Doubly Heavy Baryons

Chris Quigg
Theoretical Physics Department
Fermi National Accelerator Laboratory
quigg@fnal.gov

- Why are heavy-heavy baryons interesting?
- $QQ^{(\prime)}q$ spectroscopy
- Weak Decays of $QQ^{(\prime)}q$ states
- Strong and electromagnetic cascades
- Production dynamics
- Work to be done

(Substituting for Anatoly Likhoded)

Why are $QQ^{(\prime)}q$ baryons interesting?

- Spectroscopy
  - ▷ Analogy between $(QQ^{(\prime)})_{\mathbf{3}^*}\,q$ and $\bar{Q}q$ as heavy-light systems
  - ▷ For single gluon exchange, $V_{(QQ^{(\prime)})_{\mathbf{3}^*}}(r) = \frac{1}{2}V_{(Q\bar{q})_{\mathbf{1}}}(r)$; deviations beyond?
  - ▷ Learn about $(QQ^{(\prime)})_{\mathbf{3}^*}$ dynamics through excitation spectrum?
  - ▷ As in $b\bar{c}$, unequal masses in bcq may expose limitations of NRQM
- Weak decays
  - ▷ Rich set of heavy $\to$ heavy and heavy $\to$ light transitions
  - ▷ Isolate different pieces of $\mathcal{H}^{\rm eff}_{\rm weak}$
- Strong and electromagnetic cascades
  - ▷ Two-scale problem: $r_H = \langle r^2_{QQ^{(\prime)}}\rangle^{1/2}$ and $r_\ell = \langle r^2_{(QQ^{(\prime)})_q}\rangle^{1/2}$
  - ▷ Expect some extremely narrow states
- Production dynamics
  - ▷ Extend ideas about fragmentation models to new regimes
  - ▷ Compare with quarkonium production dynamics

$QQ^{(\prime)}q$ spectroscopy

- $SU(3)$ classification of baryon states: the multiplets

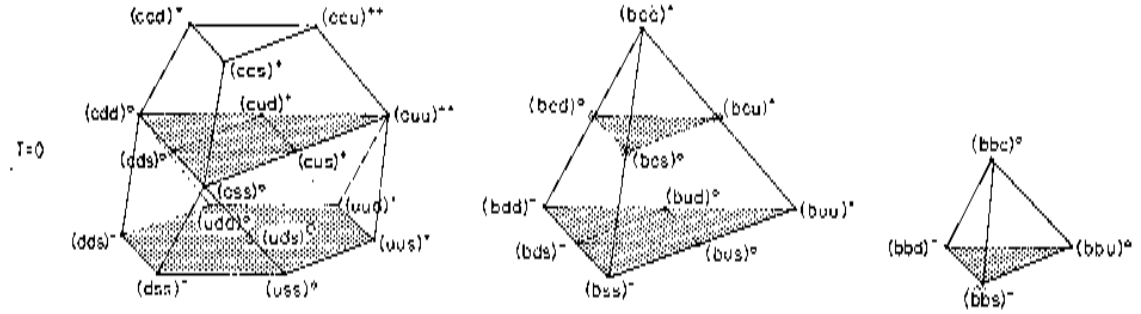


Fig. 28. $J^P = 1/2^+$ baryon states in flavor SU(6). The circled states occur twice, as do those that lie in both [6] and [3*] of $SU(3)_{uds}$. There are 70 states in all.

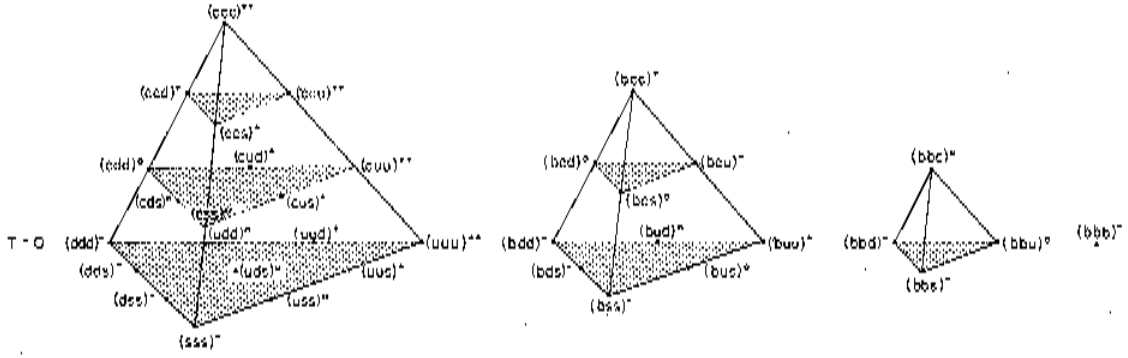


Fig. 29. $J^P = 3/2^+$ baryon states in flavor SU(6). There are 56 states in all.

$QQ^{(\prime)}q$ spectroscopy ...

- NRQM (potential-model) calculations of ground-state masses

  ▷ The pioneers: S. Fleck and J.-M. Richard, Prog. Theoret. Phys. **82,** 760 (1989); J.-M. Richard, "Hadrons with Two Heavy Quarks," CHARM2000 Workshop at Fermilab (1994). [Born–Oppenheimer]

  ▷ S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, A. I. Onishchenko, Heavy Ion Phys. 9:133-144, 1999 hep-ph/9811212. [Quark–diquark]

  ▷ M. L. Stong, "Spectra of Baryons Containing Two Heavy Quarks," hep-ph/9505217.

  Diquark is larger than corresponding quarkonium state: In a potential $V(r) = \lambda r^{\nu}$, lengths scale as

  $$L \propto (\mu|\lambda|)^{-1/(2+\nu)}$$

- QCD sum rule estimates of ground-state masses

  ▷ V. V. Kiselev and A. I. Onishchenko, "Doubly heavy baryons in sum rules of NRQCD," hep-ph/9909337.

Masses of the ccq baryons

Quark Content	Baryon	Mass [GeV/c^2] Fleck & Richard	Gershtein, et al.	NRQCD Sum Rules
(ccq)	Ξ_{cc}	3.613	3.478	3.47 ± 0.05
(ccq)	Ξ^*_{cc}	3.741		
(ccs)	Ω_{cc}	3.703		
(ccs)	Ω^*_{cc}	3.835		

Masses of the bcq baryons

Quark Content	Baryon	Mass [GeV/c^2] Fleck & Richard	Gershtein, et al.	NRQCD Sum Rules
(bcq)	Ξ_{bc}	6.876	6.82	6.80 ± 0.05
(bcq)	Ξ_{bc}	6.932		
(bcq)	Ξ^*_{bc}	6.985		
(bcs)	Ω_{bc}	6.951		
(bcs)	Ω_{bc}	7.007		
(bcs)	Ω^*_{bc}	7.065		

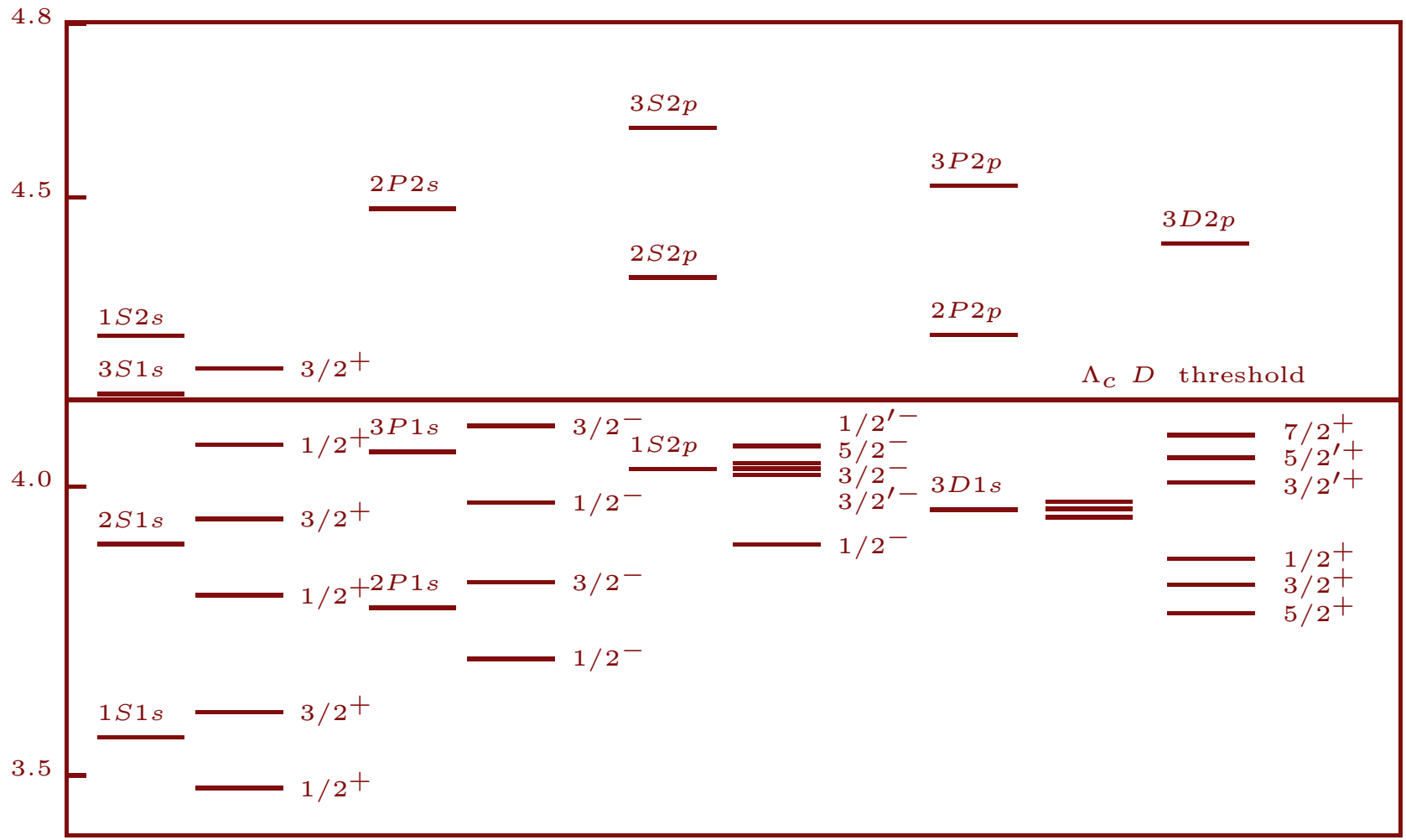
Masses of the bbq baryons

Quark Content	Baryon	Mass [GeV/c^2] Fleck & Richard	Gershtein, et al.	NRQCD Sum Rules
(bbq)	Ξ_{bb}	10.129	10.093	10.07 ± 0.09
(bbq)	Ξ^*_{bb}	10.188		
(bbs)	Ω_{bb}	10.186		
(bbs)	Ω^*_{bb}	10.255		

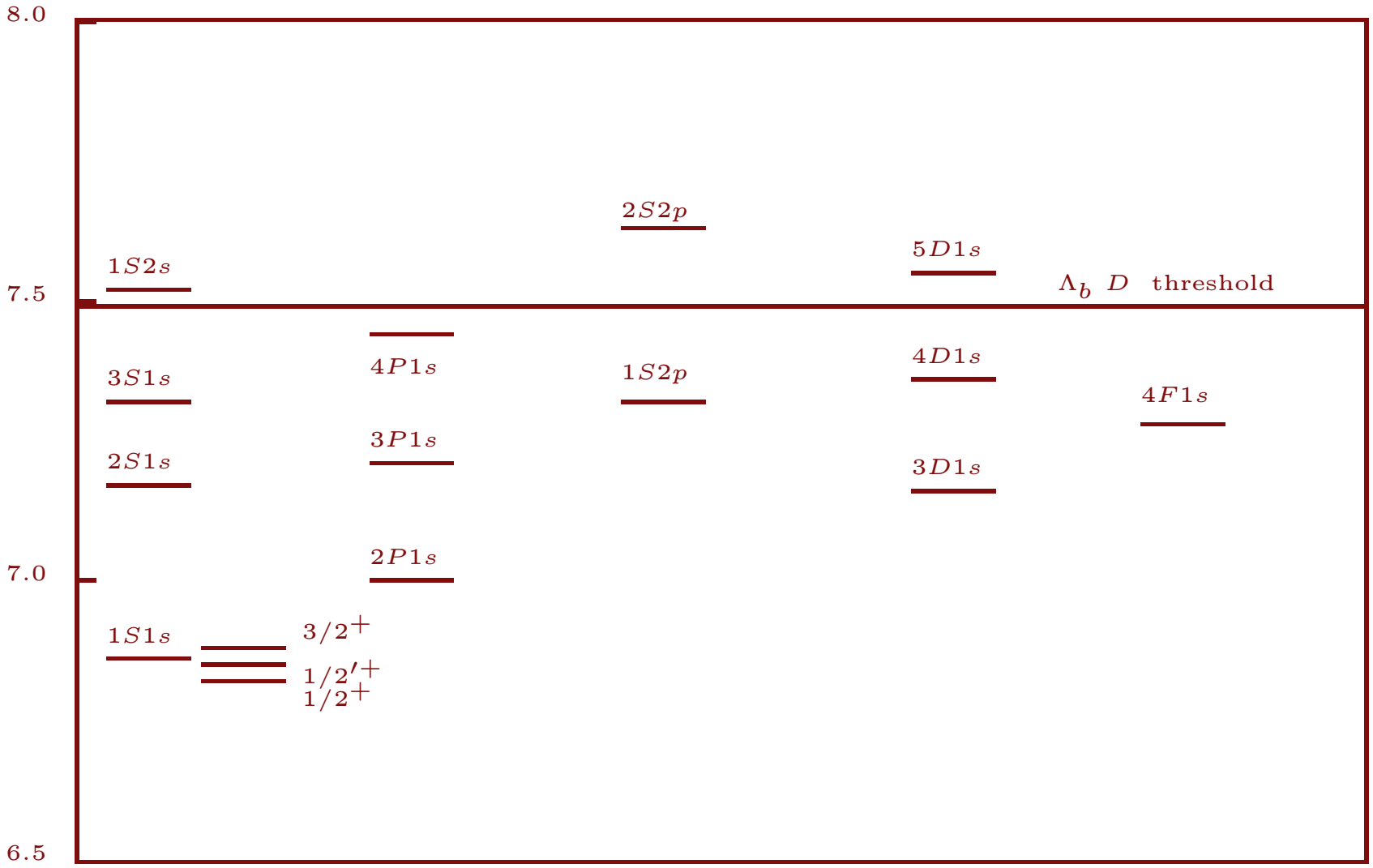
$QQ^{(\prime)}q$ spectroscopy ...

- Exploration of excited states; relation to $\bar{Q}q$ spectrum
  - ▷ In the limit $m_Q, m_{Q'} \to \infty$, the $QQ^{(\prime)}q$ spectrum will be analogous to that of $\bar{Q}q$.
  - ▷ For large but finite values of $m_Q, m_{Q'}$, the $2J_H + 1$ degeneracy of the spin-J_H diquark enriches the $QQ^{(\prime)}q$ spectrum.
  - ▷ The characteristic scales of light-quark and heavy-quark excitations are different: $V_{(QQ^{(\prime)})_{\mathbf{3}^*}}(r) = \frac{1}{2} V_{(Q\bar{q})_{\mathbf{1}}}(r)$.
  - ▷

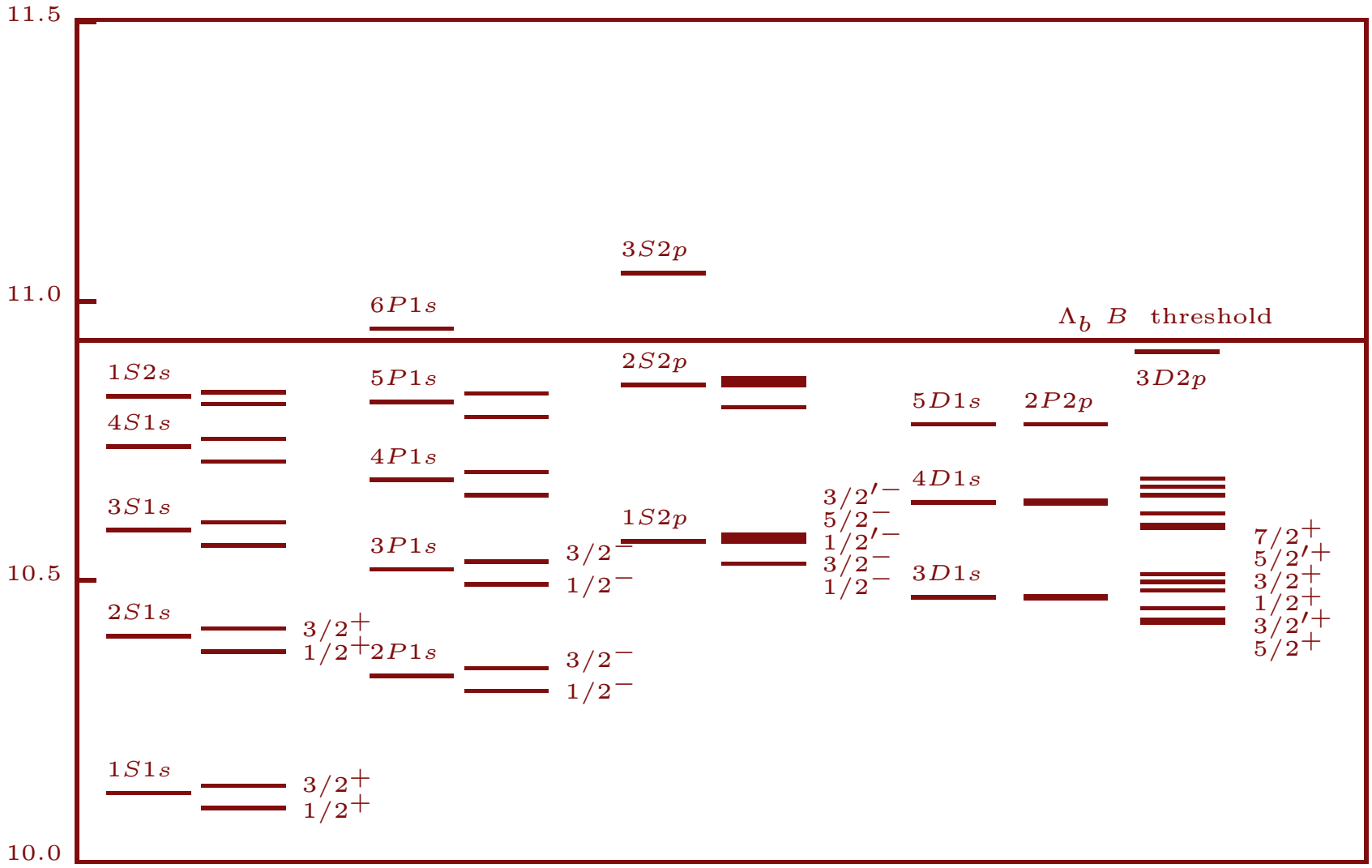
$\Xi_{cc}^{+,++}$ Spectrum



$\Xi_{bc}^{0,+}$ Spectrum



$\Xi_{bb}^{-,0}$ Spectrum



Weak decays ...

- For doubly charmed states, Savage and Springer give an extensive catalogue of two-body decay modes and $SU(3)$ decomposition.
- A similar catalogue is needed for bcq and bbq states, to identify possible discovery modes and to understand what could be learned.
- Lifetime estimates: Serpukhov group argues that Cabibbo-allowed W-exchange shortens Ξ_{cc}^{+} lifetime. They predict ...

$$\begin{aligned} \tau(\Xi_{cc}^{++}) &= 0.43 \pm 0.11 \text{ ps} \\ \tau(\Xi_{cc}^{+}) &= 0.11 \pm 0.03 \text{ ps} \\ \\ \tau(\Xi_{bc}^{+}) &= 0.33 \pm 0.08 \text{ ps} \\ \tau(\Xi_{bc}^{0}) &= 0.28 \pm 0.07 \text{ ps} \end{aligned}$$

- Also worth looking at ccs, ccc, bcs, bcc, bbs, bbc, bbb.

Cascades to the ground states

- Analyze cascade down the light-quark levels using heavy-quark symmetry, as for $\bar{Q}q$ mesons.
- Analyze cascades down diquark levels using the multipole formalism applied to quarkonium transitions.
- Some excited states may be extremely narrow:
  - ▷ 2P1s $\rightarrow$ 1S1s transition requires a sudden change of both L_H and S_H.
  - ▷ Higher excitations, like 3D1s $J^P = 7/2^+, 5/2^+$ states, decay only through high (E2, etc.) multipoles.
  - ▷ To what degree does configuration mixing broaden these states?

Production of $QQ^{(\prime)}q$ States

- Fragmentation models, à la quarkonium production.
- Full $\mathcal{O}(\alpha_s^4)$ evaluation of

$$\begin{aligned} gg &\to (QQ^{(\prime)})_{\mathbf{3}^*} + \text{anything} \\ q\bar{q} &\to (QQ^{(\prime)})_{\mathbf{3}^*} + \text{anything} \end{aligned}$$

- Cross section $\propto |R_{(QQ^{(\prime)})_{\mathbf{3}^*}}(0)|^2$.
- Estimates from Serpukhov group (for $p_\perp > 5$ GeV/c and $|y| < 1$):

$$\begin{aligned} \sigma(\Xi_{cc}) &\approx 0.13 \text{ nb} \quad [M(\Xi_{cc}) \approx 3.5 \text{ GeV}/c^2] \\ \sigma(\Xi_{bc}) &\approx 1 \text{ nb} \quad [M(\Xi_{bc}) \approx 6.8 \text{ GeV}/c^2] \end{aligned}$$

  A surprising result! Larger cross section for Ξ_{bc} attributed to

  - ▷ Smaller size of $(bc)_{\mathbf{3}^*}$, compared to $(cc)_{\mathbf{3}^*}$
  - ▷ Combinatorial factors

Work to be done . . .

- Critically examine the ground-state mass estimates.
- Look for ways to encounter non–potential-model dynamics in the excitations of the $(QQ^{(\prime)})_{\mathbf{3}^*}$ system.
- Catalogue the two-body (discovery?) modes of $\Xi_{cc}^{+,++}$, $\Xi_{bc}^{0,+}$, and $\Xi_{bb}^{-,0}$.
- Estimate the lifetimes of $\Xi_{cc}^{+,++}$, $\Xi_{bc}^{0,+}$, and $\Xi_{bb}^{-,0}$.
- Identify possible quasistable excited states.
- Analyze the cascade decays of excited states, taking into account the different sizes of the heavy diquark and the quark-diquark system.
- Consider mechanisms for the production of doubly (or triply!) heavy baryons and relate them to mechanisms for quarkonium production.
- Are the $\Xi_{cc}^{+,++}$ states significantly produced in the weak decays of $\Xi_{bc}^{0,+}$?
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