Study of Inclusive Charmonium Production in $e^+e^-$ annihilation and B decays at BABAR

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Overview

• Inclusive $B \rightarrow XK$ two-body decays are studied

• Update of 2005 study (Phys. Rev. Lett. 96, 052002 (2006)) to now use 424 fb$^{-1}$ of the BABAR dataset (previous study – 210 fb$^{-1}$)

• Increased luminosity and precision reduces uncertainties and allows for new measurements to be taken.
Motivation

• Provide a clear picture of charmonium spectroscopy

• Determine absolute branching fractions for all known two-body decays of form $B^\pm \rightarrow X_{cc} K^\pm$

• Measure a BF (or upper limit) of $B^\pm \rightarrow K^\pm X(3872)$
\[ B \rightarrow X + K^\pm \]

- In these decays, \( X \) is mostly a \( c\bar{c} \) state with large phase space.
  - Many different charmonium states are allowed
    - \( J/\psi, \eta_c, \chi_c, \psi', \eta_c', X(3872), \cdots \)

- We search along a full range of mass to fully characterize these decays and search for exotic charmonium states.
  - Make new measurements on D states as well

- An original method to study inclusive two-body decays is introduced.
\[
B \rightarrow X_{c\bar{c}} + K
\]

**Traditional Method**

- Exclusively reconstruct each charmonium \((X_{c\bar{c}})\) state
- Use that measurement to deduce a measurement of \(B \rightarrow X_{c\bar{c}} K\)

**This Study**

- Use \(K\) momentum in \(B\) center of mass frame.
- From the spectrum of kaon momentum, one can directly deduce BF of \(B \rightarrow X_{c\bar{c}} K\)
- Details of \(X_{c\bar{c}}\) decay not required for measurement
B and K selection

- Fully reconstruct B’s
  - Look for the presence of either a $D^{(*)}$, $J/\psi$, or $D_s^\pm$ + multihadrons
  - 1,670,000 ± 4,230 $B^\pm (stat) ± 80,000 (syst)$ events obtained (BABAR preliminary)
- Increase S/N - reject secondary kaons
  - Secondary kaons have an isotropic distribution
Analysis method - detailed

• Reconstruction of one B in the event gives the momentum of the other.
  – If non-reconstructed B is a two-body decay, one can calculate the mass of X:
    \[ m_x = \sqrt{m_B^2 + m_K^2 - 2E_K m_B} \]

• Fit excess kaons amongst the momentum spectrum at target X’s mass to get number of \( B \rightarrow K^\pm + X \) events \( (N_x) \)
Analysis method - detailed

• Two ways to calculate BF of $B \rightarrow K^{\pm} + X$:
  
  – Directly from $N_X$:

  $$BF(B \rightarrow K^{\pm} + X) = \frac{N_X}{\epsilon_X \cdot N_B}$$

  – Normalization of $J/\psi$:

  $$BF(B \rightarrow K^{\pm} + X) = \frac{N_X}{N_{J/\psi}} \cdot \frac{\epsilon_{J/\psi}}{\epsilon_X} \cdot BF(B \rightarrow K^{\pm} + J/\psi)$$
Low mass charmonium

$BF(B^\pm \rightarrow K^\pm \ J/\psi) = (9.6 \pm 1.2(stat) \pm 0.8(sys)) \times 10^{-4}$

$BF(B^\pm \rightarrow K^\pm \ \eta_c) = (13.3 \pm 1.8(stat) \pm 0.3(ref)) \times 10^{-4}$

(both BABAR Preliminary)
Low mass charmonium

\[ BF(B^\pm \rightarrow K^\pm J/\psi) = (9.6 \pm 1.2(stat) \pm 0.8(sys)) \times 10^{-4} \]
\[ BF(B^\pm \rightarrow K^\pm \eta_c) = (13.3 \pm 1.8(stat) \pm 0.3(ref)) \times 10^{-4} \]
(both BABAR Preliminary)
Search for high mass charmonium

Tangible fits for $\chi_0, \chi_1, \eta_c', \text{and } \psi'$
Search for high mass charmonium

BABAR Preliminary
Search for high mass charmonium

- Confirmed coupling of excited states $\psi' - \eta_c(2S)$ related to $J/\psi - \eta_c$ doublet
- No signal observed for $\chi_2$
  - This violates the democratic decay rate for charmonium in two body decays
- Upper limit on $X(3872)$ is set
Very high mass resonances

- High background due to low kaon momentum.
  - Only sensitive to narrow resonances (‘best’ candidate found at 1.0425 GeV/c)
- No signal found from Y(4260) and its excited states – large width.
Excited D resonances

<table>
<thead>
<tr>
<th>Particle</th>
<th>Yield</th>
<th>Peak Position</th>
<th>BF (10^{-4})</th>
<th>PDG 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>126±20</td>
<td></td>
<td>3.5±0.5(stat)±0.3(sys)</td>
<td>3.7±0.17</td>
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<td>$D^{*0}$</td>
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<td>4.2±0.34</td>
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<td>$D_1(2420)^0$</td>
<td>97±25</td>
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<td>2.1±0.5(stat)±0.3(sys)</td>
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<tr>
<td>$D^{**0}(2680)$</td>
<td>95±29</td>
<td>2.68±0.003</td>
<td>2.1±0.6(stat)±0.3(sys)</td>
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<td>$D^\pm$</td>
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<td>$D^{*\pm}$</td>
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BABAR Preliminary
Charged Charmonium

- Analysis is redone with reconstructed $B^0$
- $372 \, 597 \pm 775 \, B^0$ sample (BABAR Preliminary)
- Measurements in D region agree with PDG
Charged Charmonium – D resonances

D resonances found in region $1.8 \text{ GeV}/c < p_K < 2.5 \text{ GeV}/c$
Charged Charmonium

- No evidence found for charmonium-like states $Z(3900)$, $Z(4050)$, and $Z(4430)$
  - Upper limits have been set
Summary & Conclusions

• An update to previous measurements using full BABAR statistics has been completed.

• We have increased the precision of
  \[ B^\pm \rightarrow \eta_c K^\pm \]

• We have observed the doublet \( \psi' \rightarrow \eta_c(2S) \)

• \( BF(B^\pm \rightarrow \chi_{c0} K^\pm) \) is now measured
Summary & Conclusions

• No measurement of X(3872), but upper limit is refined

• Evidence of new particle (D family?) at $p_K = 1.92 \text{ GeV}/c$ corresponding to mass $2.68 \text{ GeV}/c^2$

• Width of charged charmonium-like particles is too large to make a measurement
  – Upper limits $Z(3900)$, $Z(4050)$, $Z(4430)$ respectively (90% CL): $3 \times 10^{-4}$, $3 \times 10^{-4}$, $5 \times 10^{-4}$ (BABAR Preliminary)
## Results

<table>
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<tr>
<td>$J/\psi$</td>
<td>516±67</td>
<td>2982±5</td>
<td>&lt;43</td>
<td>9.6±1.2(sta)±0.8(sys)</td>
</tr>
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<td>$\eta_c$</td>
<td>655±77</td>
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<td>13.3±1.8(stat)±0.4(sys)±0.3(ref)</td>
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<td>$\chi_{c0}$</td>
<td>218±76</td>
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<td></td>
<td>4.4±0.9</td>
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<td>$\chi_{c1}$</td>
<td>192±35</td>
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<td>$\chi_{c2}$</td>
<td>0±32</td>
<td></td>
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<td>&lt;1.2</td>
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<tr>
<td>$\eta_c$ (2S)</td>
<td>283±94</td>
<td>3632±0.007</td>
<td>&lt;33</td>
<td>6.0±2.1(stat)±0.4(sys)</td>
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<td>$\psi'$</td>
<td>293±90</td>
<td></td>
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<td>6.2±2(stat)±0.6(sys)</td>
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<td>$\psi(3770)$</td>
<td>0±49</td>
<td></td>
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<td>&lt;2.0</td>
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<tr>
<td>$X(3872)$</td>
<td>75±81</td>
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<td>1.4±1.5 or &lt; 4.4</td>
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