Bottom and charmed hadron spectroscopy from lattice QCD

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Abstract. A survey of recent lattice QCD simulations for the mass spectrum of bottom and charmed hadrons is presented.

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INTRODUCTION

During the three years since the previous meson-nucleon (MENU) conference, there have been many lattice QCD computations of bottom and charmed hadron masses. These studies must handle challenges due to the physical quark masses being spread out relative to the natural lattice scales, $\lambda_{\text{QCD}}$ and $1/a$ (the ultraviolet cutoff):

$$m_u \approx m_d < m_s \approx \Lambda_{\text{QCD}} < m_c < \frac{1}{a} < m_b.$$ (1)

BOTTOM BARYONS

During the past three years, the CDF and D0 collaborations have published first observations of the $\Sigma_b[1]$, $\Sigma_b^*[1]$, $\Xi_b[2, 3]$ and $\Omega_b[4, 5]$ baryons. The two results for the $\Omega_b$ are not consistent with one another.

Various lattice QCD groups have computed the mass spectrum using different b-quark actions ($\text{NRQCD}[6, 7]$, $\text{Fermilab}[8]$, static[9, 10, 11]), different light-quark actions ($\text{nonperturbatively-tuned clover}[6]$, $\text{chirally-improved}[9]$, $\text{domain wall}[7, 10]$, $\text{improved-staggered sea with domain wall valence}[11]$) and different gauge actions ($\text{Iwasaki}[6, 7, 10]$, $\text{one-loop Symanzik/Lüscher-Weisz}[8, 9, 11]$). Any action with the correct continuum limit is a valid approach, and these complementary studies provide valuable information about systematic uncertainties at present lattice spacings and volumes. Chiral extrapolations toward the physical u and d quark masses are also a source of systematic uncertainty, and the recent bottom baryon studies reach a minimum pion mass near 275 MeV[10], 290 MeV[8, 11], 331 MeV[7], 461 MeV[9] and 600 MeV[6].

Figure 1 conveys an impression of some results from these recent studies of bottom baryons, but of course the original publications provide many additional insights. For example, [8] provides a discussion of systematically-large splittings for ($\Lambda_b$, $\Xi_b$) versus ($\Sigma_b$, $\Xi_b$, $\Omega_b$) that arise with a staggered lattice action due to the inability to separate $J^p = \frac{3}{2}^-$ and $\frac{1}{2}^+$ states using the spin projection operators.

It is clear from figure 1 that lattice simulations are consistent with the CDF measurement of the $\Omega_b$ mass as opposed to the D0 result. Lattice findings also agree with experiment for all other available masses, and lattice predictions are in place for comparison to future experimental discoveries.

Two related preprints have appeared after the MENU 2010 conference. Wagner and Wiese[12] have computed the baryon spectrum in the limit of a static bottom quark, where the twisted mass action was used for u,d quarks. Meinel[13] has produced a preprint that is focused on the mass of the $\Omega_{bbb}$. Using NRQCD bottom quarks on dynamical lattice configurations, he arrives at

$$M_{\Omega_{bbb}} = 14.371 \pm 0.004_{\text{stat}} \pm 0.011_{\text{syst}} \pm 0.001_{\text{exp}} \text{ GeV}$$ (2)

where the third uncertainty arises from required experimental input. This mass with exclusively heavy valence quarks can be of significant value for testing the content of theoretical models.
FIGURE 1. Bottom baryon spectrum from lattice QCD from [6, 7, 9, 10, 11]. Not shown are preliminary results from [7] for singly- and doubly-b baryons, valuable data from [8] for mass differences among singly- and doubly-b baryons, and the prediction for $M_{\Omega_{bb}}$ given in equation (2).

FIGURE 2. Charmed baryon spectrum from lattice QCD[8, 14] compared to older quenched results from [15, 16, 17]. Not shown are results in [8] for mass differences, including $\Xi_{cc}^+$ and $\Omega_{cc}^+$. This graph has been taken directly from [14].

CHARMED BARYONS

In contrast to $m_b$, the charmed quark mass is smaller than the standard lattice cutoff so neither NRQCD nor static quark actions are generally useful. Two lattice groups[8, 14] have recently used the Fermilab action for the charmed quark and gauge configurations containing staggered u,d,s sea quarks to obtain charmed baryon masses. Liu, Lin, Orginos and Walker-Loud[14] used domain wall valence u,d,s quarks while Na and Gottlieb[8] used the staggered action. The lightest u,d masses correspond to $m_{\pi} = 290$ MeV.

Some results are shown in figure 2, which was taken directly from [14]. It is interesting to see the consistency of the new results with the older simulations[15, 16, 17] which had relied on the quenched approximation.

BOTTOM MESONS

Recent lattice results for $B$, $B_s$ and $B_c$ mesons are compiled from [6, 18, 19, 20, 21] in figure 3 and compared to experimental data where available. Two groups[6, 21] used the NRQCD action for the bottom quark while the others[18, 19, 20] extrapolated from static quark simulations. The light quark action was nonperturbatively-improved
FIGURE 3. Bottom meson spectrum from lattice QCD[6, 18, 19, 20, 21].

FIGURE 4. Meson spectrum of a static valence anti-quark with a u, d or s valence quark[9, 19, 20]. Black ovals are only to guide the eye in grouping relevant simulation results.

clover[6, 18], twisted mass[19, 20] or HISQ (staggered)[21].

Systematic deviations of lattice from experiment are observed in some cases. The spread among lattice results in figure 3 provides an impression of the systematic errors in current lattice simulations, but for detailed discussions see the original lattice papers[6, 18, 19, 20, 21].

It should be noted that the precise and accurate lattice result for the $B_c$ mass, coming from the HPQCD collaboration, was obtained by tuning the standard QCD inputs to match the experimental masses of pion, kaon, $\eta_c$, and $\Upsilon[21]$. Their $B_c^*$ mass stands as a precise prediction for future experiments.

Interesting work has also been reported for mesons in the limit of a static (infinitely-heavy) bottom quark[9, 19, 20]. This unphysical limit shares many qualitative features with the physical spectrum and has been used in combination with charmed meson masses to interpolate to the region of physical bottom mesons. As evident from figure 4, a long list of quantum numbers has been studied. The variance among different lattice determinations of some masses suggests the presence of significant systematic effects. Details can be found in the original articles[9, 19, 20].
CHARMED MESONS

The spectrum of charmed mesons has not received much attention recently from the lattice community, and thus represents a future opportunity. Dong et al.[22] have studied the $D_s$ spectrum, motivated in part by published speculations that the experimentally-observed $D_s^0(2317)$ might not be a $c\bar{s}$ state but rather a DK molecule, a four-quark state or a threshold effect. They use domain wall sea quarks, overlap valence quarks and an Iwasaki gauge action with a lattice spacing of 0.08 fm, a lattice volume of (2.7 fm)$^3$ and a pion mass as light as 331 MeV. Figure 5 is taken directly from their conference report[22]. Dong et al. conclude that their preliminary results are consistent with the $D_s^0(2317)$ being a standard $c\bar{s}$ meson.

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REFERENCES

1. CDF collaboration: T. Aaltonen et al., Phys. Rev. Lett. 99, 202001 (2007).
2. D0 collaboration: V. Abazov et al., Phys. Rev. Lett. 99, 052001 (2007).
3. CDF collaboration: T. Aaltonen et al., Phys. Rev. Lett. 99, 052002 (2007).
4. D0 collaboration: V. Abazov et al., Phys. Rev. Lett. 101, 232002 (2008).
5. CDF collaboration: T. Aaltonen et al., Phys. Rev. D80, 072003 (2009).
6. R. Lewis and R.M. Woloshyn, Phys. Rev. D79, 014502 (2009).
7. S. Meinel, W. Detmold, C.-J. Lin and M. Wingate, PoS(LAT2009)105 (2009).
8. H. Na, Ph.D. thesis, Indiana University (2008); H. Na and S. Gottlieb, PoS(LAT2008)119 (2008).
9. T. Burch, C. Hagen, C.B. Lang, M. Limmer and A. Schäfer, Phys. Rev. D79, 014504 (2009).
10. W. Detmold, C.-J. Lin and M. Wingate, Nucl. Phys. B818, 17 (2009).
11. H.-W. Lin, S.D. Cohen, N. Mathur and K. Orginos, Phys. Rev. D80, 054027 (2009).
12. M. Wagner and C. Weise, arXiv:1008.0653 (2010).
13. S. Meinel, arXiv:1008.3154 (2010).
14. L. Liu, H.-W. Lin, K. Orginos and A. Walker-Loud, Phys. Rev. D81, 094505 (2010).
15. N. Mathur, R. Lewis and R.M. Woloshyn, Phys. Rev. D66, 014502 (2002).
16. J.M. Flynn, F. Mescia and A.S.B. Tariq, JHEP 07, 066 (2003).
17. T.-W. Chiu and T.-H. Hsieh, Nucl. Phys. A755, 471 (2005).
18. J. Koponen, Phys. Rev. D78, 074509 (2007).
19. K. Jansen, C. Michael, A. Shindler and M. Wagner, JHEP 12, 058 (2008).
20. C. Michael, A. Shindler and M. Wagner, arXiv:1004.4235 (2010).
21. E.B. Gregory, C.T.H. Davies, E. Follana, E. Gamiz, I. Kendall, G.P. Lepage, H. Na, J. Shigemitsu, K.Y. Wong, arXiv:0911.2133 (2009).
22. S.J. Dong, A. Alexandru, T. Draper, K.F. Liu, A. Li, T. Streuer and J.B. Zhang, PoS(LAT2009)090 (2009).