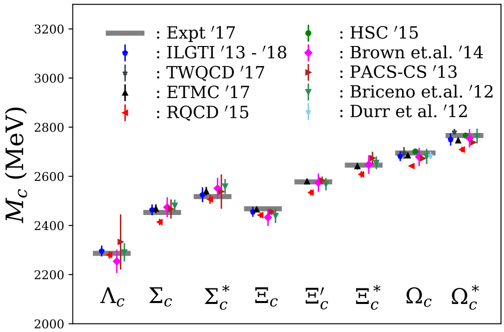


Fig. 1. Top: summary of lattice estimates for positive parity light and strange baryons from selected lattice investigations - ETMC N_f=2 [10], ETMC N_f=2+1+1 [14], QCDSF-UKQCD N_f=2+1 [15], PACS-CS N_f=2+1 [8] and BMW N_f=2+1 [7]. Bottom: summary of lattice estimates for positive parity singly charm baryons : ILGTI '13-'18 [16,17], TWQCD '17 [18], ETMC '17 [10], RQCD '15 [19], HSC '15 [20,21], Brown *et al* '14 [22], PACS-CS '13 [8], Briceño *et al* '12 [23], Dürr *et al* '12 [24].

interpolators (as in eqn. 2) plus baryon-meson interpolators (corresponding to the allowed strong decay modes). The masses of baryon resonances then have to be inferred from the infinite volume scattering matrices build from the discrete spectrum extracted from such correlation matrices. Such investigations are being practised extensively by many collaborations to understand various mesonic resonances (see Ref. [3]), while existing lattice investigations of baryon resonances in this direction are limited to a few [25,26].

Doubly heavy baryons : In Fig. 2, a summary of lattice QCD estimates for positive parity doubly charm baryon ground states at the top is presented. For the $\Xi_{cc}(1/2^+)$ baryon, good agreement between all lattice estimates (all of which predates the LHCb-discovery [6]) and with LHCb estimate is quite evident from the figure. At this point, the reader is reminded of the observation of another baryon resonance by SELEX collaboration in 2002 [27] at a mass of 3519(1) MeV,

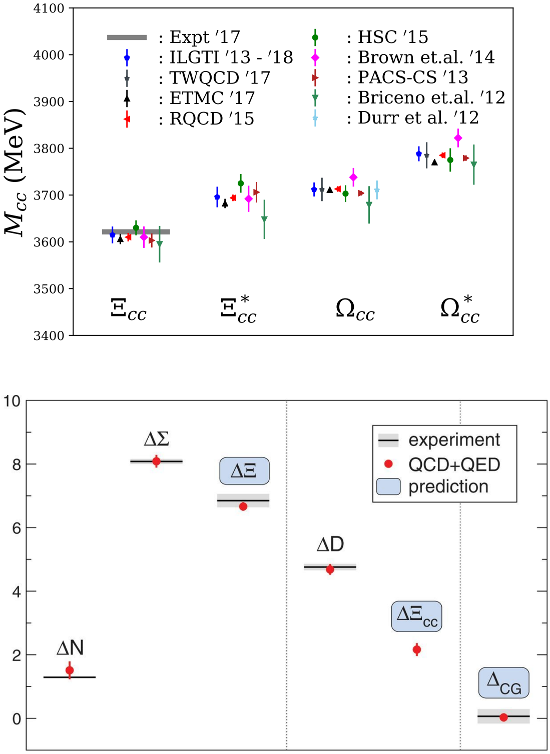


Fig. 2. Top: summary of lattice estimates for positive parity doubly charm baryons. References as given in Fig. 1 caption. Bottom: Hadron isospin splittings as determined by BMW collaboration [9].

which is addressed as a $\Xi_{cc}(1/2^+)$ baryon. All lattice estimates, being well above this energy, disfavors this observation. The bottom figure shows a summary of baryon isospin splittings as calculated by BMW collaboration [9]. This calculation involved lattice QCD and QED computations with four non-degenerate fermion flavors to estimate the isospin mass splitting in the nucleon, Σ, Ξ, D and Ξ_{cc} isospin multiplets. Precise estimation of the neutron-proton isospin splitting and the other known splittings demonstrate the reliability of these estimates. In this calculation, the isospin splitting of $\Xi_{cc}(1/2^+)$ baryon was estimated to be 2.16(11)(17) MeV. This excludes the possibility that LHCb and SELEX candidates for $\Xi_{cc}(1/2^+)$ baryon are isospin partners.

Estimates for other doubly charm baryons, that are yet to be discovered, can also be observed to be very well determined and consistent between different lattice calculations from the top of Fig. 2. Anticipating a near future discovery of the charmed-bottom hadrons at LHCb, at the top of Fig. 3 lattice predictions for such hadrons from a recent investigation [28] are shown. The lattice prediction for only know charmed-bottom hadron, B_c meson, is found to be in agreement with the experiment, while the lattice predictions for other channels considered are consistent with another preceding calculation [22] with less control over systematics.

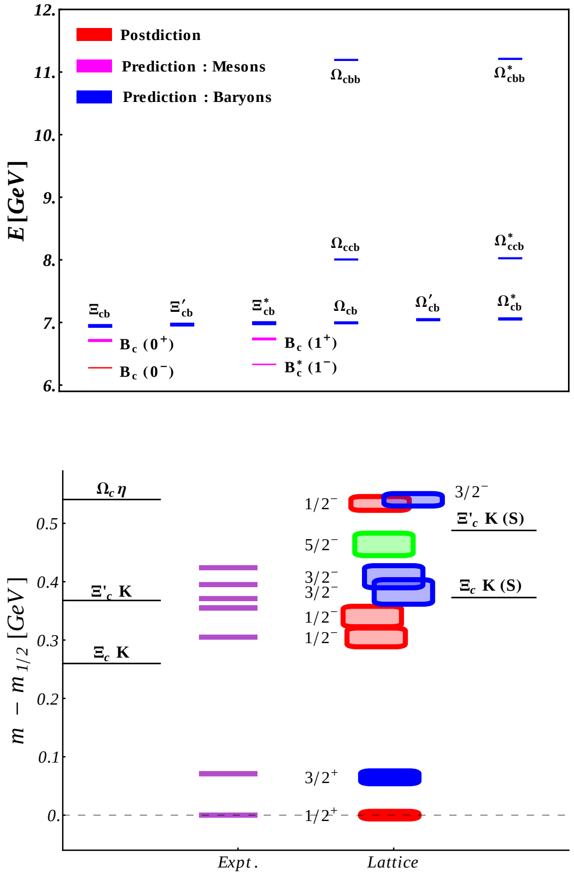


Fig. 3. Top: summary of lattice estimates for low lying charmed-bottom hadrons as determined in Ref. [28]. Bottom: Comparison plot from Ref. [32] between the lattice estimates and the experimental values for the energies of Ω_c excitations.

Excited baryons : As discussed in the introduction, one of the major landmark in the year 2017 is the LHCb discovery of five narrow Ω_c resonances in $\Xi_c^+K^-$ invariant mass distribution in the energy range between 3000 − 3120 MeV [4]. Following this discovery, Belle collaboration has confirmed four out of these five excited states [5]. Many more highly excited baryons are coming into light with more discoveries. e.g. the observation of a $\Omega^{*-}(3/2^-)$ candidate with a mass of 2012.4(9) MeV by Belle collaboration [29], which is in very good agreement with lattice prediction for such a baryon [30, 31]. Below we discuss the first and only existing lattice investigation of highly excited Ω_c resonances (Ref. [32]) that predicts the five excited Ω_c baryons as observed by LHCb.

Following a detailed baryon interpolator construction procedure as invented in Ref. [33,34] a large basis of baryon interpolators, that is expected to extensively scan the radial as well as orbital excitations, are built. By solving the GEVP for correlation matrices constructed out of these interpolators on a lattice ensemble with $m_\pi \sim 391$ MeV (for details see [21]), one extract the Ω_c baryon spectrum on the lattice. The bottom of Fig. 3 shows a comparison of the lattice energy estimates for the lowest nine Ω_c excitations with the seven experimentally observed Ω_c resonances. The relevant strong decay thresholds in the infinite volume are shown as black lines at the top, whereas the black lines at the bottom indicate the relevant non-interacting levels on the lattice. The lowest two levels represent the well known $1/2^+$ and $3/2^+$ excitations. Lattice estimates for these excitations agree well with the experiment. In the energy region, where the five narrow resonances were observed, lattice predicts exactly five levels. Of these five excitations four are in good agreement with the experiment, while the fifth is possibly a $5/2^-$ baryon related to the remaining higher lying experimental candidate. Identifying the quantum information of these lattice levels from the Z_i^ns, these five states are argued to be the p-wave excitations [32].

Considering the exploratory nature of this first study, investigating Ω_c baryon spectrum on multiple lattice ensembles with close to physical m_π and larger volumes would be an immediate extension. It would also be an interesting direction to extract the infinite volume scattering matrices considering the allowed baryon-meson scattering channels in the analysis of desired quantum channels in appropriate lattice ensembles. However, the presence of a valence heavy quark, the absence of any valence light quarks and the resonance widths being quite narrow ($<$ 10 MeV) [6] indicates our estimates to be robust with such extensive investigations.

4 Summary

Over the past decade, lattice QCD has availed multiple precision determinations of the ground state baryon masses using full QCD lattice ensembles with good control over the systematic uncertainties. A summary of lattice determinations of various baryons along with their masses from experiment, where available, are given in Figs. 1, 2 and 3. The only existing exploratory lattice determination of the highly excited Ω_c states in relation to the recent LHCb discovery and its possible extensions are also discussed.

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