Masses, Lifetimes and Mixing of B and D Hadrons

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Moriond QCD, 18 March, 2007
The heavy-light quark bound system: an ideal testing ground for quark models:

- light-quark component becomes independent of $m_Q$ as $m_Q \rightarrow \infty$: flavour symmetry
- heavy/light quark angular momentum degrees of freedom become good quantum numbers: spin symmetry

Mass spectrum predictions from HQET:

$$m_H = m_Q + \Lambda + \frac{-\lambda_1 + d_J \lambda_2}{2m_Q},$$

$L = 0$ mesons: $d_{J=0} = -3, d_{J=1} = 1$

with “binding energy” $\Lambda$ and parameters $\lambda_1, \lambda_2$ following from models, lattice QCD, etc. (different for ground state, orbital excitations, mesons ↔ baryons, but independent of $m_Q$)
Excited b-baryons

Until a year ago, relatively little was known about b-baryons:

- $\Lambda_b$ was well established, with likely $I(J^P) = 0(\frac{1}{2}^+)$
- evidence from LEP 1 for $\Xi^0_b$, $\Xi^{\pm}_b$ (in $\Xi^{\pm}\ell^{\pm}$), with supposedly $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$, no mass estimate

The $\Sigma_b$ states: $I = 1$ (flavour symmetric), $J^P = 1^+$ light diquark states $\Rightarrow$ combined with b-quark spin:

- $\Sigma_b$: $J^P = \frac{1}{2}^+$
- $\Sigma^*_b$: $J^P = \frac{3}{2}^+$

Predictions:

- $m(\Sigma_b) - m(\Lambda_b) \approx m(\Sigma_c) - m(\Lambda_c) = 210$ MeV
- mass splitting $m(\Sigma^*_b) - m(\Sigma_b) = \frac{m_c}{m_b}(m(\Sigma^*_c) - m(\Sigma_c)) \approx 20$ MeV
- widths $\sim 10$ MeV, decay modes saturated by $\Lambda_b \pi$

(Theory: J. Rosner, PRD 75 (2007) 013009)
Blind search in full Run IIa dataset:

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b \pi^\pm,$$

$$\Lambda_b \rightarrow \Lambda_c^+ \pi^-,$$

$$\Lambda_c^+ \rightarrow pK^-\pi^+$$

**Essential:** displaced track trigger (purely hadronic decay chain), high statistics

- clean $\Lambda_b$ selection
- hide signal region while optimizing cuts
- unblind
CDF $\Sigma_b$ Search

Blind search in full Run Ila dataset:

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CDF II Preliminary, $L = 1.1~$fb$^{-1}$

$Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m_\pi$ (GeV/c$^2$)
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A very significant result!
Results

Background dominated by true $\Lambda_b$ combined with additional “hadronization” tracks: from (reweighted) PYTHIA

Fit constraints:

- $m(\Sigma_{b}^{*-}) - m(\Sigma_{b}^{-}) = m(\Sigma_{b}^{*+}) - m(\Sigma_{b}^{+})$
- decay widths fixed from theory:

$$
\Gamma(\Sigma \to \Lambda \pi) = \frac{1}{6\pi} \frac{m(\Lambda)}{m(\Sigma)} |f_p|^2 |p_\pi|^3
$$

$$
f_p^{-1} = 123 \text{MeV (PCAC)}
$$

$\Rightarrow \Gamma(\Sigma_{b}) \approx 8 \text{MeV}, \Gamma(\Sigma_{b}^{*}) \approx 15 \text{MeV}$

Results in agreement with theory

$$
m(\Sigma_{b}^{+}) = 5808^{+2.0}_{-2.3} \pm 1.7 \text{MeV} \quad m(\Sigma_{b}^{-}) = 5816 \pm 1 \pm 1.7 \text{MeV}
$$

$$
m(\Sigma_{b}^{*+}) = 5829^{+1.6}_{-1.8} \pm 1.7 \text{MeV} \quad m(\Sigma_{b}^{*-}) = 5837^{+2.1}_{-1.9} \pm 1.7 \text{MeV}
$$
Orbitally Excited B Mesons

A continuation of last year’s story...

The 2006 PDG shows only the $L = 0$ B meson states (B** signal “blurred”), last year three new results by DØ were shown for $L = 1$ orbital excitations (two in B, one in $B_s$). This time: full complement of CDF results.

**Theory (both B, $B_s$):**

- $B_0^*(J = 0), B_1^*(J = 1)$:
  
  \[ J_q = \frac{1}{2}, \text{ decay via S-wave} \Rightarrow \text{too broad (} \Gamma \sim 100 \text{ MeV) to be observable} \]

- $B_1(J = 1), B_2^*(J = 2)$:
  
  \[ J_q = \frac{3}{2}, \text{ D-wave decay,} \]
  \[ \Gamma \sim 10 \text{ MeV} \]

- $m(B_2^*) - m(B_1) \approx 14 \text{ MeV (} = \frac{m_c}{m_b}(m(D_2^*) - m(D_1)) \)

(Theory: D. Ebert et al., PRD 57 (1998) 5663)
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  $(= \frac{m_c}{m_b}(m(D_2^*) - m(D_1)))$

(Theory: D. Ebert et al., PRD 57 (1998) 5663)
Decays considered:

\[
\begin{align*}
B_1 & \rightarrow B^{*+}\pi^- \\
B & : B_1^* & \rightarrow & B^{*+}\pi^- \\
B_2^* & \rightarrow & B^+\pi^- \\
B_{s1} & \rightarrow & B_s^{*+}K^- \\
B_s^* & \rightarrow & B_s^{*+}K^- \\
B_{s2}^* & \rightarrow & B_s^+K^- \\
\end{align*}
\]

\[\gamma \text{ from } B^{*+} \rightarrow B^+\gamma \text{ not observed } \Rightarrow \text{ add } \pi^-, K^- \text{ to } B^+\]

B\(^+\) work horses:

- \(J/\psi \) \(K^+\) (DØ, CDF)
- \(D^0\pi^+\) (CDF)

DØ RunII Preliminary

\[
\begin{align*}
\text{Number of Events} \\
\text{vs } M(J/\psi K^*) \text{ (GeV/c}^2) \\
1 \text{ fb}^{-1}
\end{align*}
\]
Decays considered:

\[ B_1 \rightarrow B^*+\pi^- \]
\[ B \quad B^*_2 \rightarrow B^*+\pi^- \quad B_s \quad B^*_s \rightarrow B^*+K^- \]
\[ B^*_2 \rightarrow B^+\pi^- \quad B^*_s \rightarrow B^+K^- \]

\( \gamma \) from \( B^{*+} \rightarrow B^+\gamma \) not observed \( \Rightarrow \)
add \( \pi^- , K^- \) to \( B^+ \)

CDF Preliminary: \( \sim 374 \text{pb}^{-1} \)

\[ \text{N}(B) = 2182 \pm 54 \]

Fit Prob = 14%
Results for the B system

**DØ:**

![DØ Run II Preliminary](image)

Obvious disagreement between experiments! DØ “clearly” observes three peaks while CDF sees only two.

**Theory mass splitting (14 MeV) in between CDF (4 MeV) and DØ(25 MeV)**

**CDF:**

![CDF Run II Preliminary](image)
Systematics estimated by considering wrong charge sign combinations (DØ), B⁺ sidebands (CDF)

$m(B₂^*)$ compatible; DØ widths ~ half the CDF constraint
(Theory: $16 \pm 6$ MeV, A. Falk et al., PRD 53 (1996) 231)
Results for the $B_s$ system

**DØ:**

- good agreement for $B^*_s2$
- CDF also find evidence for $B_{s1}$ (mass splitting (10 MeV) marginally consistent with theory)

**CDF (1 fb$^{-1}$):**

- CDF Run 2 Preliminary 1.0 fb$^{-1}$

![Graph showing data for $B^*_s$ system](image)

- $B^+ K^-$
- $B^+ K^+$
- Signal
- Background
Summary

Results for the $B_s$ system:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m(B_{s2}^*)$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ</td>
<td>$5839.1\pm1.4\pm1.5$ (syst.)</td>
</tr>
<tr>
<td>CDF</td>
<td>$5839.6\pm0.4\pm0.1$ (syst.) $\pm0.5$ (PDG)</td>
</tr>
<tr>
<td>CDF</td>
<td>$5829.4\pm0.2\pm0.1$ (syst.) $\pm0.6$ (PDG)</td>
</tr>
</tbody>
</table>

Note: mass assignment not proven

Results for the $B$ system:

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<tr>
<td>DØ (1)</td>
<td>$5746.0\pm2.4\pm5.4$ (syst.)</td>
</tr>
<tr>
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<td>$5720.8\pm2.5\pm5.3$ (syst.)</td>
</tr>
<tr>
<td>CDF</td>
<td>$5734\pm3\pm2$ (syst.)</td>
</tr>
<tr>
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<td>$5738\pm5\pm1$ (syst.)</td>
</tr>
</tbody>
</table>

Observation of double peak for $B_{2}^*$ lends confidence to $B_{2}^*$ mass assignment... BUT: discrepancies between experiments to be resolved ($B_1$ mass??)

(1) From $m(B_1)$ and mass difference $m(B_{2}^*) - m(B_1)$ (my combination)
HQET + Lattice QCD also provides precise predictions for (ratios of) lifetimes of B and D hadrons decaying weakly

- “well” (> 100 MeV) below threshold for strong decays
- theory improvements (2003) by unquenched lattice QCD calculations

\[
\frac{\tau_1}{\tau_2} = 1 + \left( \frac{\Lambda}{m_Q} \right)^2 \cdot ((\text{small}) \text{ isospin breaking}) + \left( \frac{\Lambda}{m_Q} \right)^3 \cdot (\text{spectator effects}) + \ldots
\]


The “Λ puzzle” (experimental lifetime values well below theory) solved?
New $\Lambda_b$ Lifetime Measurements in $\Lambda_b \rightarrow J/\psi \Lambda^0(p\pi^-)$

Both CDF and DØ made new measurements in 2006 (1 fb$^{-1}$).

Measurement principle:

\[
ct = \frac{L_{xy}}{(\beta\gamma)_{\Lambda_b, T}} = L_{xy} \frac{m(\Lambda_b)}{p_T(\Lambda_b)},
\]

\[
L_{xy} = L_{xy} \cdot \hat{p}_T(\Lambda_b)
\]

Advantages:

- full reconstruction $\Rightarrow p_T(\Lambda_b)$ known precisely
- negligible $J/\psi$ lifetime $\Rightarrow$ $L_{xy} = L_{xy}(J/\psi)$
- Important cross-check using $B^0 \rightarrow J/\psi K_S$: similar signature and kinematics

Drawback: statistics (low BR for decay to $J/\psi$) …

Very similar analysis procedure:

- unbinned simultaneous likelihood fit to mass and lifetime distributions
- resolution modeling (as opposed to assumption of fixed resolution)
Results

DØ:

CDF:

Similar ct resolutions
Results

**DØ:**

CDF mass resolution $\sim$ 4 times better, higher yield

**CDF:**

CDF II Preliminary 1.0 fb$^{-1}$

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B/D hadrons  
Moriond QCD, 18 March, 2007  
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Results

DØ:

\[ \tau(\Lambda_b) = \begin{cases} 
1.593^{+0.083}_{-0.078} \pm 0.033 \text{ ps CDF} \\
1.580 \pm 0.077 \pm 0.012 \text{ ps CDF}^{(*)} \\
1.298 \pm 0.137 \pm 0.050 \text{ ps DØ} 
\end{cases} \]

(*) Update, November 2006

CDF:

\[ \Lambda_b^0 \rightarrow J/\psi \Lambda^0 \]

CDF II Preliminary 1.0 fb⁻¹

To be continued...
New measurement by DØ. A challenge!

- partial reconstruction only $\Rightarrow$ measure $p_T(\Lambda_c^+\mu^-)$,

$$\lambda = L_{xy} \frac{m(\Lambda_b)}{p_T(\Lambda_c^+\mu^-)}$$

estimate

$$K \equiv \frac{p_T(\Lambda_c^+\mu^-)}{p_T(\Lambda_b)}$$

from MC

- $\tau(\Lambda_c) = 200 \pm 6$ ps (PDG): not negligible $\Rightarrow$ three vertices to be reconstructed

Analyze $m(K_Sp)$ spectrum in bins of $\lambda$
New \( \Lambda_b \) Lifetime Measurement in \( \Lambda_b \rightarrow \Lambda_c^+(K_S p)\mu^-\bar{\nu}_\mu X \)

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Analyze \( m(K_S p) \) spectrum in bins of \( \lambda \)

\[
m(K_S p) \) distribution for \( \Lambda_b \) candidates (3.4 GeV \( \leq m(K_S p\mu^-) \leq 5.4 \) GeV)
New $\Lambda_b$ Lifetime Measurement in $\Lambda_b \rightarrow \Lambda_c^+(K_{S}p)\mu^-\bar{\nu}_\mu X$

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Analyze $m(K_{S}p)$ spectrum in bins of $\lambda$

Result:

$$\tau(\Lambda_b) = 1.28^{+0.12}_{-0.11} \pm 0.09 \text{ ps}$$
Comparison between experiments (note: black results superseded)

(My) Conclusion:
- the “Λb puzzle” is not yet resolved
- but at the very least, there is an experimental issue
The $B_c$ Meson

New results from CDF:

$B_c$ mass:
- previously, $m(B_c)$ was known only to 60 MeV (2 OPAL candidate events)
- reconstructed in $B_c \rightarrow J/\psi \pi$

Result: $m(B_c) = 6276.5 \pm 4.0 \pm 2.7$ MeV

$B_c$ lifetime:
- PDG ’06: $\tau(B_c) = 0.46_{-0.16}^{+0.18} \pm 0.03$ ps
- partially reconstructed in $B_c \rightarrow J/\psi e^+ \nu_e$

Result: $\tau(B_c) = 0.463_{-0.065}^{+0.073} \pm 0.036$ ps
The $B_c$ Meson

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Also the $c$ quark can decay:

$$\Gamma_{tot} = \Gamma(b \rightarrow X) + \Gamma(c \rightarrow X) + \Gamma(\text{ann.}) + \Gamma(\text{PI})$$

$\Gamma(\text{PI})$: interference with initial-state $c$ quark for $b \rightarrow c\bar{c}s$ transitions
(Theory: V.V. Kisselev, hep-ph/0308214)
Conclusions

Exciting new results on B hadron masses:

- $\Sigma_b$ baryons observed for the first time
- existence of $B_{s2}^*$ confirmed by CDF, evidence for $B_{s1}$
- issues with $B_2^*$, $B_1$
- $B_c$ mass measurement to a few MeV

Progress on B hadron lifetimes:

- Significant improvement in $\tau(\Lambda_b)$ accuracy – but there are issues to be resolved
- uncertainty on $\tau(B_c)$ measurement halved: significantly more accurate than theory prediction!

Data is flowing in ever more rapidly. Be prepared for more exciting results in the near future.
**Other Results**

### DØ: Bs lifetime in $B_s \rightarrow D_s^- (\phi \pi) \mu^+ \nu \mu X$

\[
\tau(B_s) = 1.398 \pm 0.044^{+0.028}_{-0.025} \text{ ps}
\]

### CDF: lifetimes from exclusive $J/\psi + (K^+, K^{*0}, K_S, \phi, \Lambda)$ decays

\[
\begin{align*}
\tau(B^0) &= 1.551 \pm 0.019 \pm 0.011 \text{ ps} \\
\tau(B^+) &= 1.630 \pm 0.016 \pm 0.011 \text{ ps} \\
\tau(B_s) &= 1.494 \pm 0.054 \pm 0.009 \text{ ps} \\
\tau(\Lambda_b) &= 1.580 \pm 0.077 \pm 0.012 \text{ ps}
\end{align*}
\]

\[
\tau(B^+)/\tau(B^0) = 1.051 \pm 0.023 \pm 0.004 \\
\tau(B_s)/\tau(B^0) = 0.963 \pm 0.047 \pm 0.005 \\
\tau(\Lambda_b)/\tau(B^0) = 1.018 \pm 0.062 \pm 0.007
\]

### CDF: mass and width of excited D mesons

\[
\begin{align*}
m(D_1^{0}) &= 2421.7 \pm 0.7 \pm 0.6 \text{ MeV} \\
m(D_2^{*0}) &= 2463.3 \pm 0.6 \pm 0.8 \text{ MeV}
\end{align*}
\]

\[
\begin{align*}
\Gamma(D_1^{0}) &= 20.0 \pm 1.7 \pm 1.3 \text{ MeV} \\
\Gamma(D_2^{*0}) &= 49.2 \pm 2.3 \pm 1.3 \text{ MeV}
\end{align*}
\]