First Observation of Inclusive B Decays to the Charmed Strange Baryons Ξ_c^0 and Ξ_c^+

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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 Ξ_c^0 and Ξ_c^+. We find 79 ± 27 Ξ_c^0 and 125 ± 28 Ξ_c^+ candidates from B decays, leading to product branching fractions of $\mathcal{B}(\overline{B} \to \Xi_c^0 X)\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (0.144 \pm 0.048 \pm 0.021) \times 10^{-3}$ and $\mathcal{B}(\overline{B} \to \Xi_c^+ X)\mathcal{B}(\Xi_C^+ \to \Xi^- \pi^+ \pi^+) = (0.453 \pm 0.096^{+0.085}_{-0.065}) \times 10^{-3}$. [S0031-9007(97)04481-5]

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Charmed baryon production from the decays of B mesons has been previously reported by ARGUS [1] and CLEO [2,3]. Assuming that charmed baryon production in B decays is saturated by Λ_c, CLEO [2] estimated $\mathcal{B}(B \to$ charmed baryon anything$) = (6.4 \pm 0.8 \pm 0.8)\%$. Studying Λ and p yields and various correlations, ARGUS [4] estimated $\mathcal{B}(B \to$ baryons anything$) = (6.8 \pm 0.5 \pm 0.3)\%$. Here, we report the first observation of the charmed-strange baryons Ξ_c^0 and Ξ_c^+ from B decays [5], which have previously been observed only in direct charm production in fragmentation of charm quark [6–11].

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 $c\overline{c}$ quarks produced in the continuum. Since the b quark couples predominantly to the c quark, B meson decays to the charmed strange baryons Ξ_c^0 (csd) and Ξ_c^+ (csu) will proceed through either spectator or exchange diagrams. Decays mediated by the coupling $b \to cW^-$ with $W^- \to \overline{u}d$ produce final states of the form $\Xi_c \overline{Y} X_h$ and $\Xi_c \overline{N} X_s$, where Y is a hyperon (Λ, Σ, Ξ, etc.), N is a nucleon, and X_h (X_s) denotes nonstrange (strange) multibody mesonic states [see Fig. 1(a)]. As shown in Fig. 1(b), decays mediated by $b \to cW^-$ with $W^- \to \overline{c}s$ can lead to states of the form $\Xi_c \overline{\Theta}_c$ [12,13], where Θ_c denotes any charmed nonstrange baryon. The authors of Refs. [14] and [15] predict branching ratios of $(1.0 - 1.8) \times 10^{-3}$ for those decays. Depending on the actual fraction of $\mathcal{B}(b \to c\overline{c}s)/\mathcal{B}(b \to \text{all})$ (currently the number is believed to be about 19% [13]), this decay process may or may not solve the long-standing question of missing charm in B decays. The process $b \to uW^-$ with $W^- \to \overline{c}s$ leads to final states of the form $\overline{\Xi}_c Y$, but should be highly suppressed by the small $b \to u$ 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 [14], baryons are modeled as bound states of quarks and scalar (vector) diquarks. The authors of Ref. [15] calculate decay amplitudes based on quantum chromodynamics (QCD) sum rules. There are also treatments that determine the rates for exclusive baryonic B decays in terms of three reduced matrix elements [16], on the basis of the quark diagram scheme [17], using the constituent quark model [18], and using the pole model [19]. The latter four calculations do not quote explicit predictions for branching fractions of B decay modes which yield Ξ_c baryons.

For this analysis we used 3.1 fb^{-1} of data taken on the $\Upsilon(4S)$ resonance, corresponding to 3.3×10^6 $B\overline{B}$ events. To estimate and subtract continuum background, 1.6 fb^{-1} of data were collected at a center-of-mass energy 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 [20] 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 (TOF) system and an electromagnetic shower detector consisting of 7800 thallium-doped

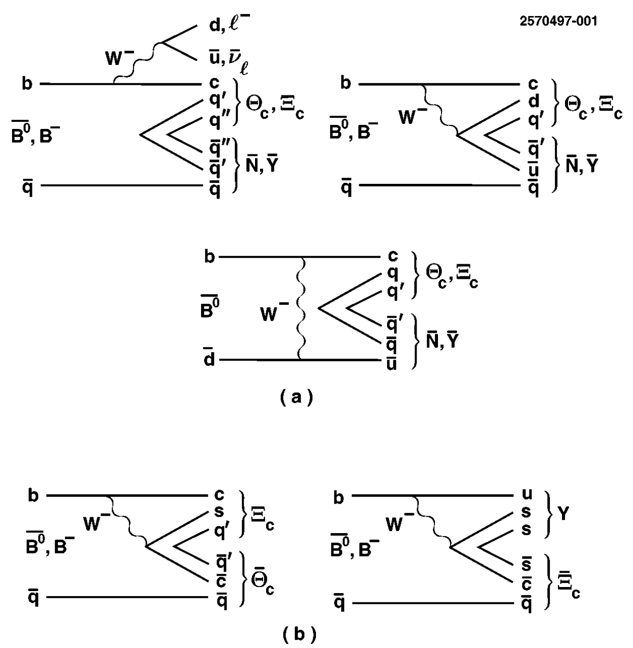

FIG. 1. Possible $B \to$ baryon decay mechanisms: (a) $\overline{B} \to \Theta_c \overline{N} X$ and $\Xi_c \overline{Y} X$, (b) $\overline{B} \to \Xi_c \overline{\Theta}_c X$ and $\overline{B} \to Y \overline{\Xi}_c X$; N stands for any nonstrange noncharmed baryon, Y for any strange and noncharmed baryon, and Θ_c for any charmed and nonstrange baryon.

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. The recently installed Silicon-Vertex-Detector was not employed for this analysis, since the data were taken before its installation. Instead, the previously installed precision tracking layer and vertex detectors were used.

Charge measurements from the drift chamber wires provide specific ionization energy loss (dE/dx) information. To obtain hadron identification, dE/dx and available time-of-flight measurements are combined to define a joint $\chi_i^2 = [\{(dE/dx)_{\rm meas} - (dE/dx)_{\rm exp}\}/\sigma_{dE/dx}]_i^2 + [\{(T)_{\rm meas} - (T)_{\rm exp}\}/\sigma_{\rm TOF}]_i^2$, where i corresponds to the pion, kaon, and proton hypotheses. A χ^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 identification level for it is greater than 0.05.

We reconstruct Ξ_c^0 (Ξ_c^+) candidates through the decay chain $\Xi_c^0 \to \Xi^- \pi^+$ ($\Xi_c^+ \to \Xi^- \pi^+ \pi^+$), $\Xi^- \to \Lambda \pi^-$, and $\Lambda \to p \pi^-$. We study the Ξ_c momentum spectra using the scaled momentum $x_p \equiv p/(E_{\rm beam}^2 - m_{\Xi_c}^2)^{1/2}$, where p and m_{Ξ_c} are the Ξ_c momentum and mass, respectively, and $E_{\rm beam}$ is the beam energy. We require $x_p < 0.5$, the kinematic limit for Ξ_c baryons produced from B decays. This requirement reduces the background from continuum $c\bar{c}$.

The Λ 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 Λ candidates has to be within 5.0 MeV/c^2 (corresponding to 2.5 standard deviations) of the known Λ mass. We have not required Λ candidates to point towards the primary vertex, since Λ's decaying from Ξ^-'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 Λ decay vertex from the beam line to be greater than 2 mm.

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

To reconstruct Ξ_c^0 candidates, we form combinations of Ξ^- with one positively charged track, and to reconstruct Ξ_c^+ candidates, we combine each Ξ^- 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 Ξ_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 Ξ_c^0 and the Ξ_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 $(\mathcal{L}_{\Upsilon(4S)}/\mathcal{L}_{\rm cont})(E_{\rm cont}^2/E_{\Upsilon(4S)}^2)$, where $\mathcal{L}_{\Upsilon(4S)}$ and $\mathcal{L}_{\rm cont}$ are the luminosities, and $E_{\Upsilon(4S)}$ and $E_{\rm cont}$ 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 ± 27 Ξ_c^0 candidates and 125 ± 28 Ξ_c^+ candidates from B decays. The errors are statistical only. The fitted Ξ_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 I and II show the continuum subtracted raw yields $y_r(x_p)$ and efficiency-corrected yields $y_c(x_p)$. We

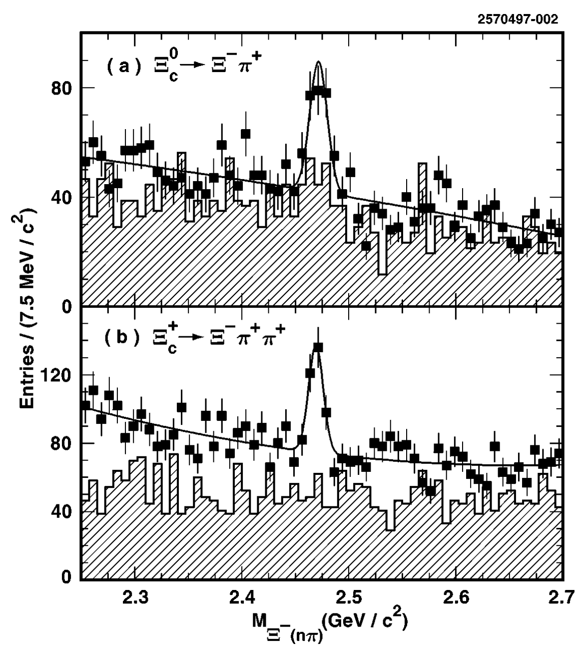

FIG. 2. Invariant mass distributions of (a) $\Xi^- \pi^+$ and (b) $\Xi^- \pi^+ \pi^+$ from $\Upsilon(4S)$ resonance (points) and scaled continuum (shaded histogram) data.

TABLE I. Inclusive Ξ_c^0 production in B decays.

Δx_p	Raw yield $y_r(x_p)$	Corrected yield $y_c(x_p)$	$(1/N_B)(dy_c/dx_p)$ $[10^{-3}]$
0.0–0.1	27.0 ± 6.5	358.8 ± 88.1	0.54 ± 0.13
0.1–0.2	33.4 ± 13.5	399.5 ± 162.3	0.60 ± 0.24
0.2–0.3	43.5 ± 13.6	482.8 ± 152.5	0.72 ± 0.23
0.3–0.4	−18.1 ± 12.2	−191.5 ± 129.5	−0.29 ± 0.19
0.4–0.5	−6.9 ± 13.3	−89.7 ± 174.1	−0.13 ± 0.26
0.0–0.5	78.9 ± 27.2	959.9 ± 323.1	

also give the fractional decay rate in each x_p interval, $(1/N_B)(dy_c/dx_p)$, where N_B is $2N_{B\overline{B}}$, for Ξ_c^0 and Ξ_c^+ production. We find $\mathcal{B}(\overline{B} \to \Xi_c^0 X)\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (0.144 \pm 0.048 \pm 0.021) \times 10^{-3}$ and $\mathcal{B}(\overline{B} \to \Xi_c^+ X) \times \mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (0.453 \pm 0.096^{+0.085}_{-0.065}) \times 10^{-3}$, 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 Λ (5%) and Ξ^- (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 errors were combined quadratically, resulting in a total systematic uncertainty of about 14%. In addition, we assign a $+12\%$ systematic uncertainty (also added in quadratically) in the $\Xi^- \pi^+ \pi^+$ case for the possible resonant substructure $\Xi^{*0}\pi^+$, since this would decrease the Ξ_c^+ reconstruction efficiency considerably.

We can convert these product branching fractions into absolute branching ratios using the following branching fractions of $\Xi_c^0 \to \Xi^- \pi^+$ and $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$, derived by CLEO [21]: $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = f_{\rm SL} f_{\Xi_c}(0.52 \pm 0.16^{+0.15}_{-0.10})\%$ and $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = f_{SL} f_{\Xi_c}(2.5 \pm 0.6^{+0.8}_{-0.5})\%$, where $f_{\Xi_c} \equiv \mathcal{B}(\Xi_c \to \Xi \ell^+ \nu_l)/\mathcal{B}(\Xi_c \to \ell^+ X) \leq 1$ (current predictions range from 0.4 to 0.9 [22,23]), and $f_{\rm SL} \equiv (\Gamma_{SL}^{\Xi_c}/\Gamma_{SL}^{\Lambda_c})(\Gamma_{SL}^{\Lambda_c}/\Gamma_{SL}^{D})$, with $\Gamma_{\rm SL}$ being the total semileptonic width. The branching fractions were obtained using the semileptonic decay modes $\mathcal{B}(\Xi_c \to \Xi^- \ell \nu_l)$ and the lifetimes of the Ξ_c. The numbers are actually slightly different from the published values, since we are now using an updated value for $\Gamma_{\rm SL}^D = (0.165 \pm 0.009)\ \mathrm{ps}^{-1}$ [24,25] (instead of the previous value of $(0.138 \pm 0.006)\ \mathrm{ps}^{-1}$). In addition, we have introduced the factor $f_{\rm SL}$ to account for predictions of the semileptonic width of the Ξ_c being quite different from that of the Λ_c [26] (two to three times as large), which in turn should be different from that of the D [27], namely, about 1.5 times as large. This leads to the following absolute branching ratios: $\mathcal{B}(\overline{B} \to \Xi_c^0 X) = f_{\rm SL}^{-1} f_{\Xi_c}^{-1}(2.8 \pm 0.9^{+1.2}_{-1.1})\%$ and $\mathcal{B}(\overline{B} \to \Xi_c^+ X) = f_{\rm SL}^{-1} f_{\Xi_c}^{-1}(1.8 \pm 0.4^{+0.8}_{-0.6})\%$. The product of the two f factors could assume any number between 1.2 and 4.0, and therefore the sum of the absolute Ξ_c branching fractions could be anywhere between 1% and 4%. This would be consistent with the current estimate of B decays to charmed baryons of roughly 6.4% [2].

In Fig. 3 we present the corresponding efficiency-corrected spectra of Ξ_c^0 and Ξ_c^+ baryons in B decays. Superimposed on the measured spectra are the results from Monte Carlo simulations of the decays $\overline{B} \to \Xi_c \overline{\Lambda}_{(c)}(n\pi)$, $n = 0, ..., 3$. Comparing the measured spectra with Monte Carlo predictions indicates that two-body final states such as $\Xi_c \overline{\Lambda}$ and $\Xi_c \overline{\Sigma}$ are suppressed, while multibody final states seem to be dominant. We are not yet sensitive to $b \to c\overline{c}s$ decays leading to final states of the form $\Xi_c \overline{\Lambda}_c$ or $\Xi_c \overline{\Sigma}_c$, which are predicted by the authors of Refs. [14] and [15] 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 $\overline{B} \to \Xi_c X$.

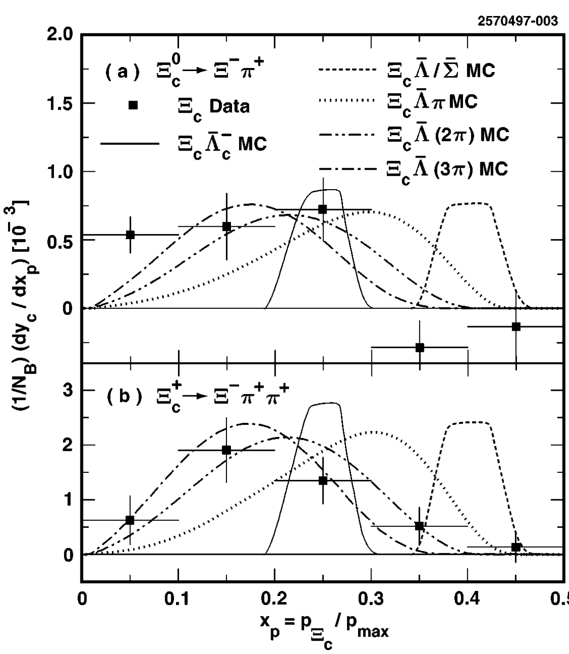

FIG. 3. Efficiency-corrected momentum spectra for (a) Ξ_c^0 and (b) Ξ_c^+ from B decays. The superimposed curves indicate the spectra derived from Monte Carlo simulation of the decays $\overline{B} \to \Xi_c \overline{\Lambda}_{(c)}(n\pi)$, $n = 0, ..., 3$. The Monte Carlo curves have been normalized to data, except for the two-body decays, where the normalization is arbitrary.

TABLE II. Inclusive Ξ_c^+ production in B decays.

Δx_p	Raw yield $y_r(x_p)$	Corrected yield $y_c(x_p)$	$(1/N_B)(dy_c/dx_p)$ $[10^{-3}]$
0.0–0.1	10.0 ± 7.0	417.1 ± 295.0	0.62 ± 0.44
0.1–0.2	47.0 ± 14.3	1273.5 ± 392.6	1.91 ± 0.59
0.2–0.3	41.8 ± 13.0	901.4 ± 285.5	1.35 ± 0.43
0.3–0.4	20.2 ± 13.6	344.2 ± 232.8	0.52 ± 0.35
0.4–0.5	6.0 ± 12.4	89.6 ± 186.0	0.13 ± 0.28
0.0–0.5	125.0 ± 27.6	3025.8 ± 641.5	

In summary, we have presented the first observation of B mesons decaying into the charmed-strange baryons Ξ_c^0 and Ξ_c^+. From an examination of the measured Ξ_c^0 and Ξ_c^+ momentum spectra, it is not clear which of the possible production mechanisms $b \to c\bar{u}d$ 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 multibody decays and decays where the Ξ_c recoils against a heavier antibaryon such as a $\overline{\Lambda}_c$ or $\overline{\Sigma}_c$ are favored.

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