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First Observation of Inclusive B Decays to the Charmed Strange Baryons Ξ_c^0 and Ξ_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 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 $\mathcal{B}(\overline{B} \to \Xi_c^+ X)\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (0.453 \pm 0.096\,^{+0.085}_{-0.065}) \times 10^{-3}$.

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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 Ξ_c^0 and Ξ_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 $c\overline{c}$ 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 non-strange (strange) multi-body mesonic states (see Figure 1(a)). As shown in Figure 1(b), decays mediated by $b \to cW^-$ with $W^- \to \overline{c}s$ can lead to states of the form $\Xi_c\overline{\Theta}_c$ [11,12], where Θ_c denotes any charmed non-strange baryon. The authors of Refs. [13] and [14] predict branching ratios of $(1.0-1.8)\times10^{-3}$ for those decays. The process $b \to uW^-$ with $W^- \to \overline{c}s$ leads to final states of the form $\overline{\Xi}_cY$, 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 [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 $q\bar{q}$ 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 Ξ_c baryons.

For this analysis we used 3.1 fb^{-1} of data taken on the $\Upsilon(4S)$ resonance, corresponding to 3.3 million $B\overline{B}$ 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 $\chi_i^2 = [\{(dE/dx)_{\rm meas} - (dE/dx)_{\rm exp}\}/\sigma_{dE/dx}]_i^2 + [\{(T)_{\rm meas} - (T)_{\rm exp}\}/\sigma_{\rm TOF}]_i^2$, 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 $c\overline{c}$.

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 3 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 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 $\mathcal{B}(\overline{B} \to \Xi_c^+ X)\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (0.453 \pm 0.096\,^{+\,0.085}_{-\,0.065}) \times 10^{-3}$, 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 result in a total systematic uncertainty of about 14%. In addition, we assign a +12% systematic uncertainty 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 [20]: $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = f_{SL} f_{\Xi_c} (0.52 \pm 0.16\,^{+\,0.15}_{-\,0.10})\%$ 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 [21,22]), and $f_{SL} \equiv (\Gamma_{SL}^{\Xi_c}/\Gamma_{SL}^{\Lambda_c})(\Gamma_{SL}^{\Lambda_c}/\Gamma_{SL}^{D})$, with Γ_{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 $\Gamma_{SL}^{D} = (0.165 \pm 0.009)$ ps^{-1} [23,24] (instead of the previous value of (0.138 ± 0.006) ps^{-1}). In addition, we have introduced the factor f_{SL} to account for predictions of the semileptonic width of the Ξ_c being quite different from that of the Λ_c [25] (2 to 3 times as large), which in turn should be different from that of the D [26], namely about 1.5 times as large. This leads to the following absolute branching ratios: $\mathcal{B}(\overline{B} \to \Xi_c^0 X) = f_{SL}^{-1} f_{\Xi_c}^{-1} (2.8 \pm 1.3\,^{+\,0.9}_{-\,0.7})\%$ and $\mathcal{B}(\overline{B} \to \Xi_c^+ X) = f_{SL}^{-1} f_{\Xi_c}^{-1} (1.8 \pm 0.6\,^{+\,0.7}_{-\,0.4})\%$.

In Figure 3 we present the corresponding efficiency-corrected momentum 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 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 $\Xi_c\overline{\Lambda}_c$ or $\Xi_c\overline{\Sigma}_c$, 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 $\overline{B} \to \Xi_c X$.

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 decays involving a heavier anti-baryon or multi-body decays are favored.

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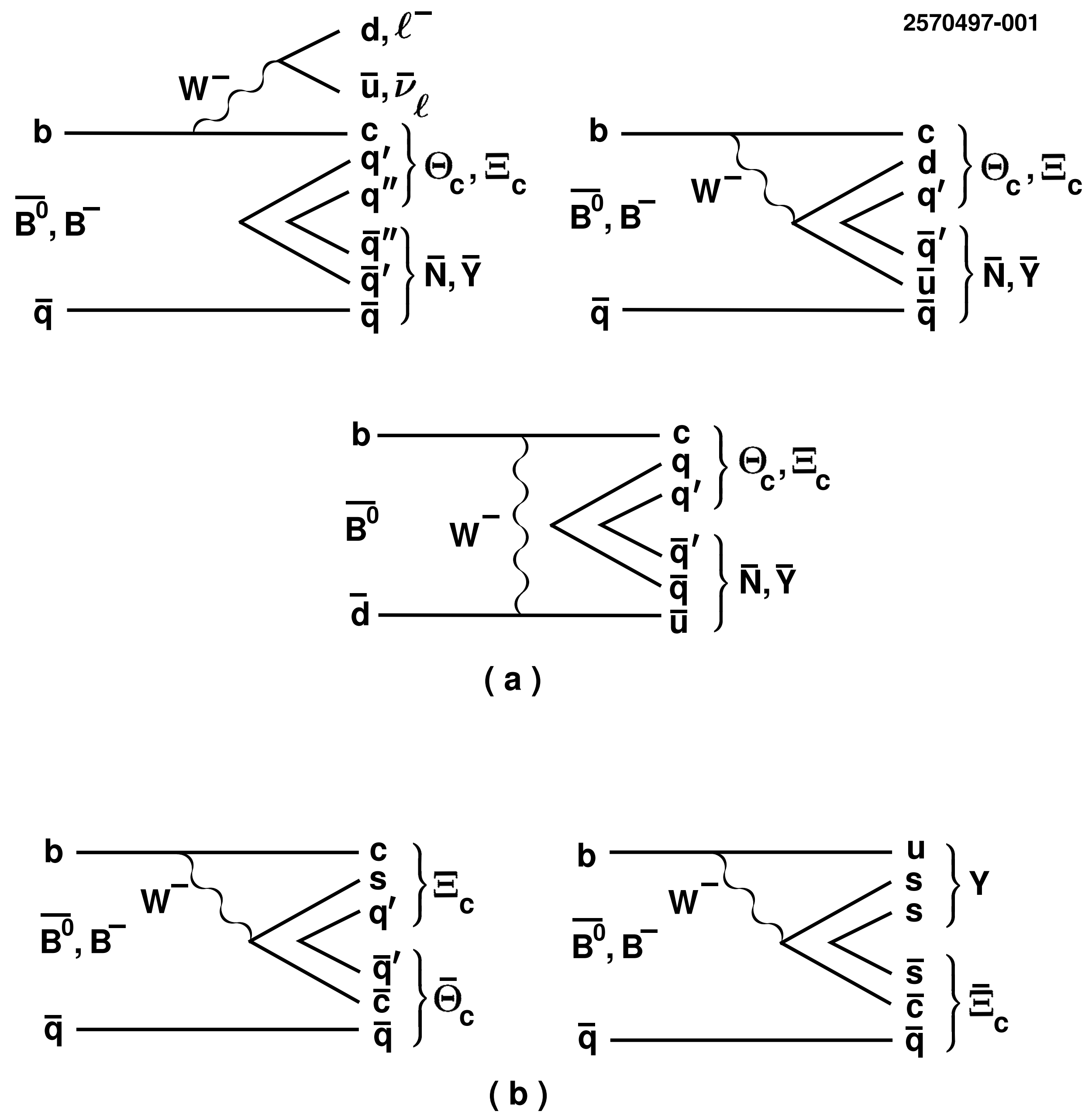

FIG. 1. Possible $B \to$ baryon decay mechanisms: (a) $\overline{B} \to \Theta_c \overline{N} X$ and $\Xi_c \overline{Y} X$, (b) $\overline{B} \to \Xi_c \overline{\Theta}_c X$ and $\overline{B} \to Y \overline{\Xi}_c X$; N stands for any non-strange non-charmed baryon, Y for any strange and non-charmed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

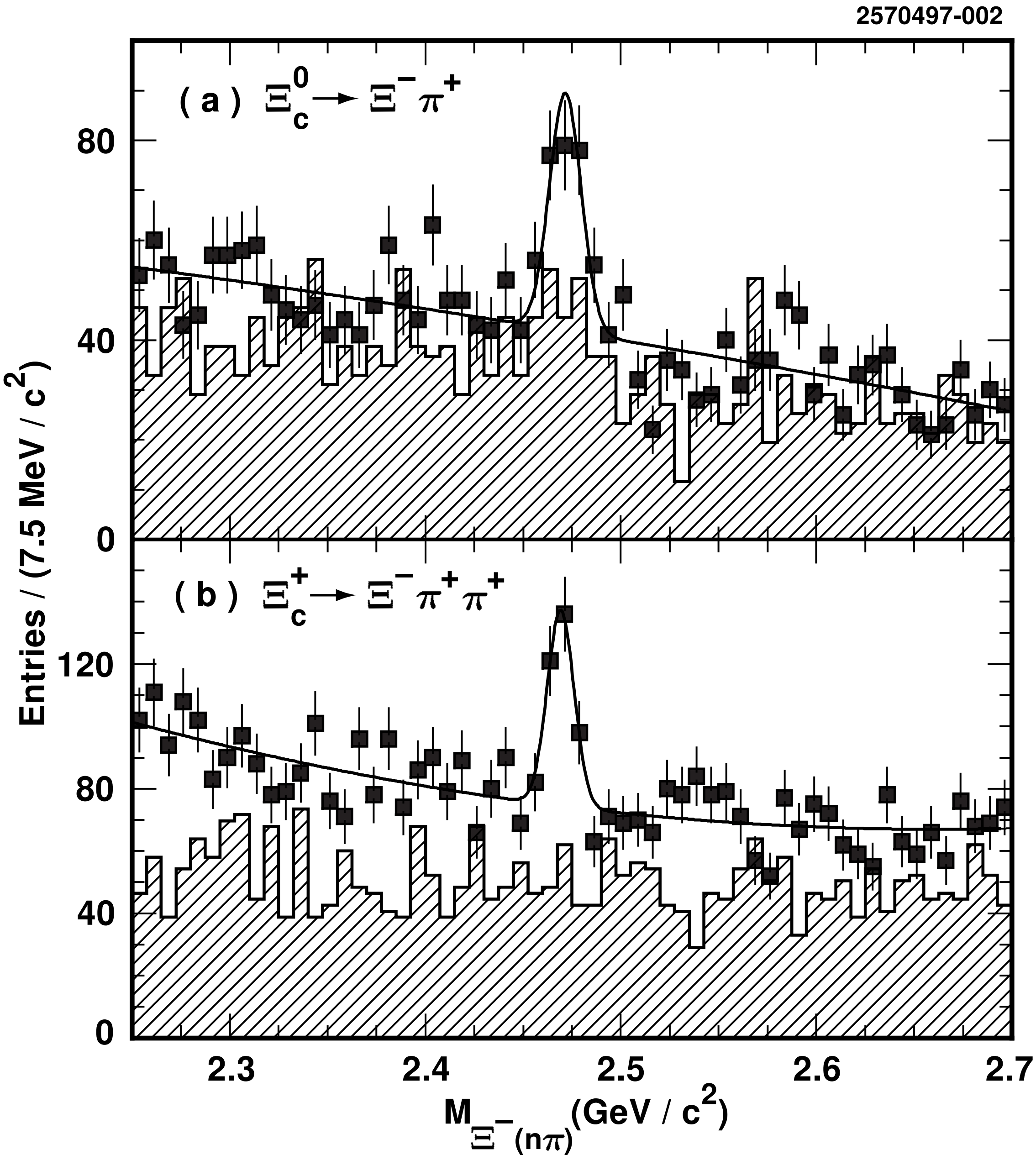

FIG. 2. Invariant mass distributions of (a) $\Xi^- \pi^+$ and (b) $\Xi^- \pi^+ \pi^+$ from $\Upsilon(4S)$ resonance (points) and scaled continuum (shaded histogram) data.

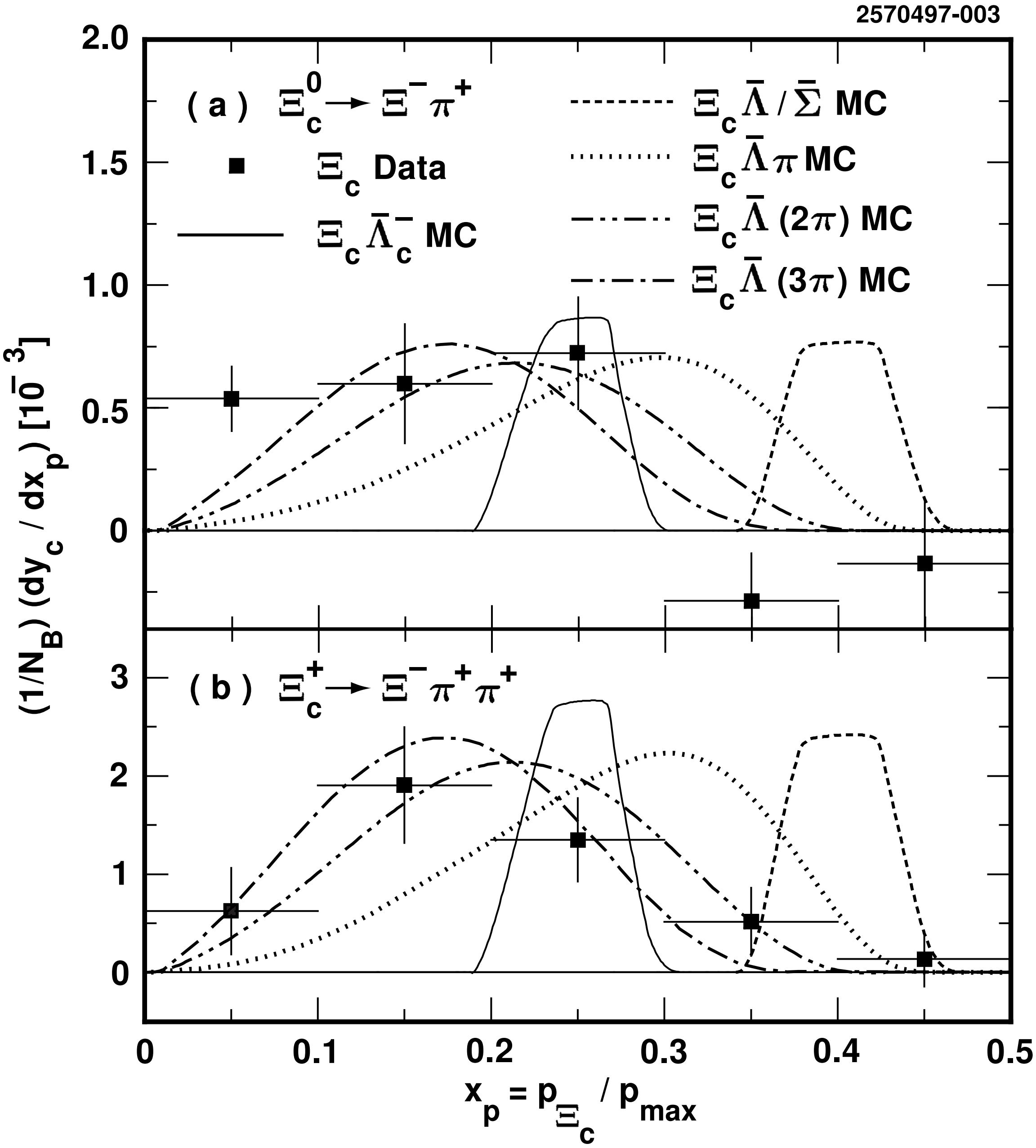

FIG. 3. Efficiency-corrected momentum spectra for (a) Ξ_c^0 and (b) Ξ_c^+ from B decays. The superimposed curves indicate the spectra derived from Monte Carlo simulation of the decays $\overline{B} \to \Xi_c \overline{\Lambda}_{(c)}(n\pi)$, $n = 0, ..., 3$. The Monte Carlo curves have been normalized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

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

Δx_p	Raw yield $y_r(x_p)$	Corr. 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	

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

Δx_p	Raw yield $y_r(x_p)$	Corr. 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	