Spectroscopy of Singly-Heavy* Hadrons

John Yelton
University of Florida
yelton@ufl.edu

*Charm and bottom are heavy, strange is strange – sometimes it is heavy and sometimes it is light

I will comment on the general patterns we see in the experimental results for heavy hadrons, and highlight some interesting recent results.
e\(^{+}\)e\(^{-}\) machines
Clean signals
Comparatively low yields

Hadron machines
HUGE yields

LHCb is the only experiment dedicated to heavy flavors at LHC:

Belle II now taking data (Belle still analyzing, previously BaBar and CLEO)

CMS and ATLAS take even more data...
(previous experiments D0 and CDF)

BES III – many results on charm decays, but fewer on spectroscopy
The Quark Model dates from 1960

Gell-Mann taught us how to construct baryons and mesons, and predicted the $\Omega$ particle

He also showed the difference between the $\Lambda$ and a $\Sigma$

In his day $H$ is strange
$L$ is up/down

Murray Gell-Mann, Sept 1929-May 2019

Heavy Meson

Heavy Baryon

$\Lambda$
Meson/Baryon Comparison for 3 Generations

1. Extra Mass for Baryon is independent of generations
2. Hyperfine splitting inversely proportional to mass of heavy quark (ratios 9:3:1)
3. Hyperfine splitting for baryons 45% of that for mesons
4. Splitting between $\Lambda$ and $\Sigma$ system is independent of generations

$$\Delta_{\text{baryon}}^{hf} / \Delta_{\text{meson}}^{hf} = 0.484$$
$$\Delta_{\text{baryon}}^{hf} / \Delta_{\text{meson}}^{hf} = 0.458$$
$$\Delta_{\text{baryon}}^{hf} / \Delta_{\text{meson}}^{hf} = 0.457$$
Repeat with the addition of one or two $s$ quarks

1. Extra Mass for Baryon is independent of generations
2. Hyperfine splitting inversely proportional to mass of heavy quark (ratios 9:3:1)
3. Hyperfine splitting for baryons 45% of that for mesons
3. Splitting between $\Xi_c$ and Excited $\Xi_c$ and $\Omega$ independent of generations

\[
\begin{align*}
\Omega_b & \text{ not seen} \\
\Omega & \\
\Xi_c & \\
\Xi_b & \\
D_s & \\
D_s^* & 2073 \\
B_s & \\
B_s^* & 5403 \\
\end{align*}
\]

\[
\begin{align*}
\frac{cs}{csq} & = 0.479 \\
\frac{bs}{bsq} & = 0.423
\end{align*}
\]
Repeat with the addition of one or two s quarks

1. Extra Mass for Baryon is independent of generations
2. Hyperfine splitting inversely proportional to mass of heavy quark (ratios 9:3:1)
3. Hyperfine splitting for baryons 45% of that for mesons

\[
\frac{\Delta_{baryon}^{hf}}{\Delta_{meson}^{hf}} = 0.479
\]

\[
\frac{\Delta_{baryon}^{hf}}{\Delta_{meson}^{hf}} = 0.423
\]
The history of measurements of the mass and lifetime of the $\Omega_c^{(css)}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Lifetime (10^{-13} s)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA 62 (1985)</td>
<td>$2748 \pm 10$</td>
<td></td>
<td>3 events and wrong mass. Ignore</td>
</tr>
<tr>
<td>ARGUS (1992)</td>
<td>$2719 \pm 7 \pm 2.5$</td>
<td></td>
<td>Wrong cross-section (by a factor of 50) Ignore</td>
</tr>
<tr>
<td>E-687 (1993)</td>
<td>$2705.9 \pm 3.3 \pm 2.0$</td>
<td></td>
<td>10 events</td>
</tr>
<tr>
<td>E-687 (1994)</td>
<td>$2699 \pm 1.5 \pm 2.5$</td>
<td>$0.86 \pm 0.24 \pm 0.28$</td>
<td>The decay mode ($\Sigma^+ K^- K^- \pi^+$) has not been seen by others! Ignore</td>
</tr>
<tr>
<td>CLEO II</td>
<td>$2694.6 \pm 2.6 \pm 1.9$</td>
<td></td>
<td>Sum of 5 channels</td>
</tr>
<tr>
<td>WA-89 (1995)</td>
<td>$2707.5 \pm 3.9$</td>
<td>$0.55 \pm 0.12 \pm 0.21$</td>
<td>Masses in different modes did not agree and are wrong! Ignore</td>
</tr>
<tr>
<td></td>
<td>$2720.0 \pm 3.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2719.8 \pm 4.7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOCUS (2003)</td>
<td>$2697.5 \pm 2.2$</td>
<td>$0.72 \pm 0.11 \pm 0.11$</td>
<td>$59 \pm 12$ events</td>
</tr>
<tr>
<td>BELLE (2009)</td>
<td>$2693.6 \pm 0.3 \pm 1.6$</td>
<td></td>
<td>725 events</td>
</tr>
<tr>
<td>LHCb</td>
<td>$2.68 \pm 0.24 \pm 0.10$</td>
<td>$978 \pm 60$ events (mode pKK\pi)</td>
<td></td>
</tr>
</tbody>
</table>

The moral is: if you want to measure a particle’s lifetime, first make sure you are seeing the particle.

<table>
<thead>
<tr>
<th></th>
<th>$\Xi_c^0$</th>
<th>$\Xi_c^+$</th>
<th>$\Lambda_c^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$1.545 \pm 0.017 \pm 0.016 \pm 0.010$</td>
<td>$4.568 \pm 0.035 \pm 0.029 \pm 0.031$</td>
<td>$2.035 \pm 0.010 \pm 0.013 \pm 0.014$</td>
</tr>
<tr>
<td>PDG</td>
<td>$1.12 \pm 0.12$</td>
<td>$4.42 \pm 0.26$</td>
<td>$2.00 \pm 0.06$</td>
</tr>
</tbody>
</table>
Repeat with the addition of one or two s quarks

1. Extra Mass for Baryon is independent of generations
2. Hyperfine splitting inversely proportional to mass of heavy quark (ratios 9:3:1)
3. Hyperfine splitting for baryons 45% of that for mesons
$\Xi_b^0 \pi^- \text{ shows 2 peaks, corresponding to } J^P=1/2^+ \text{ and } J^P=3/2^+$

$\Xi_b^- \pi^+ \text{ shows only one peak, presumably the other is below strong-decay threshold, and remains to be discovered}$
Repeat with the addition of one or two s quarks

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\[
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\frac{\Delta_{\text{baryon}}^{hf}}{\Delta_{\text{meson}}^{hf}} = 0.423
\]

bcc baryon
Using masses of $D_s, D_s^*, B_s, B_s^*, \Omega_c, \Omega_c^*$, we can predict the mass of the $\Omega_b$ to be 6050 MeV

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0 (2008)</td>
<td>$6165 \pm 10 \pm 13$</td>
<td>Claimed to be $&gt; 5\sigma$</td>
</tr>
<tr>
<td>CDF (2009)</td>
<td>$6054.4 \pm 6.9 \pm 0.9$</td>
<td></td>
</tr>
<tr>
<td>LHCb (2013)</td>
<td>$6046.0 \pm 2.2 \pm 0.5$</td>
<td></td>
</tr>
<tr>
<td>CDF (2014)</td>
<td>$6047.5 \pm 3.8 \pm 0.6$</td>
<td>(replaces earlier analysis)</td>
</tr>
<tr>
<td>LHCb (2016)</td>
<td>$6045.1 \pm 3.2 \pm 0.8$</td>
<td></td>
</tr>
</tbody>
</table>

$\Omega_b^*$ not yet seen (low energy photon transition), predicted mass 6070 MeV
In p-wave heavy baryons (i.e. 1 unit of orbital angular momentum), the orbital angular momentum can be in two different places - either between the heavy quark and light di-quark (\(\lambda\)-modes, low mass excitation) or between the two lighter quarks (\(\rho\)-mode, higher mass excitation).

The di-quark itself can be spin-0, or spin-1 (the latter being the only one possible when both quarks are the same flavor). This leads to many different states.

For the \(\Lambda_{c/b}(\text{hud})\) and \(\Xi_{c/b}(\text{hsd and hsu})\) this leads to two “low” mass orbital excitations (\(J^P=1/2^-\) and \(3/2^-\)).

HQET tells us that in decays, the rule of transitions between different \(J^P\) states, must be obeyed both for the entire state, and separately for the “light” degrees of freedom. The heavy quark just sits there and cannot move. This makes many narrow states

\[\Xi_c^+\] is an example
Add a $\lambda$ excitation to a $\Lambda$

If the $\Lambda(1405)$ had not been known, a particle close to that mass would have been predicted
For the $\Omega_c$(css) the model leads to five ($J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$)

5 narrow states are expected, with masses around 3000 MeV and mass splittings of around 30 MeV

Rips the ss diquark apart – makes it narrow?

No consensus as to which state is which, or if they are all orbital excitations.

When identifying the states, we should remember that not just the mass and width, but the relative yields might be important. (e.g. the 3119 could be $3/2^-$)

R. Aaij et al PRL 118, 182001 (2017) LHCb
An aside – there is another particle with an ss diquark, the $\Xi$

Looking at the substructure of the $\Xi_c^+ \rightarrow \Xi \pi^+ \pi^+$ we can look for excited $\Xi^0$ resonances.

Fit includes:
- $\Xi^0(1530)$
- $\Xi^0(1620)$
- $\Xi^0(1690)$

(Belle data 50,000 signal plus 11,500 background within signal band)

<table>
<thead>
<tr>
<th>$\Xi$ States mass</th>
<th>Main Decay</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1620</td>
<td>$\Xi \pi$</td>
<td>60 MeV</td>
</tr>
<tr>
<td>1690</td>
<td>$\Lambda/\Sigma$</td>
<td>narrow</td>
</tr>
<tr>
<td>1820</td>
<td>$\Lambda/\Sigma$</td>
<td>24 MeV</td>
</tr>
<tr>
<td>1950</td>
<td>$\Lambda/\Sigma$</td>
<td>60 MeV</td>
</tr>
<tr>
<td>2030</td>
<td>$\Lambda/\Sigma$</td>
<td>20 MeV</td>
</tr>
</tbody>
</table>

Note that the quark-diquark model predicts 5 $L=1$ states, 2 of which have $J^P=1/2^-$, only one of which decays easily to $\Xi \pi$.

M. Sumihama et al, PRL 122, 072501 (2019)
Will now review latest news for the excited states of the following systems:

$\Lambda_c^+ (cud)$  $\Xi_c^{+/0} (csu, csd)$  $\Lambda_b(cud)/\Sigma_b(bud, buu, bdd)$  $\Xi_b^{+/0} (bsu, bsd)$  $\Omega_b (bss)$

**News about the excited $\Lambda_c$ system:**

2765 state clearly exists.

Not seen in $\Sigma_c^{++/0}\pi^0$

It is a $\Lambda_c$

Copious production!

Potential models suggest 2S state ??
In similar mass range, LHCb look use an amplitude analysis of $\Lambda_b \rightarrow D^0 p \pi^-$

$$\Lambda_c(2860)^+ \quad \Lambda_c(2880)^+ \quad \Lambda_c(2940)^+$$

**New resonance:** $\Lambda_c(2860)^+$, $J^P = 3/2^+$

$$M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5 \text{(syst)}^{+1.1}_{-5.6} \text{(model)} \text{ MeV}$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4 \text{(syst)}^{+5.9}_{-20.0} \text{(model)} \text{ MeV}$$

Confirms $\Lambda_c(2880)^+$ has $J^P = 5/2^+$

Implies $\Lambda_c(2940)^+$ has $J^P = 3/2^-$

(mass is very close to $pD^*$ threshold, seems a little low for a 2P state)

**Question:**
Why is the $\Lambda_c(2880)$ so narrow? Why doesn’t $\Sigma^*\pi$ via $p$-wave dominate?

*JHEP, 1705 030 (2017), LHCb*
News on the excited $\Xi_c$ system:

Observation of the $\Xi_c(2930)^0$ and Evidence of the $\Xi_c(2930)^+$

Most charmed baryons analyses performed by Belle have been using continuum production, e.g. Belle have made measurements of the masses and widths of the: $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2970)$, $\Xi_c(3055)$ and $\Xi_c(3080)$ iso-doublets.

In 2008, BaBar reported a peak in the $\Lambda_c^+K^-$ mass projection of $\Lambda_c^-\Lambda_c^+K^-$ from B decays, but this remained only a “one-star” resonance PDG with no new analyses until now.

Recently Belle has performed searches for both the $\Xi_c(2930)^0$ and $\Xi_c(2930)^+$ in the resonant substructure of B decays using largest sample of BB pairs in the world: $(772\pm11) \times 10^6$

$M(\Xi_c(2930)^0) = 2928.9 \pm 3.0 ^{+0.9}_{-12.0} \text{ MeV}/c^2 \quad 5.1 \sigma$
$\Gamma = 19.5 \pm 8.4 ^{+5.9}_{-7.9} \text{ MeV} \quad \text{Y.B. Li et al, EPJ C78, 252 (2018)}$

$M(\Xi_c(2930)^+) = 2942.3 \pm 4.4 \pm 1.6 \text{ MeV}/c^2 \quad 3.9 \sigma$
$\Gamma = 14.8 \pm 8.8 \pm 2.5 \text{ MeV} \quad \text{Y.B. Li et al, EPJ C78, 928 (2018)}$
<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass/Width (positive state)</th>
<th>Mass/Width (neutral state)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ξ_c/</td>
<td>2578.57 ± 0.5 -</td>
<td>2679.2 ± 0.5 -</td>
<td>1/2+</td>
</tr>
<tr>
<td>Ξ_c (2645)</td>
<td>2645.57 ± 0.26 2.14 ± 0.19</td>
<td>2645.57 ± 0.21 2.35 ± 0.22</td>
<td>3/2+</td>
</tr>
<tr>
<td>Ξ_c (2790)</td>
<td>2792.4 ± 0.5 8.9 ± 0.6 ± 0.8</td>
<td>2794.1 ± 0.5 10.0 ± 0.7 ± 0.8</td>
<td>1/2-</td>
</tr>
<tr>
<td>Ξ_c (2815)</td>
<td>2816.73 ± 0.21 2.43 ± 0.20 ± 0.17</td>
<td>2820.36 ± 0.27 2.54 ± 0.18 ± 0.17</td>
<td>3/2-</td>
</tr>
<tr>
<td>Ξ_c (2930)</td>
<td>2942.3 ± 4.4 ± 1.5 14.8 ± 8.8 ± 2.5</td>
<td>2929.7+2.8-5.0 26 ± 8</td>
<td>?? Only observed in B decays</td>
</tr>
<tr>
<td>Ξ_c (2970)</td>
<td>2967.8 +0.9 -0.7 20.9 +2.5 -3.5</td>
<td>2969.4 ± 0.8 28.1+3.4-4.0</td>
<td>1/2+ ??? Radial excitation?</td>
</tr>
<tr>
<td>Ξ_c (3055)</td>
<td>3055.9 ± 0.4 7.8 ± 1.2 ± 1.5</td>
<td>3059.0 ± 0.5 ± 0.6 6.4 ± 2.1 ± 1.1</td>
<td>3/2+ ??</td>
</tr>
<tr>
<td>Ξ_c (3080)</td>
<td>3077.2 ± 0.4 3.6 ± 1.1</td>
<td>3079.9 ± 1.4 5.6 ± 2.2</td>
<td>5/2+ ??</td>
</tr>
<tr>
<td>Ξ_c (3123)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Also absolute b.f. now measured:

\[ B(Ξ_c^+→Ξ^-π^+π^+) = (2.86 ± 1.2)\% \]
\[ B(Ξ_c^0→Ξ^-π^+) = (1.80 ± 0.5)\% \]

Y. Li et al, PRL 122, 082001(2019) and arXiv:1904.12093 (Belle)
LHCb look at dipion decays into $\Lambda_b$ to look for excited $\Lambda_b$

$\Lambda_b^* \rightarrow \Lambda_b \pi^+\pi^-$

$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  
LHCb preliminary

$\Lambda_b^0 \rightarrow J/\psi pK^-$

$\Lambda_b^*$ decay candidates

$\Sigma_b$ region
LHCb preliminary

$\Sigma^*_b$ region

NR region

$M(\Lambda_b(6152)^0) = 6152.51 \pm 0.26 \text{ MeV/c}^2$

$M(\Lambda_b(6146)^0) = 6146.17 \pm 0.33 \text{ MeV/c}^2$

$\Gamma(\Lambda_b(6152)^0) = 2.11 \pm 0.81 \text{ MeV/c}^2$

$\Gamma(\Lambda_b(6146)^0) = 2.90 \pm 1.28 \text{ MeV/c}^2$

Submitted to PRL, arXiv:1907.13598
Note that the new states cannot decay into pB so are narrower than the analogous charm states.
News on excited \( \Sigma_b \) (bud/buu/bdd)

In addition to the \( \Sigma_b^{+/-} \) and \( \Sigma_b^{*+/-} \) (confirming CDF result) and there is another state at a higher mass.

In addition, one clear higher mass, wider peak. This is in the region where we expect orbital excitations. Maybe more than one particle? Maybe others are too wide? It feels similar to the \( \Sigma_c(2800) \)
LHCb

A new excited $\Xi_b$

M = 6226.9 $\pm$ 2.1 MeV/c$^2$

PRL 121 072002 (2018) LHCb

What is it? Maybe a radial excitation?
Heavy (charm and bottom) Mesons

HQET expects 4 $L=1$ states. $D_0$, $D_1(j_{\text{light}}=1/2)$, $D_1(j_{\text{light}}=3/2)$, $D_2$

Two of these are expected to be very wide, because they can decay s-wave with

- Very wide $D_0$ (used to be the $D^{*}_0(2400)$, now the $D^{*}_0(2300)$)
- Very wide $D_1$ (charged state not yet found)
- Very wide $D_2$
- Well-defined $D_1$, $j_{\text{light}}=1/2^+$
- Narrow state reported only by Delphi. Wrong!
- Wide state with contradictory masses
- Wide state at 2550, radial excitation?
- Spin weighted average of ground state set to zero

D(3000) now measured to have $M = 3214 \pm 29 \pm 49$ with a comprehensive analysis by LHCb, Phys. Rev. D94, 072001
$D_s$ produced a major surprise in 2003

Two low mass (and thus narrow) states. Their masses and mass difference might indicate $DK$ and $D^*K$ molecular states rather than conventional $D^{*0}$ and $D_{s1}$.

- Seen by 3 experiments, $J^P = 1^-$ radial excitation?
- Well-understood $L=1$ orbital excitations.
- 2 states on top of each other, one is $J^P = 1^-$, one is $J^P = 3^-$
- Seen by BaBar – needs confirmation.

Spin weighted average of ground state set to zero.
26

“narrow states” as expected
1 wide state, with no recent measurements
Very wide, needs confirmation
2 charged states agree, 2 experiments
2 “narrow states” as expected
1 wide state, with no recent measurements
Spin weighted average of ground state set to zero
$B_s$ Spectrum

- $B_{s2}^* (5840)$
- $B_{s1} (5830)$

Also seen by CDF, D0 and LHCb

A. Sirunyam, EPJ C78 939 (2018) CMS

Mass (MeV/c$^2$)

- 1200
- 1000
- 800
- 600
- 400
- 200
- 0
- -200

- $D$
- $D_s$
- $B$
- $B_s$

$m_{B^* K}$ [GeV]
B_{c} Spectroscopy “The Last Meson”

Mass = 6274.9 ± 0.8 MeV 4 separate LHCb measurements as well as CDF and D0
Lifetime = (5.10 ± 0.09) x 10^{-13} s (LHCb and CMS)

What about excited states? The B_{c}(2S) → B_{c}ππ would be expected to be narrow. Claim by ATLAS at 6842 ± 4 ± 5 MeV
Thought to be $B_c(2S) \rightarrow B_c \pi^+ \pi^-$

Thought to be $B_c^*(2S) \rightarrow B_c^* \pi^+ \pi^- \rightarrow B_c \gamma \pi^+ \pi^-$

LHCb Experiment

$M(B_s(2S)) = 6871.0 \pm 1.2 \pm 0.8 \pm 0.8 \text{ MeV} / c^2$
$29 \pm 1.5 \pm 0.7 \text{ MeV} / c^2$ CMS

$M(B_s(2S)) = 6871.1 \pm 1.3 \pm 0.1 \pm 0.8 \text{ MeV} / c^2$
$31.0 \pm 1.4 \pm 0.0 \text{ MeV} / c^2$ LHCb

LHCb second signal is weak (3.9σ)
CONCLUSIONS

1. Many new results in the Heavy Hadron systems, particularly in baryons

2. Many more results will appear soon.

3. The heavy hadrons tend to be narrower, better defined and easier to interpret than lighter hadrons. However, there are many mysteries to be investigated.

4. If we want to understand hadrons, we need to look at them all – heavy and light – and look at all their properties (mass, width, decay channels, production mechanism).
EXTRA SLIDES
A simultaneous fit yields a peak of $8.3 \, \sigma$ statistical significance. Narrow-resonance data only!

Final result:

$$M = 2012.4 \pm 0.7 \pm 0.6 \text{ MeV}/c^2$$

$$\Gamma = 6.4^{+2.5}_{-2.0} \pm 1.6 \text{ MeV}$$

Significance of signal, including systematics $> 7 \, \sigma$

J. Yelton et al, PRL 121, 052003 (2018)

First guess is that this is a $3/2^-$ orbital excitation, however there are models that propose a $\Xi(1530)K$ “molecular” state description. Such a state would likely also decay to $\Xi(1530)K$ (despite the lack of phase space).

No sign of it decaying to $\Xi(1530)\pi$

S. Jia et al, arXiv:1906:00194 (Belle)