Heavy quark spectroscopy and prediction of bottom baryon masses

Marek Karliner
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in collaboration with B. Keren-Zur, H.J. Lipkin and J. Rosner
Constituent Quark Models (CQM)

- QCD describes hadrons as valence quarks in a sea of gluons and q-qbar pairs.
- at low E, $\chi_{SB}$
- \[ \rightarrow \text{quark constituent mass} \]
- hadron can be considered as a bound state of constituent quarks.
- Sakharov-Zeldovich formula:

\[
M = \sum_i m_i
\]

- the binding & kinetic energies “swallowed” by the constituent quarks masses.
Color Hyperfine (HF) interaction

- 1st correction – color hyperfine (chromo-magnetic) interaction

\[ M = \sum_i m_i + \sum_{i<j} V_{ij}^{HF} \]

\[ V_{ij}^{HF(QCD)} = v_0 \left( \vec{\lambda}_i \cdot \vec{\lambda}_j \right) \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} \langle \psi \left| \delta (r_i - r_j) \right| \psi \rangle \]

- A contact interaction
- Analogous to the EM hyperfine interaction – a product of the magnetic moments.

\[ V_{ij}^{HF(em)} \propto \vec{\mu}_i \cdot \vec{\mu}_j = e^2 \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} \]

- In QCD, SU(3) generators take the place of the electric charge.
Constituent Quark Model: *caveat emptor*

- a low energy limit, phenomenological model
- still awaiting derivation from QCD
- far from providing a full explanation of the hadronic spectrum, but it provides excellent predictions for mass splittings and magnetic moments

**assumptions:**
- HF interaction considered as a perturbation
  - does not change the wave function
- same masses for quarks inside mesons and baryons.
- no 3-body effects.
constituent quark masses

example I:
quark mass differences from baryon mass differences:

\[ M_\Lambda_c - M_\Lambda = \]
\[ = (m_u + m_d + m_c + V_{ud}^{HF} + V_{uc}^{HF} + V_{dc}^{HF}) - \]
\[ - (m_u + m_d + m_s + V_{ud}^{HF} + V_{us}^{HF} + V_{ds}^{HF}) = \]
\[ = m_c - m_s = 0 \]
constituent quark masses

• example II:

\[ M_{K^*} - M_K = v_0 \left( \frac{\vec{\lambda}_u \cdot \vec{\lambda}_s}{m_u m_s} \right) \left[ (\vec{\sigma}_u \cdot \vec{\sigma}_s)_{K^*} - (\vec{\sigma}_u \cdot \vec{\sigma}_s)_K \right] \langle \psi | \delta(r) | \psi \rangle \]

\[ = 4v_0 \left( \frac{\vec{\lambda}_u \cdot \vec{\lambda}_s}{m_u m_s} \right) \langle \psi | \delta(r) | \psi \rangle \]

• extracting quark masses ratio:

\[ \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = \frac{4v_0 \left( \frac{\vec{\lambda}_u \cdot \vec{\lambda}_s}{m_u m_s} \right) \langle \psi | \delta(r) | \psi \rangle}{4v_0 \left( \frac{\vec{\lambda}_u \cdot \vec{\lambda}_c}{m_u m_c} \right) \langle \psi | \delta(r) | \psi \rangle} \approx \frac{m_c}{m_s} \]
quark mass difference is the same in mesons and baryons

\[ \langle m_i - m_j \rangle_{dBar} \approx \langle m_i - m_j \rangle_{dMes} \]

but depends on the spectator quark

→ challenge to npQCD

MK & Lipkin, hep-ph/0307243

| observable    | baryons | mesons | \(\Delta m_{Bar}\) | \(\Delta m_{Mes}\) |
|---------------|---------|--------|-------------------|-------------------|
| \(\langle m_s - m_u \rangle_d\) | \(\Lambda\) | \(N\) | \(K^*\) | \(\rho\) | \(K\) | \(\pi\) | 177 | 179 |
| \(\langle m_s - m_u \rangle_c\) | \(c\bar{s}\) | \(c\bar{u}\) | \(c\bar{s}\) | \(c\bar{u}\) | \(D_s^*\) | \(D_s^*\) | \(D_s\) | \(D_s\) | 103 |
| \(\langle m_s - m_u \rangle_b\) | \(b\bar{s}\) | \(b\bar{u}\) | \(b\bar{s}\) | \(b\bar{u}\) | \(B_s^*\) | \(B_s^*\) | \(B_s\) | \(B_s\) | 91 |
| \(\langle m_c - m_u \rangle_d\) | \(\Lambda_c\) | \(N\) | \(D^*\) | \(\rho\) | \(D\) | \(\pi\) | 1346 | 1360 |
| \(\langle m_c - m_u \rangle_c\) | \(c\bar{c}\) | \(u\bar{c}\) | \(c\bar{c}\) | \(u\bar{c}\) | \(\psi\) | \(D_s^*\) | \(\eta_c\) | \(D\) | 1095 |
| \(\langle m_c - m_s \rangle_d\) | \(\Lambda_c\) | \(\Lambda\) | \(D^*\) | \(K^*\) | \(D\) | \(K\) | 1169 | 1180 |
| \(\langle m_c - m_s \rangle_c\) | \(c\bar{c}\) | \(s\bar{c}\) | \(c\bar{c}\) | \(s\bar{c}\) | \(\psi\) | \(D_s^*\) | \(\eta_c\) | \(D_s\) | 991 |
| \(\langle m_b - m_u \rangle_d\) | \(\Lambda_b\) | \(N\) | \(b\bar{d}\) | \(u\bar{d}\) | \(b\bar{d}\) | \(u\bar{d}\) | 4685 | 4700 |
| \(\langle m_b - m_u \rangle_s\) | \(b\bar{s}\) | \(u\bar{s}\) | \(b\bar{s}\) | \(u\bar{s}\) | \(B_s^*\) | \(K^*\) | \(B_s\) | \(K\) | 4613 |
| \(\langle m_b - m_s \rangle_d\) | \(\Lambda_b\) | \(\Lambda\) | \(b\bar{d}\) | \(s\bar{d}\) | \(b\bar{d}\) | \(s\bar{d}\) | 4508 | 4521 |
| \(\langle m_b - m_c \rangle_d\) | \(\Lambda_b\) | \(\Lambda_c\) | \(b\bar{d}\) | \(c\bar{d}\) | \(b\bar{d}\) | \(c\bar{d}\) | 3339 | 3341 |
| \(\langle m_b - m_c \rangle_s\) | \(b\bar{s}\) | \(c\bar{s}\) | \(b\bar{s}\) | \(c\bar{s}\) | \(B_s^*\) | \(D_s^*\) | \(B_s\) | \(D_s\) | 3328 |
color hyperfine splitting in baryons

• The $\Sigma$ (uds) baryon HF splitting:
  – $\Sigma^*$: total spin 3/2
    - u and d at relative spin – 1
  – $\Sigma$: isospin – 1
    • Symmetric under exchange of u and d
    • u and d at relative spin – 1

\[
(\vec{\sigma}_u \cdot \vec{\sigma}_d)_{\Sigma^*} = (\vec{\sigma}_u \cdot \vec{\sigma}_d)_{\Sigma}
\]

• the ‘ud’ pair does not contribute to the HF splitting

\[
M_{\Sigma^*} - M_\Sigma = 6v_0 \frac{(\vec{\lambda}_u \cdot \vec{\lambda}_d)}{m_u m_s} \langle \psi | \delta(r_{ij}) | \psi \rangle
\]
Quark mass ratio from HF splittings in mesons and baryons

\[
\left( \frac{m_c}{m_s} \right)_{\text{Bar}} = \frac{M_{\Sigma^*} - M_{\Sigma}}{M_{\Sigma^*_c} - M_{\Sigma_c}} = 2.84 = \left( \frac{m_c}{m_s} \right)_{\text{Mes}} = \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = 2.81
\]

\[
\left( \frac{m_c}{m_u} \right)_{\text{Bar}} = \frac{M_{\Delta} - M_p}{M_{\Sigma^*_c} - M_{\Sigma_c}} = 4.36 = \left( \frac{m_c}{m_u} \right)_{\text{Mes}} = \frac{M_{\rho} - M_{\pi}}{M_{D^*} - M_D} = 4.46
\]

New type of mass relations with more heavy flavors

\[
\left( \frac{1}{m_u^2} - \frac{1}{m_u m_c} \right)_{\text{Bar}} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_{\Sigma} - M_{\Lambda}} = 2.16 \approx \left( \frac{1}{m_u^2} - \frac{1}{m_u m_c} \right)_{\text{Mes}} = \frac{(M_{\rho} - M_{\pi}) - (M_{D^*} - M_D)}{(M_{\rho} - M_{\pi}) - (M_{K^*} - M_K)} = 2.10
\]
Similar relation for bottom baryons → prediction for $\Sigma_b$ mass

$$\frac{M_{\Sigma_b} - M_{\Lambda_b}}{M_{\Sigma} - M_{\Lambda}} = \frac{(M_\rho - M_\pi)}{(M_\rho - M_\pi) - (M_{B^*} - M_B)} = 2.51$$

$$M_{\Sigma_b} - M_{\Lambda_b} = 194\,\text{MeV}$$

(MK & Lipkin, hep-ph/0307243)
Observation of New Heavy Baryon $\Sigma_{b}^{(*)}$ and $\Sigma_{b}^{(*)}$

This web page summarizes the results of the search for new heavy baryons $\Sigma_{b}^{(*)}$ and $\Sigma_{b}^{(*)}$ based upon 1fb$^{-1}$ of data. The results have been approved as of September 21, 2006. The ratio of likelihoods of the null-hypothesis (no $\Sigma_{b}^{(*)}$ signal) and the hypothesis of four $\Sigma_{b}^{(*)}$ states is $2.6 \times 10^{-19}$. Using the fully reconstructed decay mode

$$\Sigma_{b}^{(*)} \rightarrow \Lambda_{b}^{0} \pi^{\pm} ; \quad \Lambda_{b}^{0} \rightarrow \Lambda_{c}^{+} \pi^{-} ; \quad \Lambda_{c}^{+} \rightarrow p K^{-} \pi^{+}$$

we measure:

- $m(\Sigma_{b}^{+}) = 5808^{+2.0}_{-2.3}$ (stat.) $\pm 1.7$ (syst.) MeV/c$^{2}$
- $m(\Sigma_{b}^{-}) = 5816^{+1.0}_{-1.0}$ (stat.) $\pm 1.7$ (syst.) MeV/c$^{2}$
- $m(\Sigma_{b}^{*-}) = 5829^{+1.6}_{-1.8}$ (stat.) $\pm 1.7$ (syst.) MeV/c$^{2}$
- $m(\Sigma_{b}^{*-}) = 5837^{+2.1}_{-1.9}$ (stat.) $\pm 1.7$ (syst.) MeV/c$^{2}$
CDF II Preliminary, $L = 1.1$ fb$^{-1}$  Fit Prob. = 76%

Candidates per 5 MeV/c$^2$

$$Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m_\pi \quad \text{(GeV/c}^2\text{)}$$
CDF obtained the masses of the $\Sigma_b^{-}$ and $\Sigma_b^{+}$ from the decay $\Sigma_b \rightarrow \Lambda_b + \pi$ by measuring the corresponding mass differences

$$M(\Sigma_b^{-}) - M(\Lambda_b) = 195.5^{+1.0}_{-1.0}\text{ (stat.)} \pm 0.1\text{ (syst.) MeV}$$

$$M(\Sigma_b^{+}) - M(\Lambda_b) = 188.0^{+2.0}_{-2.3}\text{ (stat.)} \pm 0.1\text{ (syst.) MeV}$$

with isospin-averaged mass difference $M(\Sigma_b) - M(\Lambda_b) = \boxed{192\text{ MeV}}$. 
can rederive without assuming $HF \sim 1/m_q$

a weaker assumption of same flavor dependence suffices

\[
\frac{V_{hyp}(q_i q_j)}{V_{hyp}(q_i \bar{q}_k)} = \frac{V_{hyp}(q_i \bar{q}_j)}{V_{hyp}(q_i q_k)}
\]

\[
\frac{M_{\Sigma_b} - M_{\Lambda_b}}{(M_\rho - M_\pi) - (M_{B^*} - M_B)} \approx \frac{M_{\Sigma_c} - M_{\Lambda_c}}{(M_\rho - M_\pi) - (M_{D^*} - M_D)} \approx \frac{M_\Sigma - M_\Lambda}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 0.32 \approx 0.33 \approx 0.325
\]

heavy Q spectroscopy  M. Karliner, BEACH 2008
also prediction for spin splitting between $\Sigma_b^*$ and $\Sigma_b$

\[
M(\Sigma_b^*) - M(\Sigma_b) = \frac{M(B^*) - M(B)}{M(K^*) - M(K)} \cdot [M(\Sigma^*) - M(\Sigma)] = 22 \text{ MeV}
\]

to be compared with 21 MeV from the isospin-average of CDF measurements

\[
M(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9} \text{ (stat.)} \pm 1.7 \text{ (syst.) MeV}
\]

\[
M(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8} \text{ (stat.)} \pm 1.7 \text{ (syst.) MeV}
\]
Effective meson-baryon supersymmetry

- meson: $Q \bar{q}$  baryon: $Qqq$
- in both cases: valence quark coupled to light quark “brown muck” color antitriplet, either a light antiquark ($S=1/2$) or a light diquark ($S=0, S=1$)

**Effective supersymmetry:**

$$T^S_{LS} |\mathcal{M}(\bar{q}Q_i)\rangle \equiv |\mathcal{B}([qq]_S Q_i)\rangle$$

- $m(\mathcal{B}) - m(\mathcal{M})$ independent of quark flavor (u,s,c,b)!
• need to first cancel the HF interaction contribution to meson masses:

$$\tilde{M}(V_i) \equiv \frac{3M_{V_i} + M_{P_i}}{4}$$

• for spin-zero diquarks:

$$M(N) - \tilde{M}(\rho) = M(\Lambda) - \tilde{M}(K^*) = M(\Lambda_c) - \tilde{M}(D^*) = M(\Lambda_b) - \tilde{M}(B^*)$$

$$323 \text{ MeV} \approx 321 \text{ MeV} \approx 312 \text{ MeV} \approx 310 \text{ MeV}$$

• for spin-one diquarks need to also cancel HF contribution to baryon masses:

$$\tilde{M}(\Sigma_i) \equiv \frac{2M_{\Sigma_i^*} + M_{\Sigma_i}}{3}; \quad \tilde{M}(\Delta) \equiv \frac{2M_\Delta + M_N}{3}$$

$$\tilde{M}(\Delta) - \tilde{M}(\rho) = \tilde{M}(\Sigma) - \tilde{M}(K^*) = \tilde{M}(\Sigma_c) - \tilde{M}(D^*) = \tilde{M}(\Sigma_b) - \tilde{M}(B^*)$$

$$517.56 \text{ MeV} \approx 526.43 \text{ MeV} \approx 523.95 \text{ MeV} \approx 512.45 \text{ MeV}$$
Magnetic moments of heavy baryons

• In $\Lambda$, $\Lambda_c$ and $\Lambda_b$ light q coupled to spin zero
• $\rightarrow$ mag. moments determined by s,c,b moments
• quark mag. moments proportional to their chromomagnetic moments

DGG: \[ \mu_\Lambda = -\frac{\mu_p}{3} \cdot \frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61 \text{ n.m.} \ (=\text{EXP}) \]

\[ \mu_{\Lambda_c} = -2\mu_\Lambda \cdot \frac{M_{\Sigma^*_c} - M_{\Sigma_c}}{M_{\Sigma^*} - M_\Sigma} = 0.43 \text{ n.m.} \]

\[ \mu_{\Lambda_b} = \mu_\Lambda \cdot \frac{M_{\Sigma^*_b} - M_{\Sigma_b}}{M_{\Sigma^*} - M_\Sigma} = -0.067 \text{ n.m.} \]
Testing confining potentials through meson/baryon HF splitting ratio

B. Keren-Zur, hep-ph/0703011 & Ann. Phys

• from constituent quarks model can derive:

\[
\frac{M_{K^*} - M_K}{M_{\Sigma^*} - M_\Sigma} = \frac{4}{3} \frac{\langle \psi | \delta(\vec{r}_u - \vec{r}_s) | \psi \rangle_{\text{meson}}}{\langle \psi | \delta(\vec{r}_u - \vec{r}_s) | \psi \rangle_{\text{baryon}}}
\]

• depends only on the confinement potential and quark mass ratio
• can be used to test different confinement potentials
Testing confining potentials through meson/baryon HF splitting ratio

- 3 measurements ($Q = s, c, b$)
- 5 potentials:
  - Harmonic oscillator
  - Coulomb interaction
  - Linear potential
  - Linear + Coulomb
  - Logarithmic
baryon/meson
HF splitting ratio

- K meson HF splitting
  \[ M_{K^*} - M_K = 4v_0 \left( \frac{\vec{\lambda}_u \cdot \vec{\lambda}_s}{m_u m_s} \right) \langle \psi | \delta(r_{us}) | \psi \rangle \]

- The \( \Sigma \) (uds) baryon HF splitting:
  \[ M_{\Sigma^*} - M_\Sigma = 6v_0 \left( \frac{\vec{\lambda}_u \cdot \vec{\lambda}_s}{m_u m_s} \right) \langle \psi | \delta(r_{us}) | \psi \rangle \]

- Using the relation:
  \( (\vec{\lambda}_u \cdot \vec{\lambda}_s)_{\text{meson}} = 2(\vec{\lambda}_u \cdot \vec{\lambda}_s)_{\text{baryon}} \)

\[
\frac{M_{K^*} - M_K}{M_{\Sigma^*} - M_\Sigma} = \frac{4}{3} \frac{\langle \psi | \delta(r_{us}) | \psi \rangle_{\text{meson}}}{\langle \psi | \delta(r_{us}) | \psi \rangle_{\text{baryon}}} 
\]
baryon/meson HF splitting ratio

\[ \frac{M_{K^*} - M_K}{M_{\Sigma^*} - M_{\Sigma}} = \frac{4 \langle \psi | \delta(r_{us}) | \psi \rangle_{\text{meson}}}{3 \langle \psi | \delta(r_{us}) | \psi \rangle_{\text{baryon}}} \]

- similar quark content, so can cancel out the HF coupling constant \((v_0)\).
- confinement potential coupling constant and quark mass scale also cancel out
- depends only on the shape of the potential and the ratio of the quark masses.
Hyperfine splitting ratio from potential models vs experiment

heavy Q spectroscopy

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hyperfine splitting ratio from potential models vs experiment

|                | $\Delta_K / \Delta_\Sigma$ | $\Delta_D / \Delta_{\Sigma_c}$ | $\Delta_B / \Delta_{\Sigma_b}$ |
|----------------|-----------------------------|---------------------------------|---------------------------------|
| $M_3/M_1$      | 1.33                        | 4.75                            | 14                              |
| EXP            | 2.08 ± 0.01                 | 2.18 ± 0.08                     | 2.15 ± 0.20                     |
| Harmonic       | 1.65                        | 1.62                            | 1.59                            |
| Coulomb        | 5.07 ± 0.08                 | 5.62 ± 0.02                     | 5.75 ± 0.01                     |
| Linear         | 1.88 ± 0.06                 | 1.88 ± 0.08                     | 1.86 ± 0.09                     |
| Cornell (K=0.28) | 2.10 ± 0.05             | 2.16 ± 0.07                     | 2.17 ± 0.08                     |
| Log            | 2.38 ± 0.02                 | 2.43 ± 0.02                     | 2.43 ± 0.01                     |
Predicting the mass of $\Xi_Q$ baryons

$\Xi_Q$: Qsd or Qsu. (sd), (sd) in spin-0

$\Xi_Q$ mass given by

$$\Xi_Q = m_q + m_s + m_u - \frac{3v \langle \delta(r_{us}) \rangle}{m_u m_s}$$

Can obtain (bsd) mass from (csd) + shift in HF:

$$\Xi_b = \Xi_c + (m_b - m_c) - \frac{3v}{m_u m_s} \left( \langle \delta(r_{us}) \rangle_{\Xi_b} - \langle \delta(r_{us}) \rangle_{\Xi_c} \right)$$
several options for obtaining $m_b - m_c$ from data:

$$m_b - m_c = \Lambda_b - \Lambda_c = 3333.2 \pm 1.2 \text{ MeV}$$

$$m_b - m_c = \left( \frac{2\Sigma_b^* + \Sigma_b + \Lambda_b}{4} - \frac{2\Sigma_c^* + \Sigma_c + \Lambda_c}{4} \right) = 3330.4 \pm 1.8 \text{ MeV}$$

- The $\Xi_Q^{(Qsq)}$ baryons contain an s quark
- Q mass differences depend on the spectator
- optimal estimate from mesons which contain both s and Q:

$$m_b - m_c = \left( \frac{3B_s^* + B_s}{4} - \frac{3D_s^* + D_s}{4} \right) = 3324.6 \pm 1.4 \text{ MeV}$$
Summary of $\Xi_b$ mass predictions

|                  | $\Lambda_b - \Lambda_c$ | $\Sigma_b - \Sigma_c$ | $B_s - D_s$ |
|------------------|--------------------------|------------------------|-------------|
| No HF correction | 5803 ± 2                 | 5800 ± 2               | 5794 ± 2    |
| Linear           | 5801 ± 11                | 5798 ± 11              | 5792 ± 11   |
| Coulomb          | 5778 ± 2                 | 5776 ± 2               | 5770 ± 2    |
| Cornell          | 5799 ± 7                 | 5796 ± 7               | 5790 ± 7    |
Predictions for masses of $\Xi_b$ baryons

Marek Karliner$^a$, Boaz Keren-Zur$^a$, Harry J. Lipkin$^{a,b,c}$, and Jonathan L. Rosner$^d$

$^a$ School of Physics and Astronomy
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, Tel Aviv 69978, Israel

$^b$ Department of Particle Physics
Weizmann Institute of Science, Rehovoth 76100, Israel

$^c$ High Energy Physics Division, Argonne National Laboratory
Argonne, IL 60439-4815, USA

$^d$ Enrico Fermi Institute and Department of Physics
University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637, USA

ABSTRACT

The recent observation by CDF of $\Sigma_b^\pm$ ($uud$ and $ddb$) baryons within 2 MeV of the predicted $\Sigma_b - \Lambda_b$ splitting has provided strong confirmation for the theoretical approach based on modeling the color hyperfine interaction. We now apply this approach to predict the masses of the $\Xi_b$ family of baryons with quark content $usb$ and $dsb$ – the ground state $\Xi_b$ at 5790 to 5800 MeV, and the excited states $\Xi_b'$ and $\Xi_b^{*}$. The main source of uncertainty is the method used to estimate the mass difference $m_b - m_c$ from known hadrons. We verify that corrections due to the details of the interquark potential and to $\Xi_b - \Xi_b'$ mixing are small.
$\Xi_b$ Mass Comparison

- **D0**
- **CDF**

Theoretical prediction:
- Jenkins
  - PRD54,4515
- Karliner et al
  - hep-ph/0706.2163
\[ \Xi_b^*, \Xi'_b \text{ mass prediction} \]

\[ \Xi'_b : \text{bsd with (sd) in } S=1; \text{ total spin } = 1/2 \]

\[ \Xi^*_b : \text{bsd with (sd) in } S=1; \text{ total spin } = 3/2 \]

spin-averaged mass of these two states

\[ \frac{2\Xi^*_q + \Xi'_q}{3} = m_q + m_s + m_u + \frac{v \langle \delta(r_{us}) \rangle}{m_um_s} \]

so that

\[ \frac{2\Xi^*_b + \Xi'_b}{3} = \frac{2\Xi^*_c + \Xi'_c}{3} + (m_b - m_c) + \frac{2\Xi^*_c + \Xi'_c - 3\Xi_c}{12} \left( \frac{\langle \delta(r_{us}) \rangle_{\Xi_b}}{\langle \delta(r_{us}) \rangle_{\Xi_c}} - 1 \right) \]
### $\Xi^*_b$, $\Xi'_b$ mass prediction

\[
\frac{(2\Xi^*_b + \Xi'_b)}{3}
\]

| $m_b - m_c$ | $\Lambda_b - \Lambda_c$ | $\Sigma_b - \Sigma_c$ | $B_s - D_s$ |
|-------------|--------------------------|------------------------|-------------|
| No HF correction | 5956 ± 3 | 5954 ± 3 | 5948 ± 3 |
| Linear | 5957 ± 4 | 5954 ± 4 | 5948 ± 4 |
| Coulomb | 5965 ± 3 | 5962 ± 3 | 5956 ± 3 |
| Cornell | 5958 ± 3 | 5955 ± 3 | 5949 ± 3 |

The difference between the spin averaged mass $\frac{(2\Xi^*_b + \Xi'_b)}{3}$ and $\Xi_b$ is roughly $150 - 160$ MeV.

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\[ \Xi_b^*, \Xi_b' \text{ mass prediction} \]

- \( \Xi_b^* - \Xi_b' \): mass difference more difficult to predict

- small due to the large \( m_b \): 
\[
\Xi_q^* - \Xi_q' = 3\nu \left( \frac{\langle \delta(r_{qs}) \rangle}{m_q m_s} + \frac{\langle \delta(r_{qu}) \rangle}{m_q m_u} \right)
\]

| Method          | Result        |
|-----------------|---------------|
| No HF correction| 24 ± 2        |
| Linear          | 28 ± 6        |
| Coulomb         | 36 ± 7        |
| Cornell         | 29 ± 6        |

\[
\frac{m_s}{m_u} = 1.5 \pm 0.1, \quad \frac{m_b}{m_c} = 2.95 \pm 0.2.
\]
Predictions for other bottom baryons

with B.Keren-Zur, H.J. Lipkin and J.L. Rosner

$\Omega_b$ mass prediction

$$\frac{2\Omega_b^* + \Omega_b}{3} = \frac{2\Omega_c^* + \Omega_c}{3} + (m_b - m_c)$$

$$= \frac{2\Omega_c^* + \Omega_c}{3} + \frac{3B_s^* + B_s}{4} - \frac{3D_s^* + D_s}{4}$$

$$= 6068.6 \pm 2.6 \text{ MeV}$$

wavefunction correction $\approx +2$ MeV.

HF splitting: $m_b/m_c$ taken to be $3.0 \pm 0.5$.

$$\Omega_b^* - \Omega_b = (\Omega_c^* - \Omega_c) \frac{m_c}{m_b} = 23.6 \pm 4.0 \text{ MeV}$$
$\Omega_b$ mass prediction

This gives the following mass predictions:

$$\Omega_b^* = 6076.5 \pm 2.9 \text{ MeV}; \quad \Omega_b = 6052.9 \pm 3.7 \text{ MeV}$$

Wavefunction corrections give a factor of 1.28, and a splitting of $30 \pm 6 \text{ MeV}$.

Work in progress:

- $\Xi_b$ isospin splitting
- $\Lambda_b$ and $\Xi_b$ orbital excitations
- $\Xi_{bc}$ ($b$cu)
- $\Xi_{cc}$ ($c$cu)

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Table 10: Comparison of predictions for $b$ baryons with those of some other recent approaches [6, 10, 11] and with experiment. Masses quoted are isospin averages unless otherwise noted. Our predictions are those based on the Cornell potential.

| Quantity | Refs. [6] | Ref. [10] | Ref. [11] | This work | Experiment |
|----------|-----------|-----------|-----------|-----------|------------|
| $M(\Lambda_b)$ | 5622 | 5612 | Input | Input | 5619.7±1.7 |
| $M(\Sigma_b)$ | 5805 | 5833 | Input | – | 5811.5±2 |
| $M(\Sigma_b^*)$ | 5834 | 5858 | Input | – | 5832.7±2 |
| $M(\Sigma_b^*) - M(\Sigma_b)$ | 29 | 25 | Input | 20.0±0.3 | $21.2^{+2.2}_{-2.1}$ |
| $M(\Xi_b)$ | 5812 | 5806$^a$ | Input | 5790–5800 | 5792.9±3.0$^b$ |
| $M(\Xi_b^*)$ | 5937 | 5970$^a$ | 5929.7±4.4 | 5930±5 | – |
| $\Delta M(\Xi_b^*)^c$ | – | – | – | 6.4±1.6 | – |
| $M(\Xi_b^*)$ | 5963 | 5980$^a$ | 5950.3±4.2 | 5959±4 | – |
| $M(\Xi_b^*) - M(\Xi_b)$ | 26 | 10$^a$ | 20.6±1.9 | 29±6 | – |
| $M(\Omega_b)$ | 6065 | 6081 | 6039.1±8.3 | 6052.1±5.6 | – |
| $M(\Omega_b^*)$ | 6088 | 6102 | 6058.9±8.1 | 6082.8±5.6 | – |
| $M(\Omega_b^*) - M(\Omega_b)$ | 23 | 21 | 19.8±3.1 | 30.7±1.3 | – |
| $M(\Lambda_{b[1/2]}^*)$ | 5930 | 5939 | – | 5929 ± 2 | – |
| $M(\Lambda_{b[3/2]}^*)$ | 5947 | 5941 | – | 5940 ± 2 | – |
| $M(\Xi_{b[1/2]}^*)$ | 6119 | 6090 | – | 6106 ± 4 | – |
| $M(\Xi_{b[3/2]}^*)$ | 6130 | 6093 | – | 6115 ± 4 | – |

$^a$Value with configuration mixing taken into account; slightly higher without mixing.

$^b$CDF [13] value of $M(\Xi_b^-)$.

$^c$M(state with $d$ quark) – M(state with $u$ quark).
Recent data from Belle: anomalously large (2 orders of mag.)

\[ \Upsilon(5S) \to \Upsilon(1S) \pi^+ \pi^- \]

\[ \Upsilon(5S) \to \Upsilon(2S) \pi^+ \pi^- \]

0802.0649 [hep-ph], Lipkin & M.K.: might be mediated by \( \bar{b}b u \bar{d}d \) tetraquark below \( B \bar{B} \) threshold:

\[ \Upsilon(mS) \to T_{bb}^{\pm} \pi^\mp \to \Upsilon(nS) \pi^+ \pi^- \]

analogous to \( Z(4430) \)? Seen in \( \psi' \pi^\pm \) but not in \( J/\psi \pi^\pm \)

heavy Q spectroscopy M. Karliner, BEACH 2008
heavy Q spectroscopy

M. Karliner, BEACH 2008

“Υ(5S)” → Υ(1S) π⁺π⁻, Υ(2S) π⁺π⁻

Expect to vanish

“Υ(5S)” : single E_CM at 10.87 GeV
Not clear whether Υ(5S) itself.

Striking!

Expect O(1) events

Hot Belle

George W.S. Hou (NTU)

FPCP08, 5/5/08 20
• E and p conservation in $Y(5S) \rightarrow Y(mS)\pi\pi$: plot of $M_{inv}[Y(mS)\pi]^2$ vs. $E_{\pi}$ linear modulo $Y(5S)$, $Y(mS)$ width

• Look for peaks in $M_{inv}$ of $Y(mS)\pi$

• Isospin: $Y(mS)\pi^+ \text{ vs. } \pi^- = Y(mS)\pi^- \text{ vs. } \pi^+$ modulo statistics
Dalitz Plot: $Z^\pm(4430)$ Echoes?\

Karliner & Lipkin, arXiv:0802.0649 [hep-ph]\

S.-K. Choi, S.L. Olsen et al., PRL ’08

Lighter than $2m_B$?\
fundamental force\n
$\Upsilon(1S)\pi^+\pi^-$\

$\Upsilon(2S)\pi^+\pi^-$\

Nondescript\

Too Early to Tell!\

Need more Data.

Hot Belle  George W.S. Hou (NTU)  FPCP08, 5/5/08  24

heavy Q spectroscopy  M. Karliner, BEACH 2008
Open questions

- need to understand the XYZ states in the charm sector and their counterparts in the bottom sector
- replacing charmed quark by bottom quark makes the binding stronger
- excellent challenge for EXP and TH
- general question of exotics in QCD
- $ccu$, $ccd$ and $bbu$, $bbd$: SELEX ccq data - isospin breaking much too large?
Summary

• Constituent quark model with color HF interaction gives highly accurate predictions for heavy baryon masses

• A challenge for theory: derivation from QCD

• Constituent quark masses depend on the spectator quarks

\[ M_{\Sigma_b} - M_{\Lambda_b} = 194 \text{ MeV} \text{ vs } 192 \text{ in EXP (CDF)} \]

\[ M(\Sigma_b^*) - M(\Sigma_b) = 22 \text{ MeV} \text{ vs } 21 \text{ MeV in EXP (CDF)} \]

\[ \mu_{\Lambda_c} = 0.43 \text{ n.m.} \quad \mu_{\Lambda_b} = -0.067 \text{ n.m.} \]

• Meson-baryon effective supersymmetry

• Meson/baryon HF splitting confirms Cornell potential

\[ \Xi_b \text{ mass prediction: } 5795 \pm 5 \text{ MeV vs } 5793 \pm 2.4 \pm 1.7 \text{ MeV} \]

• Puzzle in \( Y(5S) \) decays: \( \bar{b}budd \) candidates?