Heavy and light spectroscopy near the physical point, Part I: Charm and bottom baryons

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Motivation

- Lattice QCD is a tool for prediction of states in nature.
- Have been previous studies (Brown-14) to compute heavy Baryon spectrum, as of yet no detection of double-heavy baryons.
- It is our job to provide accurate descriptions of where to look.
- We use gauge fixed wall sources, near physical pions and a decent inverse lattice spacing ($a^{-1} = 2.194(10)$ GeV).
- As we were saving propagators for our main project (next talk) this study was more or less free.

Operators & Correlators

Correlators are formed as,

$$C^{s_1 s_2}_{\mathcal{O}_1\mathcal{O}_2}(p,t) = \langle \sum_x e^{ip\cdot x}\mathcal{O}_1^{s_1}(x,t)\mathcal{O}_2^{s_2}(0,0)^\dagger \rangle \ ,$$
$$= \sum_n \langle 0|\mathcal{O}_1^{s_1}|n\rangle\langle n|\mathcal{O}_2^{s_2}|0\rangle e^{-E_{\mathcal{O}_1\mathcal{O}_2}(p)t} \ .$$

Typical (0^+) meson interpolating operators,

$$P(x) = \bar{u}(x)^\alpha_a \gamma_5^{\alpha\beta} d^\beta_a(x), \quad A_t(x) = \bar{u}^\alpha_a(x)\gamma_5^{\alpha\kappa}\gamma_t^{\kappa\beta} d^\beta_a(x) \ .$$

Baryon interpolating operators are generically given by,

$$B^\kappa_i(x) = \epsilon_{abc}\left((\psi^\alpha_a(x))^T C\Gamma_i^{\alpha\beta}\chi^\beta_b(x)\right)\phi(x)^\kappa_c \ .$$

Baryon correlator $B^{\kappa\kappa'}_{ij}(p,t)$ with open dirac indices and no parity.

Gauge and Light quark (u-s) action

Iwasaki gauge action ($\beta = 1.9$, $c_1 = -0.331$),

$$S_g = \beta \sum_{x,\mu,\nu} \mathrm{Re} \left((1 - 8c_1) U_{\mu\nu}(x) + c_1 \sum_{i}^{3} R^{(i)}_{\mu\nu}(x) \right) .$$

Non-perturbatively Clover-improved Wilson fermions $C_{SW} = 1.715$,

$$\begin{aligned} M(x,y) &= \delta_{x,y} \left(1 - \kappa c_{SW} \sum_{\mu,\nu} F_{\mu\nu}\sigma_{\mu\nu} \right) \\ &\quad - \kappa \sum_{\mu} \left((1-\gamma_\mu) U_{x,\mu} \delta_{x+\hat{\mu},y} + (1+\gamma_\mu) U^\dagger_{x,\mu} \delta_{x,y+\hat{\mu}} \right) . \end{aligned}$$

PACS-CS 2009.

Heavy quark actions

relativistic c quarks (Tsukuba tuning) by Ikeda et al, Phys Lett B729 (2014) 85:

$$M(x,y) = \delta_{x,y}\left(1 - \kappa c_E \sum_i F_{i4}\sigma_{i4} - \kappa c_B \sum_{i,j} F_{ij}\sigma_{ij}\right)$$
$$- \kappa \sum_\mu \left((r_\mu - \nu\gamma_\mu) U_{x,\mu}\delta_{x+\hat{\mu},y} + (r_\mu + \nu\gamma_\mu) U^\dagger_{x,\mu}\delta_{x,y+\hat{\mu}}\right).$$

b quarks use a tadpole-improved NRQCD Hamiltonian ($c_i = 1$):

$$H = -\frac{\Delta^{(2)}}{2M_0} - c_1 \frac{(\Delta^{(2)})^2}{8{M_0}^3} + \frac{c_2}{U_0^4}\frac{ig}{8{M_0}^2}(\tilde{\boldsymbol{\Delta}} \cdot \tilde{\boldsymbol{E}} - \tilde{\boldsymbol{E}} \cdot \tilde{\boldsymbol{\Delta}})$$
$$- \frac{c_3}{U_0^4}\frac{g}{8{M_0}^2}\boldsymbol{\sigma} \cdot (\tilde{\boldsymbol{\Delta}} \times \tilde{\boldsymbol{E}} - \tilde{\boldsymbol{E}} \times \tilde{\boldsymbol{\Delta}}) - \frac{c_4}{U_0^4}\frac{g}{2M_0}\boldsymbol{\sigma} \cdot \tilde{\boldsymbol{B}}$$
$$+ c_5 \frac{a^2\Delta^{(4)}}{24M_0} - c_6 \frac{a(\Delta^{(2)})^2}{16n{M_0}^2}.$$

Extracting meson masses and decay constants

Pseudoscalar-meson gauge fixed wall source correlation functions are fit to:

$$C_{PP}^{WL} = f_3 f_1 \left(e^{-f_0 t} + e^{-f_0 (L_t - t)} \right), C_{A_t A_t}^{WL} = f_4 f_2 \left(e^{-f_0 t} + e^{-f_0 (L_t - t)} \right),$$
$$C_{PA_t}^{WL} = f_3 f_2 \left(e^{-f_0 t} - e^{-f_0 (L_t - t)} \right), C_{A_t P}^{WL} = f_4 f_1 \left(e^{-f_0 t} - e^{-f_0 (L_t - t)} \right),$$
$$C_{PP}^{WW} = f_3 f_3 \left(e^{-f_0 t} + e^{-f_0 (L_t - t)} \right), C_{A_t A_t}^{WW} = f_4 f_4 \left(e^{-f_0 t} + e^{-f_0 (L_t - t)} \right),$$
$$C_{PA_t}^{WW} = f_3 f_4 \left(e^{-f_0 t} - e^{-f_0 (L_t - t)} \right), C_{A_t P}^{WW} = f_4 f_3 \left(e^{-f_0 t} - e^{-f_0 (L_t - t)} \right) .$$

8 correlators, 5 fit parameters

Extract the decay constant with,

$$f_P = Z_A \sqrt{\frac{2 f_2^2}{L_x^3 f_0}} .$$

Parity & spin projections

We must pick a parity for our baryon correlators, we use

$$L^{\alpha\beta}_{4/5} = \frac{1}{2}(I \pm \gamma_t)^{\alpha\beta} \ , \quad B^{(L)}_{ij}(p,t) = L^{\kappa'\kappa} B^{\kappa\kappa'}_{ij}(p,t) \ .$$

At zero momentum there exist (Benmerrouche-89, Bowler-96) the following spin projections,

$$P^{1/2}_{ij} = \frac{1}{3}\gamma_i\gamma_j, \quad P^{3/2}_{ij} = \delta_{ij} - \frac{1}{3}\gamma_i\gamma_j \ .$$
$$B^{\kappa\kappa'}_{(P)}(p,t) = P_{kj} B^{\kappa\kappa'}_{jk}(p,t) \ .$$

L_4 behaves like a time reversal of L_5 and so they can be averaged together.

Code & methodology

- We required a code that could contract together both NRQCD and dirac propagators offline.
- Execution time was some concern. Small CPU allocation ≈ 150 core years. GPC machine uses Xeon architecture so SSE4.2 supported.

We wrote the Contractual Obligations library to deal with this.

- Hand-unrolled intrinsics for linear algebra, sparse (index-based) gamma multiplies. Multithreaded.
- Coulomb gauge fixing using the FACG of the GLU library.
- Light quark inversions using DDHMC package.

Ensemble properties

Label	E_H	E_M	E_L
Extent	$32^3 \times 64$	$32^3 \times 64$	$32^3 \times 64$
a^{-1} [GeV]*	2.194(10)	2.194(10)	2.194(10)
κ_l	0.13754	0.13770	0.13781
κ_s	0.13666	0.13666	0.13666
am_π	0.18928(36)	0.13618(46)	0.07459(54)
am_K	0.27198(28)	0.25157(30)	0.23288(25)
f_K/f_π	1.0827(14)	1.1151(33)	1.2012(75)
M_Υ [GeV]	9.528(79)	9.488(71)	9.443(76)
Configurations	400	800	195
Measurements	800	800	3078

Overview of our ensemble parameters: $am_{\pi,K}$ are from global cosh/sinh fits to a shared mass and common amplitudes over the C_{PP}, $C_{A_tA_t}$, and C_{A_tP} correlators using both wall-local and wall-wall data. Fit ranges were chosen so that $\chi^2/d.o.f$ was close to 1. These configurations use the Iwasaki gauge action with $\beta = 1.9$ and clover coefficient $c_{SW} = 1.715$. *Nakamura-2013.

Tuning the NRQCD action

We use the fourth root of the plaquette rather than the mean Landau link. Retuned NRQCD action (using point sources) for these ensembles by fitting linearly in $\tilde{p}^2$ to,

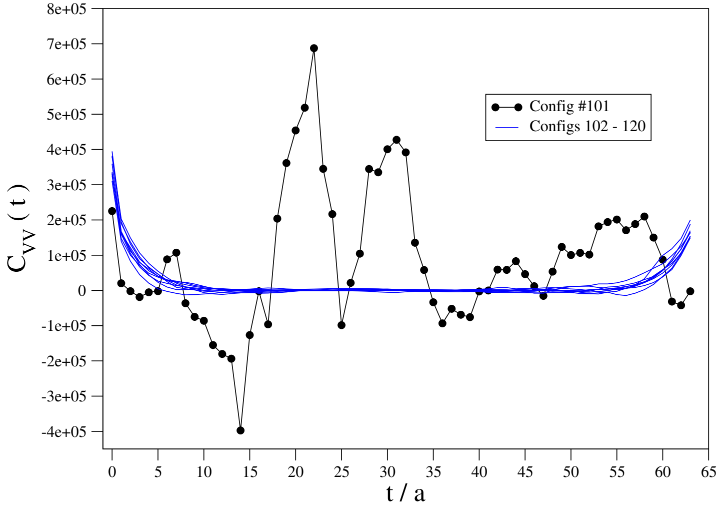
$$aE(p) = aM_0 + \frac{\tilde{p}^2}{2aM_{\mathrm{ph}}}, \quad \tilde{p}_\mu = a\sin\left(\frac{2\pi n_\mu}{L_\mu}\right) .$$

aM_{ph} is the physical hadron mass we tune to M_Υ.

Ensemble	E_H	E_M	E_L
U_0^4	0.86899	0.86911	0.86923
M_0	1.93	1.93	1.825
Measurements	120	200	198

Retuned NRQCD parameters for our ensembles

Vector meson exceptional configurations

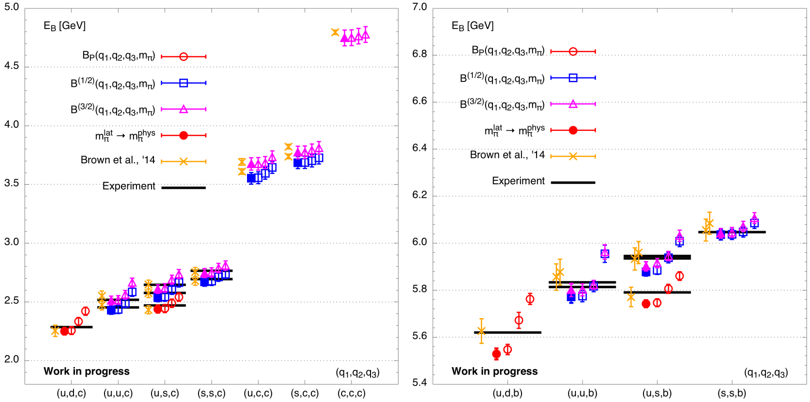


Excessive particle table

uuu	uds	usb	ssc	ccc
uud	udc	ucc	ssb	ccb
uus	udb	ucb	scc	cbb
uuc	uss	ubb	scb	bbb
uub	usc	sss	sbb	-

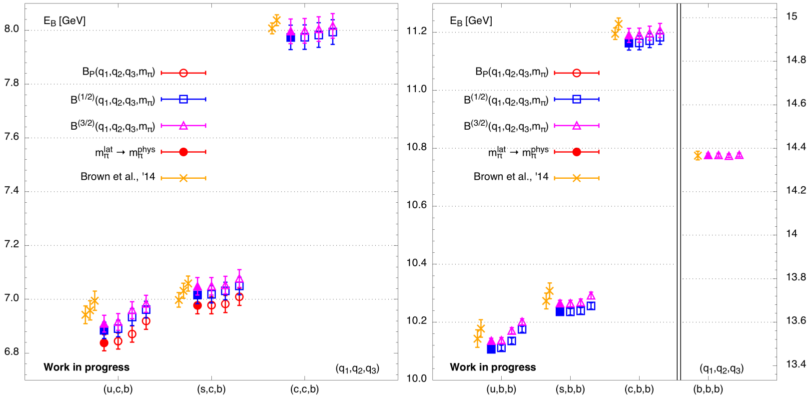
List of Baryons we have analysed. Red indicates that only $C\gamma_5$ and spin 3/2 $C\gamma_i$ operators are available, all other options have both spin1/2 and spin-3/2 components.

Experimentally observed particles and first predictions



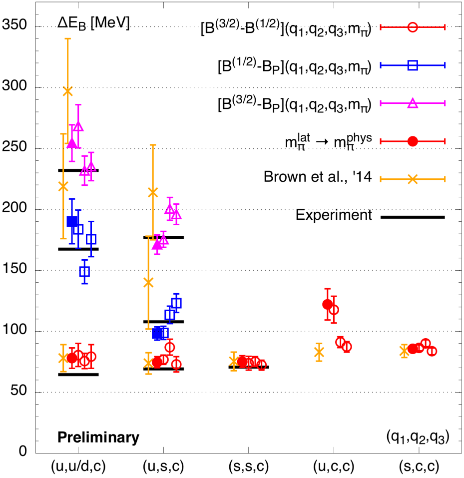
- **Work in progress:** Double systematics from tuning and $\delta(a_{lat})$
- Still: Spectra for $c > 0$ and/or $b = 1$ baryons agree well with experiment and (Brown-14)

Heavy baryon predictions



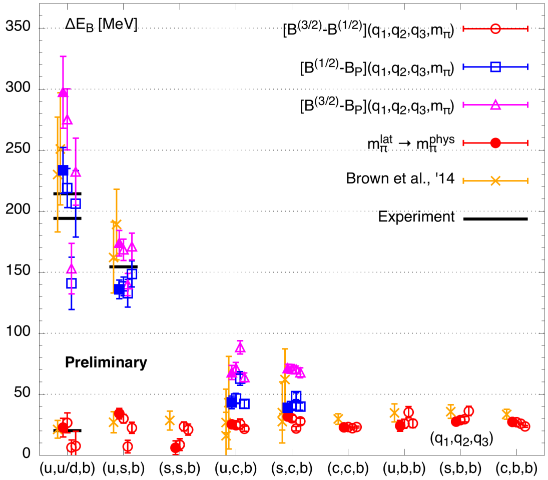
- **Work in progress:** Double systematics from tuning and $\delta(a_{lat})$
- Predictions for $c \geq 0$ and $b \geq 1$ baryons compatible with (Brown-14)

$b = 0$ baryon mass splittings



- Some systematics cancel in the difference
- Precise results also at low m_π
- Chiral extrapolation short and accurate
- Results compatible with (Brown-14) and experiment

$b > 0$ baryon mass splittings



- Some systematics cancel in the difference
- No NRQCD mass-shift required
- Precise results also at low m_π
- Chiral extrapolation short and accurate
- Results compatible with (Brown-14) and experiment

Summary

- We have thousands of saved propagators and can perform large spectrum calculations easily.
- Have good agreement with experiment $\rightarrow$ well tuned heavy quark actions.
- Near physical pions, (barring exceptional configurations) and gauge fixed wall sources have been beneficial.
- Updated PACS-CS values for m_π, f_K/f_π retuned NRQCD action, introduced our ensembles for tetraquark talk.