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CHARMED BARYON PRODUCTION AND DECAY: RECENT RESULTS FROM CLEO AND E687

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Abstract

The CLEO and E687 experiments have been prolific in the study of charmed baryons. Several new decay modes of the Λ_c^+ have been observed. Two new excited charmed baryons, $\Lambda_c^{*+}(2593)$ and $\Lambda_c^{*+}(2625)$, have been observed to decay into $\Lambda_c^+\pi^-\pi^+$ and are identified as the orbitally excited Λ_c^+ baryons. E687 has observed the Ω_c^0 baryon decaying into $\Sigma^+K^-K^-\pi^+$ and measured the Ω_c^0 mass. The $B \to$ baryon decay mechanism has been investigated by CLEO. Λ_c^+ – lepton correlations and the observation of $B \to \Xi_c X$ suggest that the $b \to c\bar{u}d$ process, which leads to final states of the form $B \to \Lambda_c^+\bar{N}X$ and $\Xi_c\bar{\Lambda}X$, dominates over the $b \to c\bar{c}s$ process, which yields $B \to \Xi_c\bar{\Lambda}_c X$ decays. Finally, the first exclusive decay of the B meson into charmed baryons, $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^-\pi^+$, has been observed.

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I. INTRODUCTION

The E687 and CLEO Collaborations have active programs in charm baryon physics, with substantially complementary physics capabilities. The E687 photoproduction experiment uses silicon detectors to isolate the charm signals and measure their lifetimes. The Cerenkov detector provides very good $\pi/K/p$ separation. However, only final states with all charged tracks can be reconstructed. On the other hand, the CLEO detector operates on and around the $\Upsilon(4S)$ resonance, and has collected approximately 3 million $B\bar{B}$ and 4 million $c\bar{c}$ events. Its excellent charged track and photon/π^0 reconstruction efficiencies allow a higher percentage of charmed baryon decay modes to be observed.

In this talk, I will present new decay modes of the Λ_c^+ baryon, excited charmed baryon states, and the observation of the Ω_c^0. I'll next discuss the mechanisms for producing baryons in B meson decays, followed by the observation of $B \to \Xi_c X$ and the first exclusive decay channel of B meson to Λ_c^+.

II. NEW DECAY MODES OF THE Λ_c^+

In the past, the decay of charmed baryons have been theoretically less understood than their brethren, the D mesons. However, because charmed baryons are more complex, they can aid us in exploring decay mechanisms not accessible to ordinary charmed meson decays. The Λ_c^+ decays are neither color suppressed nor helicity suppressed, so they can have substantial contributions from non-factorizable internal W-emission and W-exchange diagrams, respectively. The decays $\Lambda_c^+ \to \Lambda\pi^+$ and $p\bar{K}^0$ are the only two-body decays with factorizable components in their decay amplitudes. Many other two-body decays, such as $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Xi^0 K^+$ have no spectator contributions because the original ud diquark from the Λ_c^+ is perturbed in the decay. It is the importance of these additional decay channels which contributes to a Λ_c^+ lifetime that is half that of the D^0 and D_s^+ mesons.

The E687 and CLEO Collaborations have recently discovered several new decay modes of the Λ_c^+ charmed baryon. E687 [1] has observed the first decay mode of the Λ_c^+ into a final state containing the Σ^- hyperon, namely $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$ (Fig. 1a). The Σ^- hyperons are identified through the decay channel $\Sigma^- \to n\pi^-$ by reconstructing the Σ^- track segment in the silicon detector and the π^- track segment in the multiwire proportional chamber (MWPC). The calorimeter must have an energy deposition at the neutron's projected point of impact. The Cabibbo suppressed decay $\Lambda_c^+ \to pK^-K^+$ has also been observed by E687 [2], as seen in Fig. 1b, although only an upper limit exists for the theoretically more interesting

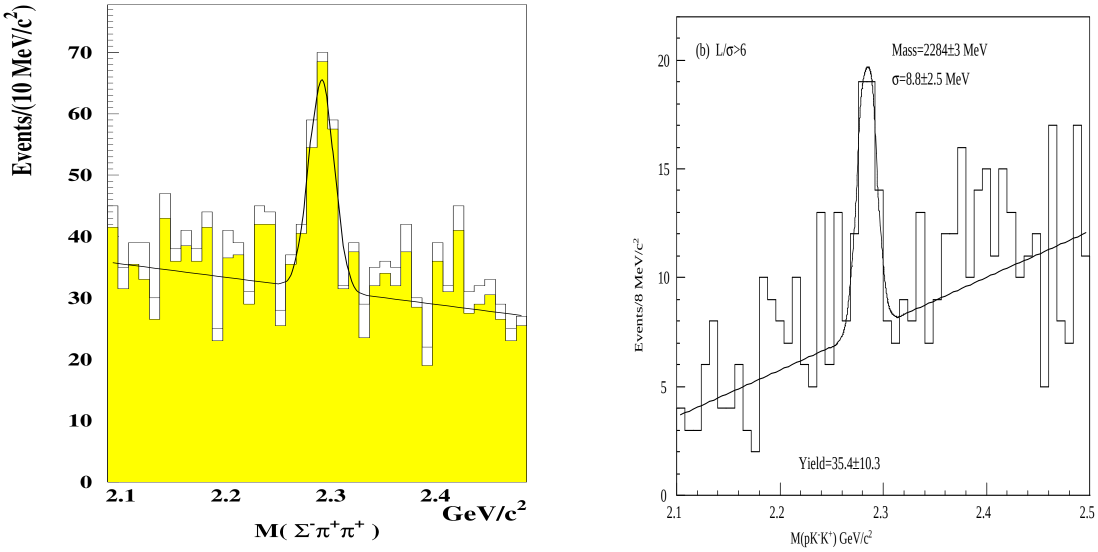

FIG. 1. (a) The invariant mass distributions for $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+$. The non-shaded (shaded) histogram is with (without) double-counting. (b) The invariant mass distributions for the Cabibbo suppressed decay $\Lambda_c^+ \to p K^- K^+$.

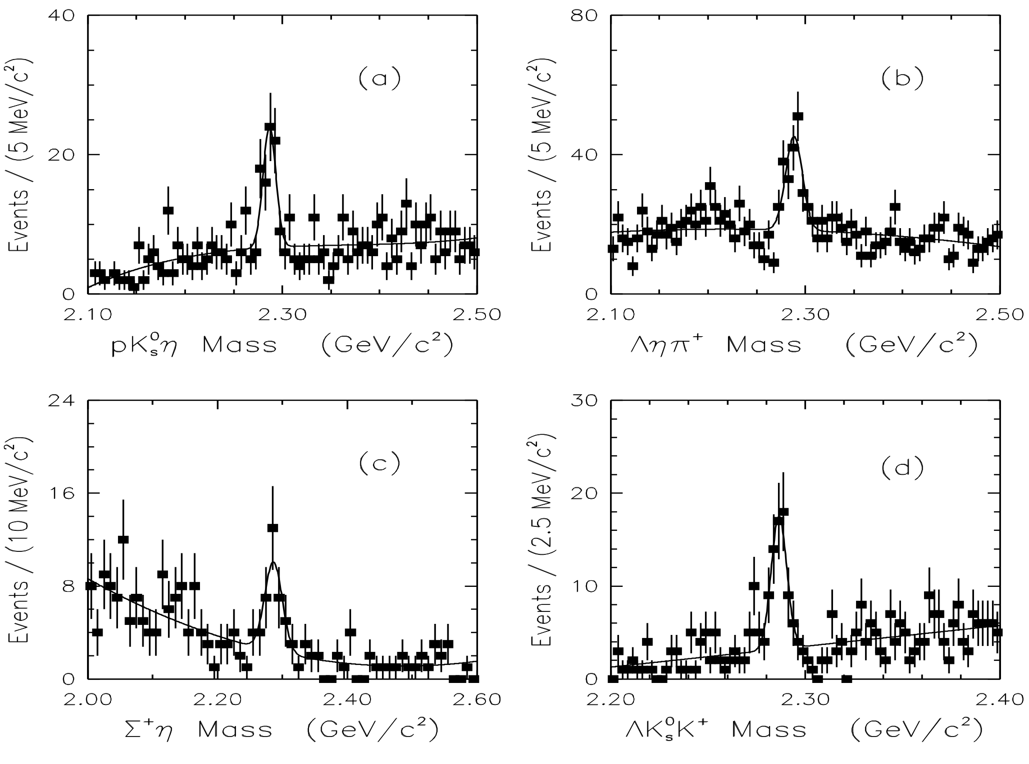

FIG. 2. The invariant mass distributions for Λ_c^+ decaying into (a) $p K_s^0 \eta$, (b) $\Lambda \eta \pi^+$, (c) $\Sigma^+ \eta$, and (d) $\Lambda K_s^0 K^+$.

TABLE I. Summary of results on new Λ_c^+ decay modes.

Decay Mode	Events	$\mathcal{B}/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$
$\Sigma^-\pi^+\pi^+$	103 ± 17	$0.36 \pm 0.10 \pm 0.07$
pK^-K^+	35 ± 10	$0.096 \pm 0.029 \pm 0.010$
$p\bar{K}^0\eta$	57 ± 10	$0.25 \pm 0.04 \pm 0.04$
$\Lambda\eta\pi^+$	116 ± 16	$0.35 \pm 0.05 \pm 0.06$
$\Sigma^+\eta$	26 ± 7	$0.11 \pm 0.03 \pm 0.02$
$\Sigma^{*+}\eta$	54 ± 14	$0.17 \pm 0.04 \pm 0.03$
$\Lambda\bar{K}^0K^+$	59 ± 9	$0.12 \pm 0.02 \pm 0.02$

decay $\Lambda_c^+ \to p\phi$, which proceeds via a purely factorizable, internal W-emission diagram. The branching fractions for all these Λ_c^+ decay modes are listed in Table I.

CLEO [3] has observed decay modes with an η meson in the final state: $\Lambda_c^+ \to pK_s^0\eta$, $\Lambda\eta\pi^+$, and $\Sigma^+\eta$; and the mode $\Lambda_c^+ \to \Lambda K_s^0 K^+$. The invariant mass distributions are shown in Fig. 2. Approximately 50% of the three-body mode $\Lambda_c^+ \to \Lambda\eta\pi^+$ proceeds through a $\Sigma^{*+}\eta$ resonance. The two-body decays, $\Lambda_c^+ \to \Sigma^+\eta$ and $\Sigma^{*+}\eta$, are particularly significant because they proceed via purely non-factorizable diagrams.

III. EXCITED CHARM BARYONS

Two new excited states of the charmed baryon Λ_c^+ have been observed, both states decaying into $\Lambda_c^+\pi^-\pi^+$ [4–6]. ARGUS discovered the $\Lambda_c^{*+}(2625)$, which was subsequently confirmed by E687 and CLEO. The lower mass excited state, $\Lambda_c^{*+}(2593)$, was later observed by CLEO. Fig. 3 shows the mass difference distribution, $\Delta M = M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$, from the CLEO data. There are 245 ± 19 events in the higher ΔM peak at $342.2 \pm 0.2 \pm 0.5$ MeV/c^2, and 113 ± 17 events in the lower ΔM peak at $307.5 \pm 0.4 \pm 1.0$ MeV/c^2. Furthermore, although no resonant substructure is evident in the $\Lambda_c^{*+}(2625)$ decay, the $\Lambda_c^{*+}(2593)$ state is observed to decay predominantly through an intermediate $\Sigma_c^{++}\pi^-$ or $\Sigma_c^0\pi^+$ state.

These two excited Λ_c^+ states are believed to be the P-wave baryons in which the ud diquark is in an $L = S = 0$ state and orbits the charm quark with one unit of orbital angular momentum. Combined with the spin of the charm quark, the doublet states have spin-parity $J^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$. Both states are forbidden by isospin to decay into $\Lambda_c^+\pi^0$. Rather, the $\frac{1}{2}^+$ state $\Lambda_c^{*+}(2593)$ decays preferentially to $\Sigma_c\pi$ via an S-wave transition; the $\frac{3}{2}^+$ state $\Lambda_c^{*+}(2625)$ would like to decay to $\Sigma_c^*\pi$ but is kinematically forbidden. The decay $\Lambda_c^{*+}(2625) \to \Sigma_c\pi$ is a

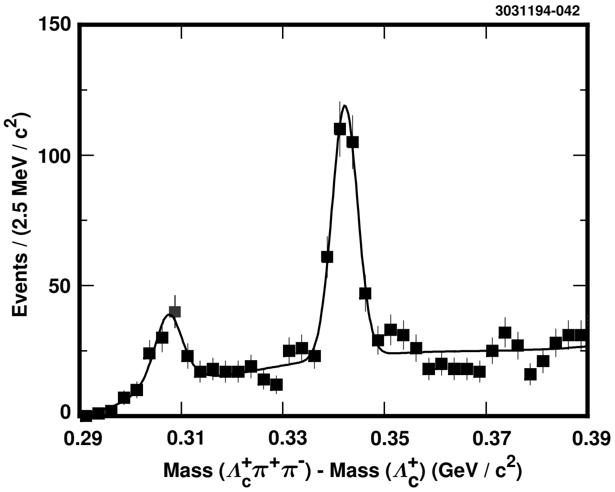

FIG. 3. The $M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$ mass difference distribution.

D-wave transition and thus heavily suppressed.

There is further evidence to suggest that the excited states are the two P-wave Λ_c^+ particles. First, the mass splitting between the two excited states is $34.7 \pm 0.5 \pm 1.2$ MeV/c^2. This is basically identical to the splitting observed in the P-wave D^{**} mesons, *i.e.* between the $J^P = 1^+$ and 2^+ states, as successfully explained by HQET. Second, while both Λ_c^{*+} excited states have narrow widths due to the limited phase space, the higher mass state is narrower, consistent with the severe phase space suppression of the $\Sigma_c^*\pi$ final state. Finally, the Λ_c^{*+} states have a much harder momentum spectrum than the $\Lambda_c^+(2285)$. The orbitally excited D^{**} mesons are similarly observed to have a harder momentum spectrum compared with the $D^{(*)}$ mesons.

IV. OBSERVATION OF THE Ω_c^0

Ever since the first hint of the doubly-strange charmed baryon Ω_c^0 was observed in 1985 by WA62 [7], a definitive observation of the Ω_c^0 has been difficult. WA62 observed three events clustered at 2740±20 MeV/c^2 in the $\Xi^- K^- \pi^+ \pi^+$ invariant mass distribution. "Proto-signals" of 12 ± 5 and 7 ± 3 events were seen by ARGUS [8,9] in the decay channels $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$ and $\Omega^- \pi^+ \pi^- \pi^+$, respectively. Evidence of $\Omega_c^0 \to \Omega^- \pi^+$ (10 ± 4 events) was reported by E687 [10].

This past year unequivocal evidence of the Ω_c^0 has finally been observed by both E687 [12] and the Σ^- hyperon beam experiment WA89 [11]. E687 observes the Ω_c^0 baryon through its decay mode $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$, shown in Fig. 4. The Σ^+ hyperon is identified through both

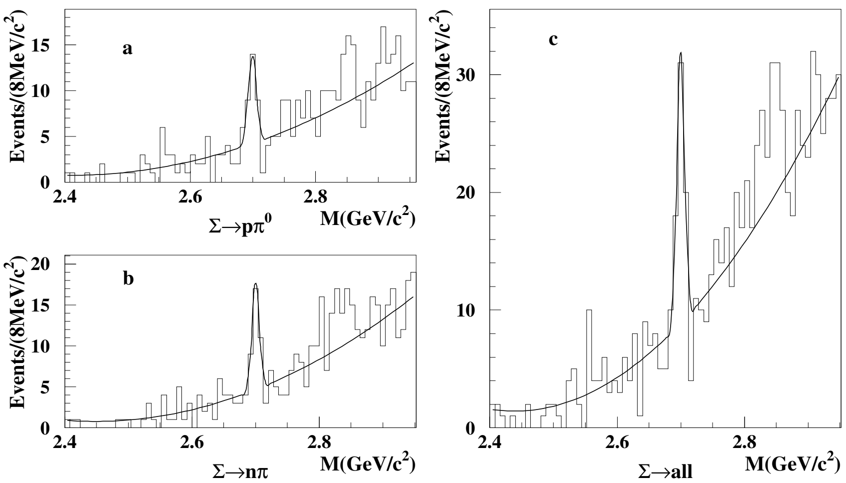

FIG. 4. The $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$ invariant mass distributions for (a) the $\Sigma^+ \to p\pi^0$ decay mode, (b) the $\Sigma^+ \to n\pi^-$ decay mode, and (c) both decay modes of the Σ^+.

the $\Sigma^+ \to p\pi^0$ and $n\pi^+$ decay channels, by reconstructing only the charged tracks segments (Σ^+, p, and π^+). E687 observes an Ω_c^0 signal of 42.5 ± 8.8, divided roughly equally between the $\Sigma^+ \to p\pi^0$ and $n\pi^+$ channels. The Ω_c^0 mass was measured to be $2699.9 \pm 1.5 \pm 2.5$ MeV/c^2, the most precise to date.

The Ω_c^0 lifetime measurement is theoretically expected to be smaller than the Λ_c^+ lifetime. Work towards making this measurement is in progress by E687.

V. B MESON DECAYS INTO CHARMED BARYONS

The B meson has been previously observed by both ARGUS [13] and CLEO [14] to decay into Λ_c^+ charmed baryons. CLEO measured $\mathcal{B}(B \to \Lambda_c^+ X) = (6.4 \pm 0.8 \pm 0.8)\%$. The Λ_c^+ momentum spectrum is surprisingly soft (Fig. 5b), suggesting that the recoiling mass M_X is large. The spectrum shows no evidence for any two-body decays $B \to \Lambda_c^+ \bar{N}$. The Σ_c^{++} and Σ_c^0 momentum spectrum from B decays has also been measured to be soft [15].

The mechanism for producing baryons is presently not well understood. In the "naive" external spectator model (Fig. 6) the dominant decay channel is $B \to \Theta_c \bar{N} X$, where Θ_c is a Λ_c^+ or Σ_c. Recently, Dunietz *et al.* [16] have suggested that the soft momentum spectrum could be explained if $B \to$ baryon decays are dominated by the internal spectator diagram via $b \to c\bar{c}s$ transitions. In this scenario, the B meson decays into $\Xi_c \bar{\Lambda}_c X$; two heavy charmed baryons are produced, which naturally acounts for the soft Λ_c^+ momentum spectrum (Fig. 5a). The internal W-emission process for $B \to$ baryons is not color suppressed as it is for $B \to D\pi^0$ decays, and may even be favored over the external W-emission process since

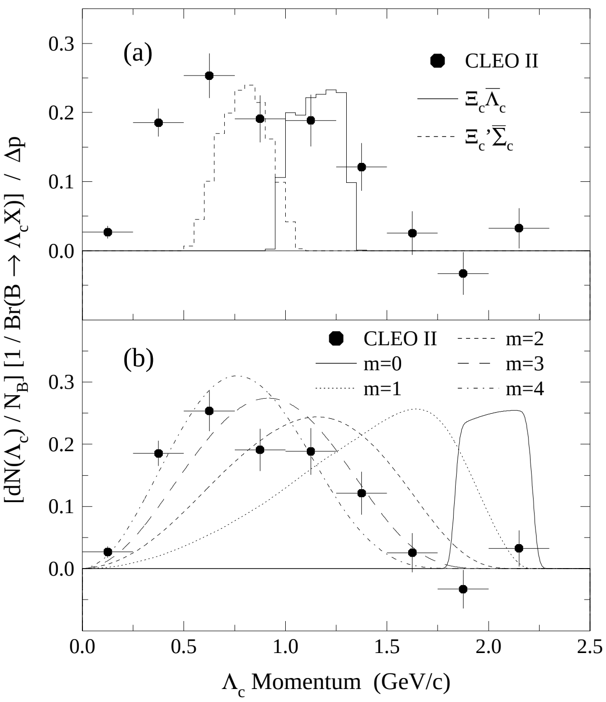

FIG. 5. The Λ_c^+ momentum spectrum in B decays (points) compared to (a) the expected shape from $\bar{B} \to \Xi_c^{(\prime)}\bar{\Lambda}_c$ decays, and (b) the expected shape from decays of the form $\bar{B} \to \Lambda_c^+ \bar{N}(m\pi)$ for $m = 0 - 4$.

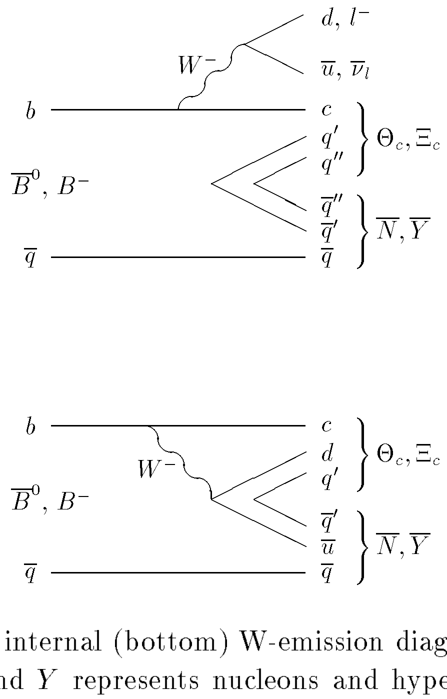

FIG. 6. External (top) and internal (bottom) W-emission diagrams for $B \to \Lambda_c^+ X$ decays. Θ_c denotes a Λ_c^+ or Σ_c, and N and Y represents nucleons and hyperons, respectively. An internal W-emission process with $W \to \bar{c}s$ leads to final states of the form $B \to \Xi_c \bar{\Lambda}_c X$. Semileptonic decays can only result from the external W-emission diagram.

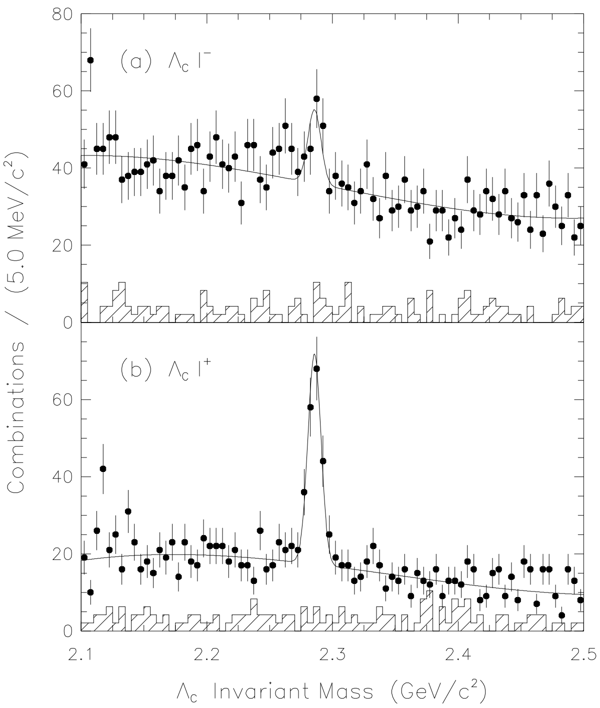

FIG. 7. The Λ_c^+ invariant mass distributions for (a) opposite-sign $\Lambda_c^+ l^-$ correlations and (b) like-sign $\Lambda_c^+ l^+$ correlations. The shaded histograms are for the continuum data.

only one $q\bar{q}$ pair must be created out of the vacuum.

CLEO has investigated the $B \to$ baryon decay mechanism by comparing the relative rate of $B \to \Lambda_c^+ X$ versus $B \to \bar{\Lambda}_c X$, and searching for inclusive $B \to \Xi_c X$ decays [17], as discussed below.

VI. Λ_c^+ – LEPTON CHARGE CORRELATIONS

B mesons can decay into both Λ_c^+ and $\bar{\Lambda}_c$ baryons through $b \to c\bar{u}d$ and $b \to c\bar{c}s$ transitions, respectively. We can measure the relative strengths of these two processes by determining whether the Λ_c^+ came from a b or $\bar{b}$ quark. The flavor of the parent B can be tagged by observing the sign of high momentum leptons which come from semileptonic decays of the other B meson in the event. Like-sign $\Lambda_c^+ l^+$ correlations occur for baryons produced in $b \to c\bar{u}d$ decays, while opposite-sign $\Lambda_c^+ l^-$ correlations indicate the $b \to c\bar{c}s$ process.

The Λ_c^+ baryons are observed through the decay channels $\Lambda_c^+ \to pK^-\pi^+$, pK_s^0, $\Lambda\pi^+$, and $\Sigma^0\pi^+$. After subtracting the contribution from the continuum, CLEO observes 3154 ± 160 Λ_c^+'s in $B\bar{B}$ events. The tagged lepton is required to have a momentum greater than 1.4 GeV/c to eliminate contributions from secondary decays $b \to c \to sl^+\nu$. CLEO measures

141 ± 16 like-sign and 43 ± 16 opposite-sign $\Lambda_c^+ l$ correlations (Fig 7). After correcting for the remaining secondary leptons, fake leptons, and $B^0\bar{B}^0$ mixing, CLEO obtains 148 ± 19 like-sign and 29 ± 19 opposite-sign correlations, which corresponds to a relative decay rate in $B \to$ baryon decays of

$$\frac{b \to c\bar{c}s}{b \to c\bar{u}d} = (20 \pm 13 \pm 4)\% \tag{1}$$

Hence, although $b \to c\bar{c}s$ transitions do not dominate baryon production in B decays, they can have a non-negligible role.

VII. OBSERVATION OF $B \to \Xi_c X$

CLEO has recently observed charmed-strange Ξ_c baryons in B decays [17]. The Ξ_c baryons can be produced through $b \to c\bar{u}d$ transitions accompanied by $s\bar{s}$ popping, *i.e.* $B \to \Xi_c \bar{\Lambda} X$, or via $b \to c\bar{c}s$ transition into final states of the form $B \to \Xi_c \bar{\Lambda}_c X$.

The Ξ_c baryons are also produced in the continuum, and after subtracting this contribution from the $\Upsilon(4S)$ data, CLEO observes 88 ± 20 events from B decays in the mode $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ and 59 ± 17 events in the $\Xi_c^0 \to \Xi^- \pi^+$ decay mode (Fig 8). The absolute Ξ_c branching fraction for these modes is estimated from the Ξ_c lifetime and the $\Xi_c \to \Xi l \nu$ branching fraction measurements. From these estimates, CLEO extracts $\mathcal{B}(B \to \Xi_c^+ X) = (2.0 \pm 0.7)\%$ and $\mathcal{B}(B \to \Xi_c^0 X) = (2.8 \pm 1.2)\%$, where the errors are statistical only. This is over half of the $B \to \Lambda_c^+ X$ branching fraction, which is $(6.4 \pm 0.8 \pm 0.8)\%$. In the absence of $b \to c\bar{c}s$ decays, the expected rate of $s\bar{s}$ to light quark popping suggests that the $B \to \Xi_c X$ rate should be $0.15\mathcal{B}(B \to \Lambda_c^+ X) \approx 1\%$. Hence, $s\bar{s}$ popping cannot alone explain the inclusive rate of Ξ_c in B decays, but must be accompanied by $B \to \Xi_c \bar{\Lambda}_c X$ decays.

VIII. EXCLUSIVE B DECAYS INTO CHARMED BARYONS

Previous attempts to fully reconstruct B meson decay channels into final states with Λ_c^+ baryons have been difficult due to high B decay multiplicities, as indicated by the soft Λ_c^+ momentum spectrum. CLEO [18] has systematically searched for exclusive $\bar{B}^0 \to \Lambda_c^+ \bar{p}(n\pi)$ decays, where $(n\pi)$ denotes up to four pions and at most one π^0.

The Λ_c^+ candidates from B meson decays are obtained from the decay modes $\Lambda_c^+ \to pK^-\pi^+$, pK_s^0, and $\Lambda\pi^+$. Since B mesons from $\Upsilon(4S)$ decays have an energy equal to the beam energy, E_{beam}, the beam-constrained mass $M_B = \sqrt{E_{beam}^2 - \left(\sum \overrightarrow{p}\right)^2}$ was used. The

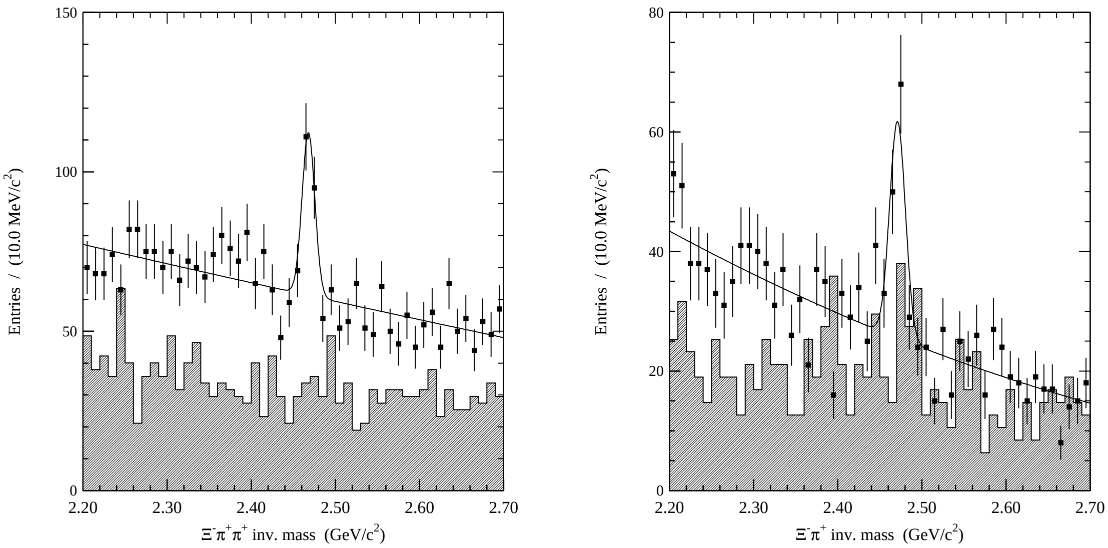

FIG. 8. The invariant mass distributions for (a) $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ and (a) $\Xi_c^0 \to \Xi^-\pi^+$ from B meson decays. The shaded histograms are for the continuum data.

resolution on M_B is ~ 2.5 MeV/c^2, about a factor of ten smaller than the invariant mass resolution. The energy difference, $\Delta E = \sum E - E_{beam}$, where $\sum E$ is the measured energy of the B candidate, was required to be less than 25 MeV ($\sim 2\sigma$). Event shape cuts are applied to reduce backgrounds from the continuum.

CLEO observes a signal of 15.0 ± 4.7 events in the beam-constrained mass distribution for $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^- \pi^+$, shown in Fig. 9. The branching fraction for this mode is measured to be $(0.187 \pm 0.059 \pm 0.056 \pm 0.045)\%$, where the last error is due to the uncertainty in the absolute branching fraction of $\Lambda_c^+ \to pK^-\pi^+$. As a check, no signal was seen in the M_B distribution for the ΔE sideband, the Λ_c^+ mass sideband, the continuum data, or wrong sign combinations. Upper limits have been placed for all other decay modes of the B meson into Λ_c^+.

IX. CONCLUSIONS

CLEO and E687 have observed several new decay modes of the Λ_c^+ charmed baryon, including two-body decays with purely non-factorizable amplitudes ($\Lambda_c^+ \to \Sigma^+\eta$ and $\Sigma^{*+}\eta$) and the Cabibbo suppressed decay $\Lambda_c^+ \to pK^-K^+$. Two orbitally excited states of the Λ_c^+ have been observed: $\Lambda_c^{*+}(2593)$ and $\Lambda_c^{*+}(2625)$. These two are analogous to the narrow P-wave D^{**} doublets. E687 has solid evidence for the Ω_c^0 baryon in the decay mode $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$ and has measured the Ω_c^0 mass to be $2699.9 \pm 1.5 \pm 2.5$ MeV/c^2.

Charmed baryon production in B meson decays were explored by CLEO. Λ_c^+ – lepton

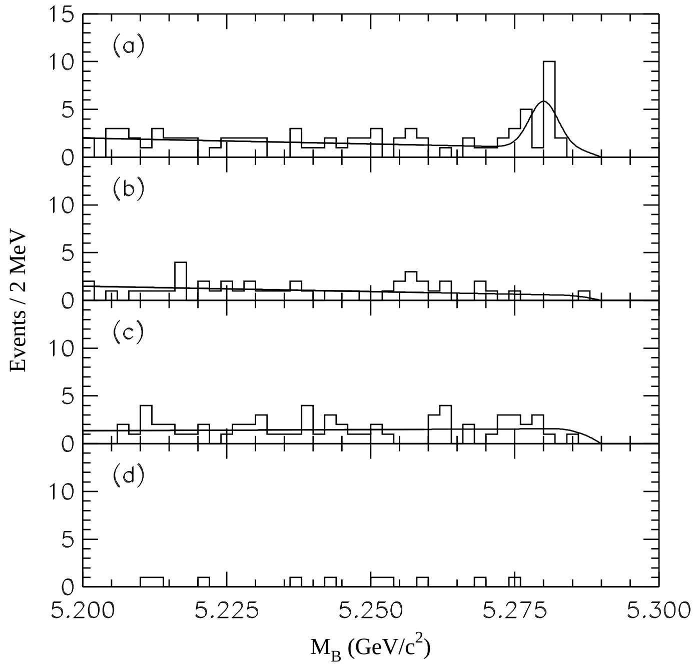

FIG. 9. (a) The beam-constrained mass distribution for $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^- \pi^+$. The same distribution for (b) the ΔE sidebands, (c) the Λ_c^+ sidebands, and (d) the continuum.

correlations and the observation of $B \to \Xi_c X$ suggest that $B \to$ baryons occurs through both the $b \to c\bar{u}d$ and $b \to c\bar{c}s$ transitions, although the former process dominates. The $b \to c\bar{u}d$ process will yield final states of the form $B \to \Lambda_c^+ \bar{N} X$ and $\Xi_c \bar{\Lambda} X$, while the $b \to c\bar{c}s$ process will lead to final states of the form $B \to \Xi_c \bar{\Lambda}_c X$. Finally, the first exclusive decay of the B meson into charmed baryons, $\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^- \pi^+$, has been observed.

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