Observation of Exclusive B Decays to Final States Containing a Charmed Baryon

CLEO Collaboration

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Abstract

Using data collected in the region of the \(\Upsilon(4S)\) resonance with the CLEO-II detector, we report on the first observation of exclusive decays of the \(B\) meson to final states with a charmed baryon. We have measured the branching fractions \(\mathcal{B}(B^- \to \Lambda_c^+ p\pi^-) = (0.62^{+0.23}_{-0.20} \pm 0.11 \pm 0.10) \times 10^{-3}\) and \(\mathcal{B}(B^0 \to \Lambda_c^+ p\pi^+\pi^-) = (1.33^{+0.42}_{-0.31} \pm 0.31 \pm 0.21) \times 10^{-3}\). In addition, we report upper limits for final states of the form \(\overline{B} \to \Lambda_c^+ \overline{p}(n\pi)\) and \(\Lambda_c^+ \overline{p}(n\pi)\pi^0\) where \((n\pi)\) denotes up to four charged pions.

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Exclusive reconstruction of $B$ mesons to final states with a $\Lambda_c^+$ is essential in understanding the mechanisms for baryon production in $B$ decays, which are expected to be dominated by $b \to c\pi d$ transitions via internal or external $W$-emission [1]. These processes lead to final states of the form $\vec{B} \to \Theta_c N X$, where $\Theta_c = \Lambda_c^+$, $\Sigma_c$ or higher excitations of the ground state baryons. Inclusive production of the charged baryon $\Lambda_c^+$ from $B$ meson decays was first reported by ARGUS [2] and confirmed by CLEO [3]. The fraction of $\Lambda_c^+$ baryons from $\Sigma_c^{++}$ and $\Sigma_c^0$ in $B$ decays is measured to be $\sim 16\%$ [4]. The branching fraction for $B$ decays to charmed baryons is $(6.4 \pm 1.1)\%$ [5]. CLEO has studied the $\Lambda_c^+$ momentum spectrum in $B$ decays and found that two-body final states are suppressed [3]. This motivates a search for multi-body final states of $\vec{B}^0$ and $B^-$ mesons of the form $\vec{B} \to \Lambda_c^+(p\pi)$ and $\Lambda_c^+\pi(n\pi)\pi^0$, where $(n\pi)$ is up to four charged pions. These modes have previously not been observed. Throughout this study the charge conjugate process is implied.

This analysis is based on 2.39 fb$^{-1}$ of data taken at the $\Upsilon(4S)$ resonance and 1.13 fb$^{-1}$ of data taken at a center-of-mass energy 60 MeV less than the $\Upsilon(4S)$ resonance which is below the threshold for producing $B$ meson pairs, hereafter referred to as continuum. Assuming equal production rates of charged and neutral $B$ mesons, a total of 2,560,000 $\pm$ 46,000 charged and an equal number of neutral $B$ mesons are in the data sample. The data was collected with the CLEO-II detector [6] at the Cornell Electron Storage Ring (CESR). Charged particles are tracked using three nested cylindrical wire chambers operating in a 1.5 T magnetic field. The tracking chambers are surrounded by time-of-flight (TOF) counters and an electromagnetic calorimeter which provides excellent $\pi^0$ reconstruction.

Candidate $\Lambda_c^+$ baryons are reconstructed in the modes $pK^-\pi^+$, $pK^*_S^0$ and $\Lambda\pi^+$, with $K_S^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$. The momentum of the $\Lambda_c^+$ is required to be less than 2.3 GeV/c, which is the kinematic limit for $\Lambda_c^+$ baryons from $B$ meson decay. Daughter $K_S^0$ and $\Lambda$ candidates are reconstructed from oppositely charged tracks which form a detached vertex in the plane transverse to the beam direction. The invariant mass of the $K_S^0$ ($\Lambda$) is required to be within 10.0 (3.0) MeV/$c^2$ of the known mass. Neutral pion candidates are formed from pairs of showers detected in the calorimeter which yield a $\gamma\gamma$ invariant mass within 2.5 $\sigma$ of the known $\pi^0$ mass ($\sigma \sim 5$ MeV).

Particle identification is accomplished by combining the specific ionization measurements from the central drift chamber with TOF information, if available, to derive probabilities for each charged track to be consistent with the pion, kaon and proton mass hypotheses. Protons produced directly from $B$ decay are required to have a probability for the proton hypothesis greater than 5% and a probability of less than 32% for the pion hypothesis [7]. Charged kaons and protons from $\Lambda_c^+$ decay are required to have a probability for the appropriate hypothesis greater than 5% and a probability of less than 5% for the pion hypothesis [8]. For charged pions from $\Lambda_c^+$ decay and protons from $\Lambda$ decay, the probability for the respective particle hypothesis is required be greater than 0.3% [9]. No particle identification requirements are made for pion candidates from $B$ decay in order to improve overall detection efficiency for low momentum pions and increase sensitivity to pions from the decay $\Sigma_c^{++}/0 \to \Lambda_c^+\pi^{\pm}$.

We relax the requirement for protons from $B$ decay compared to protons from $\Lambda_c^+$ decay to increase our efficiency since the average momentum is greater for protons directly from $B$ decay. This is necessary because the efficiency of our particle identification decreases with increasing momentum. The efficiencies of these particle identification requirements are derived from data using high purity samples of protons, kaons and pions from the decays
\[ \Lambda \to p\pi^-, D^{*+} \to D^0\pi^+ \text{ with } D^0 \to K^-\pi^+, \text{ and } K^0_S \to \pi^+\pi^-, \text{ respectively.} \]

To suppress continuum background, the normalized Fox-Wolfram second moment [10] is required to be less than 0.35. The numbers of \( \Lambda_c^+ \) candidates from the \( \Upsilon(4S) \) data and the continuum are determined separately, where continuum data is scaled to account for the differences in luminosity and center-of-mass energies. After subtracting this contribution, the \( \Lambda_c^+ \) yield from \( B \) decays is 3343 \( \pm \) 215.

Exclusive \( B \) decays are reconstructed by selecting \( \Lambda_c^+ \) candidates whose mass is within 2.5 \( \sigma \) of the nominal mass and forming \( \Lambda_c^+\overline{p}(n\pi) \) and \( \Lambda_c^+\overline{p}(n\pi)\pi^0 \) combinations, where \((n\pi)\) denotes up to four charged pions. We define the beam-constrained mass as 
\[ M_B = \sqrt{E_{\text{beam}}^2 - (\sum_i \overline{p}_i)^2}, \]
where \( \overline{p}_i \) is the 3-momentum vector for the \( i^{th} \) daughter of the \( B \) candidate and \( E_{\text{beam}} \) is the beam energy. The resolution of \( M_B \) is about 2.6 MeV/\( c^2 \), a factor of five better than the resolution in invariant mass, and is dominated by the spread of the CESR beam energy.

For correctly reconstructed \( B \) mesons the measured energy, \( E_{\text{meas}} \), must equal the beam energy within the experimental resolution. The width of the energy difference distribution, \( \Delta E = E_{\text{meas}} - E_{\text{beam}} \), is predicted by Monte Carlo to be 10 to 16 MeV, depending on the final state. We reduce the combinatorial background significantly by requiring \( |\Delta E| < 25 \) MeV. A further reduction in background is achieved by cutting on \( \Theta_B \), the polar angle of the \( B \) in the laboratory frame with respect to the \( e^+e^- \) axis. The distribution of \( \cos \Theta_B \) is proportional to \( \sin^2 \Theta_B \) for \( e^+e^- \to \Upsilon(4S) \to B\overline{B} \), whereas background events are distributed nearly isotropically. We require \( |\cos \Theta_B| < 0.9 \). If there are multiple candidates in an event with \( M_B > 5.2 \) GeV/\( c^2 \) for a given decay channel, the entry with the smallest absolute value of \( \Delta E \) is selected.

After application of these cuts, statistically significant signals are seen in the decay modes \( B^- \to \Lambda_c^+\overline{p}\pi^- \) and \( B^0 \to \Lambda_c^+\overline{p}\pi^+\pi^- \), shown in Fig. 1(a) and (c), respectively. The \( M_B \) signal distribution is fit using a Gaussian signal of width equal to 2.64 MeV/\( c^2 \) and a background function composed of a straight line with a parabolic kinematic cutoff [11]. The \( M_B \) distributions from the \( \Delta E \) signal and sideband region are fit simultaneously to obtain the slope of the background function. The fits yield 12.0\( ^{+4.4}_{-3.8} \) events for \( B^- \to \Lambda_c^+\overline{p}\pi^- \), and 24.0\( ^{+8.5}_{-7.3} \) events for \( B^0 \to \Lambda_c^+\overline{p}\pi^+\pi^- \).

The background contributions to the \( M_B \) distribution have been studied in several ways. The beam-constrained mass distribution from combinations in the \( \Delta E \) signal region (defined as the region satisfying \( 50 < |\Delta E| < 100 \) MeV) shows no enhancement in the signal region, shown in Fig. 1(b) and (d) for \( B^- \to \Lambda_c^+\overline{p}\pi^- \) and \( B^0 \to \Lambda_c^+\overline{p}\pi^+\pi^- \), respectively. The background distributions are fit with the background functional form described above. Similar distributions made from the \( \Lambda_c^+ \) mass sidebands and continuum data show no enhancement in the signal region.

The \( \Delta E \) distributions for \( B^- \to \Lambda_c^+\overline{p}\pi^- \) and \( B^0 \to \Lambda_c^+\overline{p}\pi^+\pi^- \) for the \( M_B \) signal region (\( \sim 2 \sigma \)), and for the \( M_B \) sideband (defined as \( 5.230 < M_B < 5.260 \) GeV/\( c^2 \)), are shown in Fig. 2(a) and (b). The \( \Delta E \) distribution from the \( M_B \) signal region is fit using a Gaussian whose width is fixed to the value predicted from Monte Carlo and a linear background function. After subtraction of the contribution from the \( M_B \) sideband, which also peaks due to our selection criteria, the signal yield is 10.1 \( \pm \) 5.0 events for \( B^- \to \Lambda_c^+\overline{p}\pi^- \) and 23.5 \( \pm \) 9.3 events for \( B^0 \to \Lambda_c^+\overline{p}\pi^+\pi^- \), consistent with the yields from the fits to the \( M_B \) distributions.
The yields from the $M_B$ distributions are quoted, however, due to their greater statistical significance.

The branching fractions are measured to be,

$$B(B^- \to \Lambda_c^+ p\pi^-) = (0.62^{+0.23}_{-0.21} \pm 0.11 \pm 0.10) \times 10^{-3},$$

$$B(B^0 \to \Lambda_c^+ p\pi^+\pi^-) = (1.33^{+0.46}_{-0.42} \pm 0.31 \pm 0.21) \times 10^{-3},$$

where the first error is statistical, the second is systematic and the third error is due to uncertainty in the $\Lambda_c^+$ branching fractions [5].

Systematic uncertainties include contributions from particle identification requirements (10%), fitting procedure (8% - 16%), charged track reconstruction (2% per track), $\pi^0$ reconstruction efficiency (5% per $\pi^0$), the number of $B\bar{B}$ events (2%), Monte Carlo statistics (2 - 4%), secondary vertex finding (1%) and the $\Lambda_c^+$ branching fractions (16%). The assumption is made that $B^- \to \Lambda_c^+ p\pi^-$ ($B^0 \to \Lambda_c^+ p\pi^+\pi^-$) proceeds via phase space decay. The reconstruction efficiency decreases by 9% (6%) if the assumption is made that 16% of the $\Lambda_c^+$ baryons come from $\Sigma_c^{++}$ and $\Sigma_c^0$ [4], which is taken as a systematic error. The total systematic errors are between 13 - 23 %, depending on the decay mode.

Figure 3 shows the distributions for decay modes of the form $B^0 \to \Lambda_c^+ p(n\pi)\pi^0$, and Fig. 4 displays the decay modes $B^0 \to \Lambda_c^+ p, B^- \to \Lambda_c^+ p\pi^-\pi^+\pi^- \text{ and } B^0 \to \Lambda_c^+ p\pi^-\pi^+\pi^-\pi^-$. In all of these $B$ decay modes no statistically significant signals are observed and 90% C.L. upper limits are calculated and summarized in Table I. Theoretical predictions exist for a number of two-body $B$ meson decays to charmed baryons and the limit for $B \to \Lambda_c^+ p$ is below theoretical predictions, which are in the range 0.04% to 0.19% [12].

In conclusion, we have made the first observation of exclusive $B$ decays to final states including the charmed baryon $\Lambda_c^+$. The branching fractions for $B^- \to \Lambda_c^+ p\pi^-$ and $B^0 \to \Lambda_c^+ p\pi^+\pi^-$ have been measured and upper limits have been set on other decay modes.

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[4] M. Procario et al., Phys. Rev. Lett. 73, 1472 (1994). CLEO measured the fraction of \( B \to \Lambda_c^+ X \) from \( B \to \Sigma_c^{++} X \) and \( B \to \Sigma_c^0 X \) to be each \( \sim 8\% \) and placed the upper limit \( \mathcal{B}(B \to \Sigma_c^+ X) < 0.011 \) @90\% C.L.


[7] This requirement corresponds to a 2\( \sigma \) consistency requirement on the selected proton and a pion veto at the 1\( \sigma \) level.

[8] This requirement corresponds to a 2\( \sigma \) consistency requirement on the selected hypothesis and a pion veto at the 2\( \sigma \) level.

[9] This requirement corresponds to a 3\( \sigma \) consistency requirement on the selected hypothesis.


TABLE I. Branching fraction results for $\bar{B} \to \Lambda_c^+ \bar{p}(n\pi)$, $\Lambda_c^+ \bar{p}(n\pi)\pi^0$ and 90% C.L. upper limits.

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<th>B Mode</th>
<th>Events</th>
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<tr>
<td>$\Lambda_c^+ \bar{p}$</td>
<td>&lt; 2.3</td>
<td>&lt; 0.21</td>
</tr>
<tr>
<td>$\Lambda_c^+ \bar{p}\pi$</td>
<td>12.0 $^{+4.4}_{-3.8}$</td>
<td>0.62 $^{+0.23}_{-0.20}$ ± 0.11 ± 0.10</td>
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<tr>
<td>$\Lambda_c^+ \bar{p}\pi^0$</td>
<td>&lt; 4.1</td>
<td>&lt; 0.59</td>
</tr>
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<td>$\Lambda_c^+ \bar{p}2\pi$</td>
<td>24.0 $^{+8.3}_{-7.5}$</td>
<td>1.33 $^{+0.46}_{-0.42}$ ± 0.31 ± 0.21</td>
</tr>
<tr>
<td>$\Lambda_c^+ \bar{p}\pi\pi^0$</td>
<td>&lt; 20.6</td>
<td>&lt; 3.12</td>
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<tr>
<td>$\Lambda_c^+ \bar{p}3\pi$</td>
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<tr>
<td>$\Lambda_c^+ \bar{p}2\pi\pi^0$</td>
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<tr>
<td>$\Lambda_c^+ \bar{p}4\pi$</td>
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<td>&lt; 2.74</td>
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<tr>
<td>$\Lambda_c^+ \bar{p}3\pi\pi^0$</td>
<td>&lt; 28.2</td>
<td>&lt; 13.4</td>
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FIG. 1. $M_B$ distribution for $B^- \rightarrow \Lambda_c^+ \overline{p}\pi^-$ from (a) $\Delta E$ signal region, (b) $\Delta E$ sideband region and $M_B$ distribution for $B^0 \rightarrow \Lambda_c^+ \overline{p}\pi^-\pi^-$ from (c) $\Delta E$ signal region, (d) $\Delta E$ sideband region.

FIG. 2. $\Delta E$ distributions for (a) $B^- \rightarrow \Lambda_c^+ \overline{p}\pi^-$ and (b) $B^0 \rightarrow \Lambda_c^+ \overline{p}\pi^+\pi^-$ from $M_B$ signal region (histogram) and sideband region (shaded histogram).
FIG. 3. $M_B$ distribution for (a) $B^0 \rightarrow \Lambda_c^+ \overline{p} n^0$, (b) $B^- \rightarrow \Lambda_c^+ \overline{p} n^- \pi^0$, (c) $\overline{B}^0 \rightarrow \Lambda_c^+ \overline{p} n^+ \pi^- \pi^0$, and (d) $B^- \rightarrow \Lambda_c^+ \overline{p} n^+ \pi^- \pi^- \pi^0$. The curve is the result of the fit and the dotted line is the 90% confidence level upper limit.

FIG. 4. $M_B$ distribution for (a) $\overline{B}^0 \rightarrow \Lambda_c^+ \overline{p}$, (b) $B^- \rightarrow \Lambda_c^+ \overline{p} n^+ \pi^- \pi^-$, and (c) $\overline{B}^0 \rightarrow \Lambda_c^+ \overline{p} n^+ \pi^- \pi^+ \pi^-$. The curve is the result of the fit and the dotted line is the 90% confidence level upper limit.