First Observation of Inclusive $B$ Decays to the Charmed Strange Baryons $\Xi^0_c$ and $\Xi^+_c$

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Abstract

Using data collected in the region of the $\Upsilon(4S)$ resonance with the CLEO II detector operating at the Cornell Electron Storage Ring (CESR), we present the first observation of $B$ mesons decaying into the charmed strange baryons $\Xi^0_c$ and $\Xi^+_c$. We find $79 \pm 27 \Xi^0_c$ and $125 \pm 28 \Xi^+_c$ candidates from $B$ decays, leading to product branching fractions of $\mathcal{B}(B \rightarrow \Xi^0_c X \Xi^0 \rightarrow \Xi^- \pi^+ X \Xi^0 \rightarrow \Xi^- \pi^+ \pi^+ \pi^+) = (0.144 \pm 0.048 \pm 0.021) \times 10^{-3}$ and $\mathcal{B}(B \rightarrow \Xi^+_c X \Xi^+ \rightarrow \Xi^- \pi^+ \pi^+) = (0.453 \pm 0.096 \pm 0.085) \times 10^{-3}$. 
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Charmed baryon production from the decays of $B$ mesons has been previously reported by ARGUS [1] and CLEO [2,3]. Here, we report the first observation of the charmed-strange baryons $\Xi_c^0$ and $\Xi_c^+$ from $B$ decays [4], which have previously been observed only in direct charm production [5–10].

In $e^+e^-$ annihilations at the $\Upsilon(4S)$ resonance (10.58 GeV), charmed baryons can be produced either from $B$ meson decay or from hadronization of $cc$ quarks produced in the continuum. Since the $b$ quark couples predominantly to the $c$ quark, $B$ meson decays to the charmed strange baryons $\Xi_c^0$ ($csd$) and $\Xi_c^+$ ($csu$) will proceed through either spectator or exchange diagrams. Decays mediated by the coupling $b \rightarrow cW^-$ with $W^- \rightarrow \pi d$ produce final states of the form $\Xi_cYN_Xh$ and $\Xi_cYN_Xs$, where $Y$ is a hyperon ($\Lambda, \Sigma, \Xi$, etc.), $N$ is a nucleon, and $X_h(X_s)$ denotes non-strange (strange) multi-body mesonic states (see Figure 1(a)). As shown in Figure 1(b), decays mediated by $b \rightarrow cW^-$ with $W^- \rightarrow cs$ can lead to states of the form $\Xi_c\Theta_c$ [11,12], where $\Theta_c$ denotes any charmed non-strange baryon. The authors of Refs. [13] and [14] predict branching ratios of $(1.0 - 1.8) \times 10^{-3}$ for those decays. The process $b \rightarrow uW^-$ with $W^- \rightarrow \pi s$ leads to final states of the form $\Xi_cY$, but should be highly suppressed by the small $b \rightarrow u$ coupling.

There are several theoretical calculations that attempt to derive the two-body contribution to charmed baryon production in $B$ decays. In the diquark model [13] baryons of spin $\frac{1}{2}(\frac{3}{2})$ are modeled as bound states of quarks and scalar (vector) diquarks. The $b$ quark decays to a scalar diquark and an antiquark; the latter combines with the light antiquark accompanying the $b$ quark to form an antidiquark. The creation of a $qq$ pair then leads to a baryon and antibaryon in the final state. The authors of Ref. [14] calculate decay amplitudes based on QCD sum rules, replacing both the $B$ meson and the charmed baryon in the final state by suitable interpolating currents. There are also treatments that determine the rates for exclusive baryonic $B$ decays in terms of three reduced matrix elements [15], on the basis of the quark diagram scheme [16], using the constituent quark model [17], and using the pole model [18]. The latter four calculations do not quote explicit predictions for branching fractions of $B$ decay modes which yield $\Xi_c$ baryons.

For this analysis we used 3.1 fb$^{-1}$ of data taken on the $\Upsilon(4S)$ resonance, corresponding to 3.3 million $BB\bar{B}$ events. To estimate and subtract continuum background, 1.6 fb$^{-1}$ of data were collected 60 MeV below the resonance. The data were collected with the CLEO II detector operating at the Cornell Electron Storage Ring, CESR. The CLEO II detector [19] is a general purpose solenoidal-magnet detector with excellent charged particle and shower energy detection capabilities. The detector consists of a charged particle tracking system surrounded by a scintillation counter time-of-flight system and an electromagnetic shower detector consisting of 7800 thallium-doped cesium iodide crystals. These detectors are installed within a 1.5 T superconducting solenoidal magnet. Incorporated in the return yoke of the magnet are chambers for muon detection.

Charge measurements from the drift chamber wires provide specific ionization loss ($dE/dx$) information. To obtain hadron identification, $dE/dx$ and available time-of-flight (TOF) measurements are combined to define a joint $\chi^2 = \frac{1}{2}[(dE/dx)_{\text{meas}} - (dE/dx)_{\text{exp}}]^2/\sigma_{dE/dx}^2 + [\{(T)_{\text{meas}} - (T)_{\text{exp}}\}/\sigma_{\text{TOF}}]^2$, where $i$ corresponds to the pion, kaon, and proton hypotheses. A $\chi^2$-probability is then calculated for each hypothesis, and particle identification levels for each of the hypotheses are derived by normalizing to the sum of the three probabilities. A particle is identified with a specific hypothesis if its particle
We reconstruct $\Xi^0_+(\Xi^+_c)$ candidates through the decay chain $\Xi^0\rightarrow \Xi^-\pi^+ (\Xi^+_c \rightarrow \Xi^-\pi^+\pi^+)$, $\Xi^- \rightarrow \Lambda\pi^-$, and $\Lambda \rightarrow p\pi^-$. We study the $\Xi_c$ momentum spectra using the scaled momentum $x_p \equiv p/(E_{\text{beam}}^2 - m_{\Xi_c}^2)^{1/2}$, where $p$ and $m_{\Xi_c}$ are the $\Xi_c$ momentum and mass, respectively, and $E_{\text{beam}}$ is the beam energy. We require $x_p < 0.5$, the kinematic limit for $\Xi_c$ baryons produced from $B$ decays. This requirement reduces the background from continuum $c\bar{c}$.

The $\Lambda$ candidates are formed from pairs of oppositely charged tracks, assuming the higher momentum track to be a proton and the lower momentum track to be a pion. We also require the higher momentum track to be consistent with the proton hypothesis. The invariant mass of $\Lambda$ candidates has to be within 5.0 MeV/$c^2$ (corresponding to 2.5 standard deviations) of the known $\Lambda$ mass. We have not required $\Lambda$ candidates to point towards the primary vertex, since $\Lambda$’s decaying from $\Xi^-$’s can travel as much as a few centimeters before decaying and can have appreciable impact parameters. To reduce the background from tracks coming from the interaction point, we require the radial distance of the $\Lambda$ decay vertex from the beam line to be greater than 2 mm.

The $\Xi^-$ candidates are formed by combining each $\Lambda$ candidate with the remaining negatively charged tracks in the event, assuming the additional track to be a pion. The decay vertex of the $\Xi^-$ candidate is reconstructed by intersecting the extrapolated $\Lambda$ path with the negatively charged track. We require the radial distance of the $\Xi^-$ decay vertex from the beam line to be greater than 2 mm and less than the radial distance of the $\Lambda$ decay vertex. In addition, the reconstructed $\Xi^-$ momentum vector has to point back to the interaction point. The invariant mass of the $\Xi^-$ candidates has to be within 6.5 MeV/$c^2$ (corresponding to 3 standard deviations) of the known $\Xi^-$ mass.

To reconstruct $\Xi^0_c$ candidates, we form combinations of $\Xi^-$ with one positively charged track, and to reconstruct $\Xi^+_c$ candidates, we combine each $\Xi^-$ with two positively charged tracks. These additional charged tracks are required to originate from the interaction point and to be consistent with the pion hypothesis.

To find the $\Xi_c$ signal yields, we fit each invariant mass distribution to the sum of a Gaussian function of fixed width and a second order polynomial background, both for the $\Upsilon$(4S) and the continuum data. The fixed widths for the two modes were determined using a Monte Carlo simulation of the detector, resulting in widths of 8.0 and 6.8 MeV for the $\Xi^0$ and the $\Xi^+_c$, respectively. We scale the continuum yields to account for the differences in luminosities and cross sections in the two data sets with the scale factor $(\mathcal{L}_T(4S)/\mathcal{L}_{\text{cont}})(E^2_{\text{cont}}/E^2_T(4S))$, where $\mathcal{L}_T(4S)$ and $\mathcal{L}_{\text{cont}}$ are the luminosities, and $E_T(4S)$ and $E_{\text{cont}}$ are the beam energies on the $\Upsilon$(4S) and on the continuum. Figure 2 shows the invariant mass distributions of the $\Xi^-\pi^+$ and $\Xi^-\pi^+\pi^+$ combinations from $\Upsilon$(4S) and scaled continuum data. After subtracting the scaled continuum yield from the $\Upsilon$(4S) yield, we observe $79 \pm 27 \Xi^0$ candidates and $125 \pm 28 \Xi^+_c$ candidates from $B$ decays. The errors are statistical only. The fitted $\Xi_c$ masses are consistent with the current world averages.

To measure the product branching fractions for the two decay modes, we divide both data and Monte Carlo into $x_p$ intervals. The reconstruction efficiency in each mode is found as a function of $x_p$ using Monte Carlo simulations. Tables II and III show the continuum subtracted raw yields $y_p(x_p)$ and efficiency-corrected yields $y_c(x_p)$. We also give the fractional decay rate in each $x_p$ interval, $(1/N_B)(dy_c/dx_p)$, where $N_B$ is $2N_{BB}$, for $\Xi^0$ and $\Xi^+_c$ production. We find
Monte Carlo simulations of the decays $B$ and $\Xi^-$, with the first error being statistical and the second being systematic. The main sources of systematic error are due to uncertainties in the reconstruction efficiencies for $\Lambda$ (5%) and $\Xi^-$ (7%), variations in the selection criteria (8-9%), uncertainties in particle identification (5%), charged particle tracking (1% per track), and the Monte Carlo predictions for the signal width (4%). These result in a total systematic uncertainty of about 14%. In addition, we assign a +12% systematic uncertainty in the $\Xi^0 - \Xi^-$ case for the possible resonant substructure $\Xi^0\pi^+$, since this would decrease the $\Xi^+_c$ reconstruction efficiency considerably.

We can convert these product branching fractions into absolute branching ratios using the following branching fractions of $\Xi^0_c \to \Xi^-\pi^+$ and $\Xi^+_c \to \Xi^-\pi^+$, derived by CLEO [20]: $B(\Xi^0_c \to \Xi^-\pi^+) = f_{SL} f_{\Xi_c}(0.52 \pm 0.16^{+0.15}_{-0.10})\%$ and $B(\Xi^+_c \to \Xi^-\pi^+) = f_{SL} f_{\Xi_c}(2.5 \pm 0.6 \pm 0.3)\%$, where $f_{\Xi_c} \equiv B(\Xi_c \to \Xi\ell^+\nu_\ell)/B(\Xi_c \to \ell^+X) \leq 1$ (current predictions range from 0.4 to 0.9 [21,22]), and $f_{SL} \equiv (\Gamma_{SL}/\Gamma_{SL}(\Xi^0_c,\Xi^+_c,\Xi^-))$, with $\Gamma_{SL}$ being the total semileptonic width. These numbers are actually slightly different from the published values, since we are now using an updated value for $\Gamma_{SL} = 0.165 \pm 0.009$ ps$^{-1}$ [23,24] (instead of the previous value of 0.138 \pm 0.006) ps$^{-1}$). In addition, we have introduced the factor $f_{SL}$ to account for variations in the selection criteria (8-9%).

In Figure 3 we present the corresponding efficiency-corrected momentum spectra of $\Xi^0_c$ and $\Xi^+_c$ baryons in $B$ decays. Superimposed on the measured spectra are the results from Monte Carlo simulations of the decays $\bar{B} \to \Xi_c \bar{\Lambda}_c(n\pi)$, $n = 0,\ldots,3$. Comparing the measured spectra with Monte Carlo predictions indicates that two-body final states such as $\Xi_c\Lambda_c$ and $\Xi_c\Sigma_c$ are suppressed while multi-body final states seem to be dominant. We are not yet sensitive to $b \to c\bar{c}s$ decays leading to final states of the form $\Xi_c\Lambda_c$ or $\Xi_c\Sigma_c$, which are predicted by the authors of Refs. [13] and [14] to have branching fractions of only $(1.0-1.8) \times 10^{-3}$ for those decays. These branching fractions are at least an order of magnitude lower than the inclusive branching fractions for $\bar{B} \to \Xi_c X$.

In summary, we have presented the first observation of $B$ mesons decaying into the charmed strange baryons $\Xi^0_c$ and $\Xi^+_c$. From an examination of the measured $\Xi^0_c$ and $\Xi^+_c$ momentum spectra, it is not clear which of the possible production mechanisms $b \to c\bar{c}d$ or $b \to c\bar{c}s$ is preferred or dominant, since the observed momentum spectra are consistent with both mechanisms. It seems, however, that decays involving a heavier anti-baryon or multi-body decays are favored.

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FIG. 1. Possible $B \to$ baryon decay mechanisms: (a) $\bar{B} \to B^{+} \Xi_{c}N \Xi_{c}$ and $\Xi_{c}YX$, (b) $\bar{B} \to \Xi_{c}B^{+}X$ and $\bar{B} \to Y \Xi_{c}X$; $N$ stands for any non-strange non-charmed baryon, $Y$ for any strange and non-charmed baryon, and $\Theta_{c}$ for any charmed and non-strange baryon.
FIG. 2. Invariant mass distributions of (a) $\Xi^-\pi^+$ and (b) $\Xi^-\pi^+\pi^+$ from $\Upsilon(4S)$ resonance (points) and scaled continuum (shaded histogram) data.
FIG. 3. Efficiency-corrected momentum spectra for (a) $\Xi^0_c$ and (b) $\Xi^+_c$ from $B$ decays. The superimposed curves indicate the spectra derived from Monte Carlo simulation of the decays $B \to \Xi_c \Lambda_c(n\pi)$, $n = 0, ..., 3$. The Monte Carlo curves have been normalized to data, except for the two-body decays, where the normalization is arbitrary.
| $\Delta x_p$ | Raw yield $y_r(x_p)$ | Corr. yield $y_c(x_p)$ | $(1/N_B)(dy_c/dx_p)$ |
|-------------|-----------------|-----------------|-----------------|
| 0.0 – 0.1   | $27.0 \pm 6.5$  | $358.8 \pm 88.1$ | $0.54 \pm 0.13$ |
| 0.1 – 0.2   | $33.4 \pm 13.5$ | $399.5 \pm 162.3$ | $0.60 \pm 0.24$ |
| 0.2 – 0.3   | $43.5 \pm 13.6$ | $482.8 \pm 152.5$ | $0.72 \pm 0.23$ |
| 0.3 – 0.4   | $-18.1 \pm 12.2$ | $-191.5 \pm 129.5$ | $-0.29 \pm 0.19$ |
| 0.4 – 0.5   | $-6.9 \pm 13.3$ | $-89.7 \pm 174.1$  | $-0.13 \pm 0.26$ |
| 0.0 – 0.5   | $78.9 \pm 27.2$ | $959.9 \pm 323.1$  |                 |

| $\Delta x_p$ | Raw yield $y_r(x_p)$ | Corr. yield $y_c(x_p)$ | $(1/N_B)(dy_c/dx_p)$ |
|-------------|-----------------|-----------------|-----------------|
| 0.0 – 0.1   | $10.0 \pm 7.0$  | $417.1 \pm 295.0$ | $0.62 \pm 0.44$ |
| 0.1 – 0.2   | $47.0 \pm 14.3$ | $1273.5 \pm 392.6$ | $1.91 \pm 0.59$ |
| 0.2 – 0.3   | $41.8 \pm 13.0$ | $901.4 \pm 285.5$ | $1.35 \pm 0.43$ |
| 0.3 – 0.4   | $20.2 \pm 13.6$ | $344.2 \pm 232.8$ | $0.52 \pm 0.35$ |
| 0.4 – 0.5   | $6.0 \pm 12.4$  | $89.6 \pm 186.0$  | $0.13 \pm 0.28$ |
| 0.0 – 0.5   | $125.0 \pm 27.6$ | $3025.8 \pm 641.5$ |                 |