Study of baryonic $B$ meson decays at BABAR

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Studies of baryonic $B$ meson decays at $BABAR$

**This Talk**

- Recent Results on baryonic $B$ decays
  
  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$
  
  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} K^+ K^-$
  
  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} p \bar{p}$
  
  $\bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda}$

(charge conjugation implied throughout)

**Reminder – $BABAR$ Physics Reach**

- $B$-physics
  - $CP$ Violation & Mixing, CKM matrix elements, hadronic, leptonic & semi-leptonic decays, penguin decays, etc

- Charm and charmonium

- Tau physics

- Initial state radiation (ISR)

- Bottomonium spectroscopy

- Two-photon physics

- Beyond the Standard Model

- More
Motivation – baryonic $B$ Decays

• In general, $B$ decays provide an important platform for understanding $CP$-Violation and the CKM mechanism
  – Does it contribute to baryon asymmetry?

• Baryonic modes involve strong interactions in hadronization and final state interaction – study fragmentation, QCD models, etc.

• Poorly understood details of baryonic $B$ decays need study

• Measurements of rare modes improve our model constraints and can signal new physics
Baryonic $B$ decay detailed motivation

- 6.8% of all $B$ decays are baryonic*
- Fewer than 10% of these are accounted for via exclusive modes!
- What about the rest?

Hou and Soni (PRL 86, 4247): for $B$ baryonic decays, energy must be taken away by particles other than baryons
- Threshold enhancement in baryon anti-baryon invariant mass
- Suppression of two-body baryonic $B$ decay modes
- $B$ (2-body) < $B$ (3-body) < $B$ (4-body)

Relative effects of resonant substructure and fragmentation on branching fractions?

### Examples for baryonic $B$-decays (PDG values)

<table>
<thead>
<tr>
<th>$B^0/B^-$ decay mode</th>
<th>branching fraction [$\times 10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+ p$</td>
<td>0.20 ± 0.04</td>
</tr>
<tr>
<td>$\Lambda_c^+ p\pi^-$</td>
<td>2.8 ± 0.8</td>
</tr>
<tr>
<td>$\Lambda_c^+ p\pi^0$</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>$\Lambda_c^+ \Lambda_c^- K^-$</td>
<td>8.7 ± 3.5</td>
</tr>
<tr>
<td>$\Lambda_c^+ \Lambda_c^- K^-$</td>
<td>22 ± 7</td>
</tr>
<tr>
<td>$D^{*0}_s p\bar{p}$</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>$D^{*+}_s p\bar{n}$</td>
<td>14 ± 4</td>
</tr>
<tr>
<td>$D^0 p\Lambda$</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>$\Lambda\bar{p}$</td>
<td>&lt; 0.003</td>
</tr>
<tr>
<td>$\Lambda\bar{p}\pi^-$</td>
<td>0.031 ± 0.003</td>
</tr>
<tr>
<td>$p\bar{p} K^0$</td>
<td>0.027 ± 0.003</td>
</tr>
<tr>
<td>$p\bar{p} K^-$</td>
<td>0.055 ± 0.005</td>
</tr>
</tbody>
</table>

*ARGUS Collaboration, ZP C56, 1 (1992)
Threshold Enhancements

\[ \bar{B}^0 \rightarrow D^0 p\bar{p} \]

\[ B^- \rightarrow \Lambda_c^+ p\pi^- \]

Previous measurements from 3-body modes

Both involve "meson pole"

[PR D85, 092017 (2012)]

[PR D78, 112003 (2008)]
Kinematics of $B$ Decays

- Fully reconstructed $B$ mesons: two variables are commonly used (exploiting the precise knowledge of the beam energy):

  \[ \Delta E = E_{\text{meas}} - E_{\text{beam}} \]

  \[ m_{ES} = \sqrt{E_{\text{beam}}^2 - p_{\text{meas}}^2} \]

  Invariant mass can also be used: \[ m_B = \sqrt{E_{\text{meas}}^2 - p_{\text{meas}}^2} \]

- Dominant background: $q\bar{q}$ ($q = u, d, s, c$), exhibiting a jet-like topology ($B\bar{B}$ events are more “spherical”).

- We separate/suppress the continuum background, combining several variables sensitive to the event shape.
\[ \bar{B}^0 \rightarrow \Lambda_c^+ p \pi^+ \pi^- \]
\[ \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \]

- There are many possible resonances – will this affect the total branching fraction?

\[
(\Lambda_c^+ \pi^+) \Rightarrow \Sigma_c^{++} (2455), \Sigma_c^{++} (2520), \text{ etc.}
\]

\[
(\Lambda_c^+ \pi^-) \Rightarrow \Sigma_c^0 (2455), \Sigma_c^0 (2520), \text{ etc.}
\]

\[
(p\pi) \Rightarrow \text{ various } N, \Delta
\]

- Will a quark difference between \( \Sigma_c^0 \) and \( \Sigma_c^{++} \) affect possible threshold enhancement in \( m(\Sigma_c \bar{p}) \)?

467 \times 10^6 \bar{B} \bar{B} \text{ pairs in analysis}
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ Fits

Charged sub-modes

Neutral sub-modes
$\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$ Results

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>fitted signal yield</th>
<th>branching fraction [$10^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B}^0 \to \Sigma_c^{++}(2455)\bar{p}\pi^-$</td>
<td>$723 \pm 32$</td>
<td>$2.13 \pm 0.10 \pm 0.10 \pm 0.55$</td>
</tr>
<tr>
<td>$\bar{B}^0 \to \Sigma_c^0(2455)\bar{p}\pi^+$</td>
<td>$347 \pm 24$</td>
<td>$0.91 \pm 0.07 \pm 0.04 \pm 0.24$</td>
</tr>
<tr>
<td>$\bar{B}^0 \to \Sigma_c^{++}(2520)\bar{p}\pi^-$</td>
<td>$458 \pm 38$</td>
<td>$1.15 \pm 0.10 \pm 0.05 \pm 0.30$</td>
</tr>
<tr>
<td>*$\bar{B}^0 \to \Sigma_c^0(2520)\bar{p}\pi^+$</td>
<td>$87 \pm 27$</td>
<td>$0.22 \pm 0.07 \pm 0.01 \pm 0.06$</td>
</tr>
<tr>
<td>$(\bar{B}^0 \to \Lambda_c\bar{p}\pi^+\pi^-)_{\text{non-}\Sigma_c}$</td>
<td>$2728 \pm 132$</td>
<td>$7.9 \pm 0.4 \pm 0.4 \pm 2.0$</td>
</tr>
</tbody>
</table>

uncertainties: statistical, systematic, and from $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$

$\mathcal{B}(\bar{B}^0 \to \Lambda_c\bar{p}\pi^+\pi^-)_{\text{total}} = (12.3 \pm 0.5 \pm 0.7 \pm 3.2) \times 10^{-4}$

More than half of this attributable to resonances

*First evidence this mode: 3.2 σ

Resonant Substructure?

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$$
Threshold Enhancements in submodes

\[ \bar{B}^0 \rightarrow \Sigma^{++} \bar{p} \pi^- \]

Different diagrams for charged and neutral Sigma
- Difference in both threshold behavior and overall production rate.

\[ \bar{B}^0 \rightarrow \Sigma^0 \bar{p} \pi^+ \]

Meson Pole

No Meson Pole

$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} K^+ K^-$
\( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} K^+ K^- \)

- Four-body mode, similar to \( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \)
  - Same baryons, meson difference due to popping an \( s\bar{s} \) pair instead of a \( d\bar{d} \) pair. Expect suppression by at least factor 3
  - Less resonant substructure available. Recall that \( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \) is dominated by resonant contributions

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471 × 10^6 \( B\bar{B} \) pairs in analysis
Results

\[ \bar{B}^0 \rightarrow \Lambda_c^+ p K^+ K^- \]

Reconstruct \( \Lambda_c^+ \rightarrow p K^+ \pi^- \)

Signal extracted with a fit to the energy-substituted mass \( m_{ES} \) and the invariant mass \( m_B \)

Statistical Significance of result

\[ S = \sqrt{-2 \log \left( \frac{L_0}{L_{\text{sig}}} \right)} = 5.4 \sigma \]

Simulated Signal

Projections of data

\[ N = 66 \pm 12 \]
\[ \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} K^+ K^- \] Resonances

- Threshold enhancement not significant, consistent with result for \( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \)

\[ \mathcal{B} \left( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} K^- K^+ \right) = \left( 2.5 \pm 0.4_{\text{stat}} \pm 0.2_{\text{syst}} \pm 0.6_{\Lambda_c^+} \right) \times 10^{-5} \]

Suppressed by factor \( \sim 50 \) compared to \( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \)
Or factor \( \sim 25 \) compared to just non-resonant part

- Find evidence for only one resonance: \( \phi \)
- Setup 90\% Confidence Level upper limit:

\[ \mathcal{B} \left( \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \phi \right) < 1.2 \times 10^{-5} \]
$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} p \bar{p}$

\[ \bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p} \]

Small phase space is available to this decay, with available kinetic energy \( \sim 1/10 \) of \( \bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^- \)

**But in baryonic decays, smaller phase space not suppressed?**

\[ B(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}) \cdot \frac{B(\Lambda_c^+ \to pK^+ \pi^-)}{5 \%} < 2.8 \times 10^{-6} \quad @ \ 90\% \ CL \]

Compare:

\[ B(\bar{B}^0 \to \Lambda_c \bar{p} \pi^+ \pi^-)_{\text{total}} = (12.3 \pm 0.5 \pm 0.7 \pm 3.2) \times 10^{-4} \]

less than half is non-resonant 4-body

471 \times 10^6 \ B\bar{B} \ pairs in analysis

Note:

\[ B(\Lambda_c \to pK\pi) \sim 5\% \]
$\bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda}$

\[ \bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda} \]

\[ \bar{B}^0 \rightarrow D^0 p\bar{p} \]

\[ B(\bar{B}^0 \rightarrow D^0 p\bar{p}) = (1.13 \pm 0.10) \times 10^{-4} \]

[PR D74, 051101 (2006)]

\[ 471 \times 10^6 \bar{B}\bar{B} \text{ pairs in analysis} \]

Expect suppression \( \sim 1/3 \) for \( s \) quark vs. \( u \)

Also suppression \( \sim 1/4 \) due to possible final states

\[ \Lambda\bar{\Lambda}, \ \Lambda\bar{\Sigma}^0, \ \Sigma^0\bar{\Lambda}, \ \Sigma^0\bar{\Sigma}^0 \]
$\bar{B}^0 \rightarrow D^0 \Lambda \Lambda$ Fits

Simultaneous fit to $D^0 \rightarrow K^- \pi^+$

$D^0 \rightarrow K^- \pi^+ \pi^0$

$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$
$\bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda}$ Results

evidence at 3.4σ

$$\mathcal{B}(\bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda}) = (9.8^{+2.9}_{-2.6} \pm 1.9_{\text{syst}}) \times 10^{-6}$$

Belle: $\mathcal{B}(\bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda}) = (10.5^{+5.7}_{-4.4} \pm 0.14) \times 10^{-6}$

Theory: $\mathcal{B}(\bar{B}^0 \rightarrow D^0 \Lambda \bar{\Lambda}) = (2.3 \pm 0.8) \times 10^{-6}$

$$\frac{D^0 \Sigma^0 \Lambda + D^0 \bar{\Sigma}^0 \Lambda}{D^0 \Lambda \bar{\Lambda}} = 1.5 \pm 0.9 \quad \text{consistent with} \quad 2$$

$\mathcal{B}(\bar{B}^0 \rightarrow D^0 p \bar{p}) = (1.04 \pm 0.07) \cdot 10^{-4}$  

Belle, BABAR average

$$\frac{D^0 \Lambda \bar{\Lambda}}{D^0 p \bar{p}} = \frac{1}{10.6 \pm 3.7} \quad \text{consistent with} \quad \frac{1}{12}$$
Summary

• Results presented this talk:

Improved measurements these modes:

\[ \mathcal{B}(B^0 \to \Lambda_c \bar{p} \pi^+ \pi^-)_{\text{total}} = (12.3 \pm 0.5 \pm 0.7 \pm 3.2) \times 10^{-4} \]

Including first evidence for \( B^0 \to \Sigma^0_{c}(2520) \bar{p} \pi^+ \)

\[ \mathcal{B}(B^0 \to D^0 \Lambda \bar{\Lambda}) = (9.8^{+2.9}_{-2.6} \pm 1.9_{\text{syst}}) \times 10^{-6} \]

And first measurements these modes:

\[ \mathcal{B}(\bar{B}^0 \to \Lambda^+_c \bar{p} K^- K^+) = \left(2.5 \pm 0.4_{(\text{stat})} \pm 0.2_{(\text{syst})} \pm 0.6_{(\Lambda^+_c)}\right) \times 10^{-5} \]

\[ \mathcal{B}(\bar{B}^0 \to \Lambda^+_c \bar{p} \phi) < 1.2 \times 10^{-5} \]

\[ \mathcal{B}(\bar{B}^0 \to \Lambda^+_c \bar{p} \bar{p} \bar{p}) \cdot \mathcal{B}(\Lambda^+_c \to p K^- \pi^+) < 2.8 \cdot 10^{-6} \text{ @ 90\% CL} \]
• **BABAR** continues producing interesting and competitive results.
  
  • new analyses improve understanding of baryon production in $B$ decays, but still ~90% of all channels unknown
  
  • Resonant substructure appears to increase baryonic $B$ decay branching fractions – not only having extra particles in the final state.
  
  • hadronisation is similar to (jet) fragmentation (e.g. $s$ quark suppression)
  
  • baryon-antibaryon threshold enhancement is qualitatively understood (no quantitative theory)

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**Thank You!**
GO BARYONS
Back Up Slides
The **B**a**B**a**R** Running Era

7 Runs over the course of 9 years

- First collisions with BaBar
  May 26, 1999
- Final data taken 12:43 p.m., April 7, 2008

BaBar

Run 1-7

PEP II Delivered Luminosity: 553.34/fb
BaBar Recorded Luminosity: 531.32/fb
BaBar Recorded Y(4s): 432.89/fb
BaBar Recorded Y(3s): 30.23/fb
BaBar Recorded Y(2s): 14.45/fb
Off Peak Luminosity: 53.74/fb

Delivered Luminosity
Recorded Luminosity
Recorded Luminosity Y(4S)
Recorded Luminosity Y(3S)
Recorded Luminosity Y(2S)
Off Peak

BaBar

As of 2008/04/07 00:00

CUSB

2015 Aug 7

B to baryons at BABAR – Brown, DPF2015
The BABAR Experiment at SLAC

- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetectors with a 40-layer drift chamber
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of CP-violation in B meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

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