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Correlated leading baryon-antibaryon production in $e^+e^- \rightarrow c\bar{c} \rightarrow \Lambda c + \Lambda\bar{c}$

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Correlated leading baryon-antibaryon production in $e^+e^- \rightarrow c\bar{c} \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- X$

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We present a study of $649 \pm 35 e^+e^- \rightarrow c\bar{c}$ events produced at $\sqrt{s} \approx 10.6$ GeV containing both a Λ_c^+ baryon and a $\bar{\Lambda}_c^-$ antibaryon. The number observed is roughly 4 times that expected if the leading charmed hadron types are uncorrelated, confirming an observation by the CLEO Collaboration. We find a 2-jet

topology in these events but very few additional baryons, demonstrating that the primary c and \bar{c} are predominantly contained in a correlated baryon-antibaryon system. In addition to the charmed baryons we observe on average 2.6 ± 0.2 charged intermediate mesons, predominantly pions, carrying 65% of the remaining energy.

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Baryon production in high-energy jets from e^+e^- annihilations has presented a series of challenges to our understanding of strong interactions. Its observation led to the competing notions of “primary” and “local” baryon correlations [1]. In the former, the e^+ and e^- annihilate into a primary diquark-antidiquark, rather than a quark-antiquark pair. The diquark and antidiquark then hadronize into jets containing a leading baryon N_1 and a leading antibaryon \bar{N}_2 , respectively, but no other (anti)baryons. N_1 and \bar{N}_2 would then share two quark flavors and typically have high, antiparallel momenta and large values of variables characterizing their separation, such as invariant mass or rapidity difference $|\Delta y|$, where $y \equiv 0.5 \ln[(E + p_{\parallel})/(E - p_{\parallel})]$, E is the baryon energy, and p_{\parallel} is the projection of its momentum on the thrust axis. Alternatively, an $N_1\bar{N}_2$ pair might be produced locally, in an individual step of a hadronization cascade, with a smaller value of $|\Delta y|$. Most experimental studies of baryon-antibaryon pairs have shown $|\Delta y|$ distributions that peak at small values [2].

Several mechanisms to describe baryon production and correlations have been implemented in Monte Carlo hadronization models [3]. In the JETSET [4] color-flux-tube model, a tube break can result in a diquark-antidiquark (rather than $q\bar{q}$) pair, producing an $N_1\bar{N}_2$ pair locally. An intermediate meson is introduced between N_1 and \bar{N}_2 with some probability (50% by default [5]) to match the measured $|\Delta y|$ distributions. In the HERWIG [6] model, an individual, color-singlet cluster may fragment into a baryon-antibaryon pair but not a multibody state with additional mesons. The model does not reproduce the measured $|\Delta y|$ distributions when tuned to other observables [2]. The UCLA [7] area-law model includes $N_1\bar{N}_2$ pairs with any number of intermediate mesons, and suppresses higher-mass intermediate meson systems by means of a tunable parameter.

Direct evidence of primary production and/or intermediate mesons would be of great interest, but previous searches for the latter using three-particle correlations [8]

or baryon flavor correlations [9] were generally inconclusive.

At center-of-mass (c.m.) energies \sqrt{s} much larger than four baryon masses, the assumption of local baryon number conservation implies that an $e^+e^- \rightarrow q\bar{q}$ event containing a leading baryon N_1 in the q jet and a leading antibaryon \bar{N}_2 in the \bar{q} jet must also contain an antibaryon \bar{N}_3 in the q jet and a baryon N_4 in the \bar{q} jet. However, if the $N_1\bar{N}_3N_4\bar{N}_2$ mass is a large fraction of \sqrt{s} , these four-baryon events would be suppressed and other processes might be visible—in particular, primary baryon production events with exactly two baryons, one in each jet. At $\sqrt{s} \approx 10$ GeV, charmed (c) baryons are of particular interest, since any high-momentum c or \bar{c} baryon must be a leading particle in an $e^+e^- \rightarrow c\bar{c}$ event, and any $N_{c1}\bar{N}_3N_4\bar{N}_{c2}$ mass exceeds $6.5 \text{ GeV}/c^2$. The CLEO Collaboration reported an excess by a factor of 3.5 ± 0.6 [10] in the number of events at $\sqrt{s} = 10.6$ GeV with both a Λ_c^+ and a $\bar{\Lambda}_c^-$, where their expectation is derived assuming local baryon number conservation in the JETSET model and from observed events with a Λ_c^+ and a D^- or \bar{D}^0 meson. This excess is evidence that the baryon production is correlated between the c and \bar{c} jets and is consistent with primary baryon production, but does not exclude the possibility of local baryon production with correlation between the jets. The two cases can be distinguished experimentally: local production would require an additional baryon and antibaryon (N_4 and \bar{N}_3) in the event, so events with exactly one Λ_c^+ , exactly one $\bar{\Lambda}_c^-$, and no additional baryons would imply primary production. CLEO investigated this and did not observe a strong signal for additional protons in the $\Lambda_c^+\bar{\Lambda}_c^-$ candidate events, but due to a limited data sample and the lack of a limit on additional neutrons they were unable to exclude local baryon production.

In this paper we exploit the particle identification capabilities of the BABAR detector [11] to select a sample of $\Lambda_c^+\bar{\Lambda}_c^-X$ events in which the Λ_c^+ and $\bar{\Lambda}_c^-$ are produced at high momentum in opposite hemispheres, and study their characteristics in detail. We use 220 fb^{-1} of data collected

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at $\sqrt{s} = 10.54\text{--}10.58$ GeV. We identify the charged tracks in the X system, looking for additional (anti)protons, and search for higher-mass baryons that could be a source of the $\Lambda_c^+ \bar{\Lambda}_c^- X$ events. We consider charged tracks measured in the silicon vertex tracker (SVT) and drift chamber (DCH), and identified as pions, kaons, or protons using the DCH and the detector of internally reflected Cherenkov light. The identification algorithm used here [12,13] is over 99% efficient for pions and kaons (protons) within the acceptance with momenta between 0.15 and 0.5 (1.2) GeV/ c , with misidentification rates below 0.5%. At higher momenta it remains over 90% efficient, with misidentification rates generally below 1%.

We construct Λ_c^+ candidates in the $pK^-\pi^+$ and pK_S^0 decay modes and $\bar{\Lambda}_c^-$ in the corresponding charge-conjugate modes. We consider a pair of oppositely charged tracks as a $K_S^0 \rightarrow \pi^+\pi^-$ candidate if a vertex fit returns a χ^2 with a confidence level (C.L.) exceeding 0.01, the vertex is displaced by 2.5–60 cm from the interaction point (IP) calculated for each event from the set of well-measured tracks in the SVT, the angle θ_{K_S} between the K_S^0 candidate's momentum and the IP-to-vertex direction satisfies $\cos\theta_{K_S} > 0.97$, and the $\pi^+\pi^-$ invariant mass is in the range 491.8–503.8 MeV/ c^2 . All combinations of a K_S^0 and a well-measured (≥ 15 hits in the DCH and ≥ 5 in the SVT) proton are considered $\Lambda_c^+ \rightarrow pK_S^0$ candidates. A combination of well-measured p , K^- , and π^+ tracks is considered a $\Lambda_c^+ \rightarrow pK^-\pi^+$ candidate if its vertex fit yields C.L. > 0.001 .

We require p^* , the momentum of the Λ_c^+ candidate in the e^+e^- c.m. frame, to exceed 2.3 GeV/ c , so that the rate of Λ_c^+ from $Y(4S)$ decays [12,14] is negligible. We select events containing at least one Λ_c^+ candidate and at least one $\bar{\Lambda}_c^-$ candidate, requiring each candidate to have mass within 190 MeV/ c^2 of the fitted Λ_c^+ peak. We then form $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs provided that they have no common tracks in their decay chains. For these 21 000 pairs we show the candidate $pK^-\pi^+$ and pK_S^0 invariant mass distributions in Fig. 1(a). Clear Λ_c^+ signals are visible over modest backgrounds. The peak mass values, rates, and momentum distributions are consistent with previous measurements [12,14,15]. We plot the invariant mass of the $\bar{\Lambda}_c^-$ candidate versus that of the Λ_c^+ candidate in Fig. 1(b). Horizontal and vertical bands are visible, corresponding to events with a real $\bar{\Lambda}_c^-$ or Λ_c^+ , respectively, and there is a substantial enhancement where they overlap.

The opening angle θ between the Λ_c^+ and $\bar{\Lambda}_c^-$ momenta in the c.m. frame is sensitive to their production mechanism. We expect $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs from gluon splitting ($e^+e^- \rightarrow q\bar{q}g \rightarrow q\bar{q}c\bar{c}$) or $e^+e^- \rightarrow c\bar{c}g$ events with a very hard gluon to have relatively small θ , but also a suppressed selection efficiency due to the p^* requirement. In the 21 000 events selected, θ values are concentrated near 180° , consistent with dominance of 2-jet $e^+e^- \rightarrow c\bar{c}$

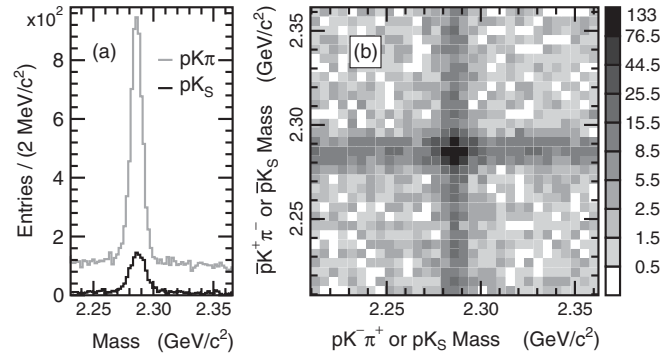


FIG. 1. (a) Invariant mass distributions for the $\Lambda_c^+/\bar{\Lambda}_c^-$ candidates in selected events, reconstructed in the $pK\pi$ (gray) and pK_S^0 (black) decay modes. (b) Invariant mass of the $\bar{\Lambda}_c^-$ candidate vs that of the Λ_c^+ candidate in the same event, in $5 \text{ MeV}/c^2$ square bins.

events. Only seven events have $\theta < 90^\circ$, one of which is in the signal region defined below. Since the small- θ background may have different characteristics from that at large θ , we require $\theta > 90^\circ$. This criterion also removes events with a hard initial state photon, the study of which would be interesting with a larger data sample and a different analysis approach, as has been done by Belle [16].

About 3% of the events have two Λ_c^+ (or two $\bar{\Lambda}_c^-$) candidates, due to the two $pK^-\pi^+$ combinations in the decay chains $\Sigma_c^{++} \rightarrow \Lambda_c^+(pK^-\pi^+)\pi^+$ and $\Lambda_c^{*+} \rightarrow \Lambda_c^+(pK^-\pi^+)\pi^+\pi^-$. We include all combinations in the sample and account for the kinematic overlap through the background subtraction. We define a circular $\Lambda_c^+ \bar{\Lambda}_c^- X$ signal region centered at our peak mass values with a radius of $12 \text{ MeV}/c^2$, which contains 919 entries. Using the single- $\Lambda_c^+/\bar{\Lambda}_c^-$ bands [13], we estimate an expected background in the signal region of 245 ± 5 events with one real Λ_c^+ or $\bar{\Lambda}_c^-$ and one fake. Using events with both masses at least $40 \text{ MeV}/c^2$ from the fitted Λ_c^+ mass, we estimate 25 ± 1 expected background events with fake Λ_c^+ and $\bar{\Lambda}_c^-$, giving a $\Lambda_c^+ \bar{\Lambda}_c^- X$ signal of $N_{\Lambda_c^+ \bar{\Lambda}_c^-} = 649 \pm 35$ events.

We can calculate an expected number of signal events, n_{exp} , under the assumption that the c and \bar{c} hadron types are uncorrelated so that all signal events are four-baryon events. Then $n_{\text{exp}} = Cn_1^2/4N_{c\bar{c}}$, where $n_1 = 420\,000$ is the number of single $\Lambda_c^+/\bar{\Lambda}_c^-$ observed in the data, $N_{c\bar{c}} = 3 \times 10^8$ is the number of $e^+e^- \rightarrow c\bar{c}$ events expected for our integrated luminosity, and the factor C accounts for the correlation between the Λ_c^+ and $\bar{\Lambda}_c^-$ reconstruction efficiencies. This formulation is independent of the Λ_c^+ branching fractions and average efficiencies. In the simple case where the efficiencies of the Λ_c^+ and $\bar{\Lambda}_c^-$ in $\Lambda_c^+ \bar{\Lambda}_c^- X$ events are uncorrelated, no correction is needed ($C = 1$) and $n_{\text{exp}} = n_1^2/4N_{c\bar{c}}$. More generally, $0 < C < 1/\varepsilon$ for an average acceptance times efficiency of ε : in the extreme case of maximal correlation $C = 1/\varepsilon$, and in the extreme

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case of maximal anticorrelation $n_{\text{exp}} = C = 0$. At *BABAR* there might be correlations because of the asymmetric beam energies and detector layout. We evaluate this correction using the JETSET, HERWIG, and UCLA models, adjusting their charm fragmentation parameters and reweighting the resulting p^* distributions to reproduce our measured distribution for inclusive Λ_c^+ [12]. Combined with smooth parametrizations of our efficiencies as functions of momentum and polar angle, the models give values of C ranging from 0.63 to 1.65, with a mean of 1.05. Even allowing for the large model dependence, the full range of $n_{\text{exp}} = 100$ –250 events is well below the observed 649 ± 35 , confirming the enhanced rate $N_{\Lambda_c^+ \bar{\Lambda}_c^-} / n_{\text{exp}} \approx 4$ reported by the CLEO Collaboration [10].

We investigate the structure of the $\Lambda_c^+ \bar{\Lambda}_c^- X$ events using the Λ_c^+ and $\bar{\Lambda}_c^-$ candidates along with additional charged tracks that have at least ten points measured in the DCH, five in the SVT, and extrapolate within 5 mm of the beam axis. We subtract appropriately scaled distributions in the background regions from those in the signal region to obtain distributions for $\Lambda_c^+ \bar{\Lambda}_c^- X$ events. Figure 2(a) shows the distribution of the number of additional tracks, as well as the numbers of identified K^\pm and p/\bar{p} among them. Were each c baryon compensated by a light antibaryon, then—assuming that half the antibaryons have an antiproton in the final state and accounting for p/\bar{p} detection efficiency—we would expect 45% of these events to contain one identified p/\bar{p} and another 20% to contain both an identified p and a \bar{p} ; we observe only 3.4% and 0.6%, respectively. Figure 2(b) shows the distribution of missing mass, calculated from the four-momenta of the initial e^+ and e^- , the reconstructed Λ_c^+ and $\bar{\Lambda}_c^-$, and all additional tracks interpreted as pions. A typical $N_{c1} \bar{n} X n \bar{N}_{c2}$ event, containing both a neutron and an antineutron, would have a missing mass well in excess of 2 GeV/c^2 .

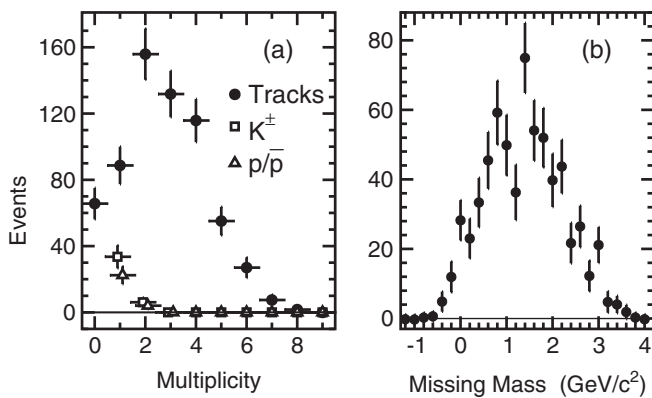


FIG. 2. Background-subtracted distributions for the 649 $\Lambda_c^+ \bar{\Lambda}_c^- X$ events in the data: (a) the numbers of additional tracks, identified K^\pm and identified p/\bar{p} ; and (b) missing mass, with imaginary masses given negative real values. Most events have no identified K^\pm or p/\bar{p} and the corresponding zero-multiplicity points are off the vertical scale in (a).

The distributions in Fig. 2 indicate that the majority of the $\Lambda_c^+ \bar{\Lambda}_c^- X$ events do not contain additional baryons, and therefore that the conservation of baryon number is realized with the primary c and \bar{c} hadrons. In the background-subtracted sample of 649 ± 35 $\Lambda_c^+ \bar{\Lambda}_c^- X$ signal events, there are 28 ± 6 additional identified p/\bar{p} candidates. These p/\bar{p} candidates include background from two main sources: interactions in the detector material and misidentified pions or kaons. We expect five protons from material interactions. We also expect about 12 pions or kaons misidentified as protons, based on the numbers and momenta of the observed additional π^\pm and K^\pm tracks. In cross-checks these expectations are found to be consistent with the data within uncertainties: there are 8 ± 4 more identified p than \bar{p} (with the excess attributed to material interactions), and there are 7 ± 3 events seen with exactly one additional identified p/\bar{p} and an event missing mass below $750 \text{ MeV}/c^2$ (inconsistent with a missing second baryon, and so attributed to a misidentified kaon or pion). Subtracting the expected contributions from these two background sources, correcting for efficiency, and assuming equal p and n production rates, we estimate that we observe 13 ± 8 true four-baryon events. This is well below the rate of 100 to 250 four-baryon events expected for uncorrelated production, let alone the observed rate of 649 ± 35 events, indicating that the four-baryon process is strongly suppressed and that the primary production process dominates.

None of the reconstructed events is consistent with the two-body process $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$. However, the signal could arise from the pair production of c baryons if one or both are excited states that decay to $\Lambda_c^+/\bar{\Lambda}_c^-$: $e^+e^- \rightarrow N_{c1} \bar{N}_{c2} \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- X$. Combining $\Lambda_c^+/\bar{\Lambda}_c^-$ candidates with one or two additional tracks assigned the pion mass hypothesis gives the invariant mass distributions in Fig. 3. The points represent sideband-subtracted signal events and the histograms the single- $\Lambda_c^+/\bar{\Lambda}_c^-$ sidebands with entries reweighted to reproduce the number of the $\Lambda_c^+/\bar{\Lambda}_c^-$ in signal events and their momentum and polar angle distributions in the lab frame. Peaks are visible in the sideband data for the $\Sigma_c^{++/0}(2455)$, $\Sigma_c^{+/0}(2520)$, and the excited Λ_c^+ states at 2593, 2625, 2765, and 2880 MeV/c^2 . We find no unexpected peaks in our $\Lambda_c^+ \pi(\pi)$, $\Lambda_c^+ K$, or $\Lambda_c^+ \bar{p}$ mass distributions. The points are consistent with the histograms, indicating similar c baryon compositions in the two event types. Only two events are kinematically consistent with $e^+e^- \rightarrow N_{c1} \bar{N}_{c2}$ for these known N_c . Distributions of θ and the decay angles in the $\Lambda_c^+ \pi$ rest frames are consistent with multihadron events, and not with very heavy states decaying into a Λ_c^+ and more than two pions. We conclude that $e^+e^- \rightarrow N_{c1} \bar{N}_{c2}$ processes represent a small fraction of our sample. From the fits in Fig. 3, we estimate that $35 \pm 3\%$ of the Λ_c^+ and $29 \pm 2\%$ of the additional pions in our sample are decay products of heavier c baryons.

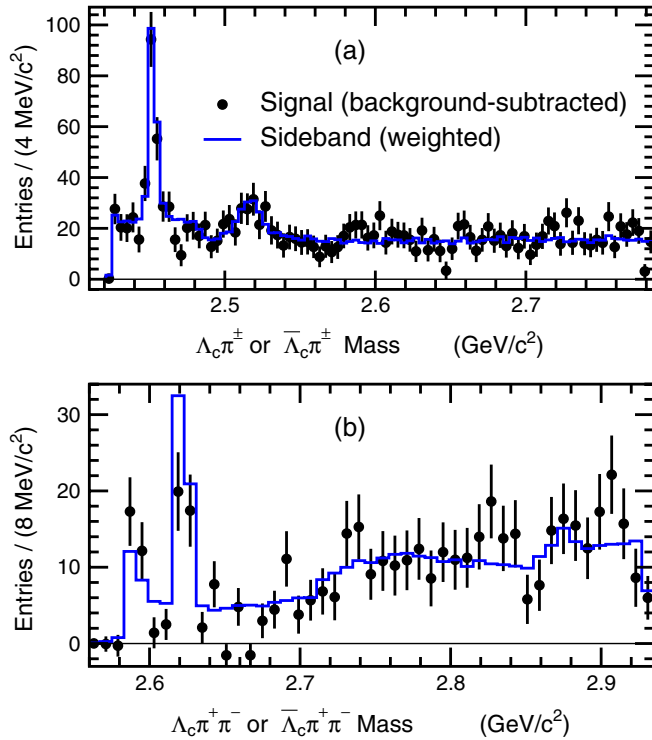


FIG. 3 (color online). Invariant mass distributions for (a) $\Lambda_c^+ \pi^+$ and $\Lambda_c^- \pi^-$ and (b) $\Lambda_c^+ / \Lambda_c^- \pi^+ \pi^-$ combinations. The points with errors represent the background-subtracted $\Lambda_c^+ \Lambda_c^- X$ events, and the weighted histograms are from the single- $\Lambda_c^+ / \Lambda_c^-$ sidebands.

Having established the presence of a category of events containing a c baryon, a \bar{c} baryon, no other (anti)baryons, and several intermediate mesons, we study the number and structure of these mesons. We exclude events with an identified p/\bar{p} or a missing mass squared below $-0.25 \text{ GeV}^2/c^4$. We estimate that the sample contains a further 5 ± 5 four-baryon events in which no p/\bar{p} is detected; we take these to have the same distributions as the events with an identified p/\bar{p} and subtract an appropriately scaled contribution to correct for them. In this sample of 619 ± 35 events, we study a number of quantities including the $\Lambda_c^+ / \Lambda_c^-$ and additional track momenta, polar angles, rapidities, and opening angles. Their inclusive distributions are quite similar to those in the single- $\Lambda_c^+ / \Lambda_c^-$ sample and similar to those in all hadronic events. In particular, signing the thrust axis such that the Λ_c^+ rapidity is positive, the Λ_c^+ and Λ_c^- rapidities cluster near $+1.1$ and -1.1 units, respectively, with the additional tracks of each charge distributed broadly and symmetrically in between.

These 619 events contain only 45 ± 10 identified K^\pm of which about 20 are expected to be misidentified pions. The events show no mass peak for K_S^0 candidates reconstructed from pairs of tracks not included in the Λ_c^+ or Λ_c^- (including tracks that do not extrapolate within 5 mm of the beam axis). The $K:\pi$ ratio is thus much lower than the value 0.3

typical of hadronic events, which might be due to the limited energy available and the fact that our c baryons are nonstrange (the lighter c - s baryons do not decay into Λ_c^+). The $\pi^+ \pi^-$, $K^+ \pi^-$, and $K^+ K^-$ invariant mass distributions show no significant resonant structure; in particular, there is no evidence for the ρ^0 . This implies a vector:pseudoscalar meson ratio much lower than the value near one typical of hadronic events, and suggests that most tracks not from c baryon decays represent distinct intermediate mesons.

The intermediate meson multiplicity is distributed broadly. We verify that the contribution from decays of heavier c baryons is not concentrated in any particular region in Fig. 2(a), but due to the limited sample size we do not attempt to correct the distribution. We observe an average of 2.7 additional charged tracks per event. Correcting for c baryon decays and tracking efficiency gives 2.6 ± 0.2 charged intermediate mesons per event, where the uncertainty includes both statistical and systematic effects. The uncertainty is dominated by the track acceptance in these events, evaluated with a set of simulations based on the observed π^\pm and K^\pm distributions. On average, the c and \bar{c} baryons carry 75% of the event energy, and the intermediate charged mesons account for about 65% of the remainder. This and the broad distribution of missing masses in Fig. 2(b) suggest the presence of additional neutral mesons. If intermediate π^0 are produced at half the π^\pm rate, as in typical hadronic events, the average intermediate meson multiplicity would be 3.9 ± 0.3 .

The new type of event observed in our data might be explained by either primary diquark-antidiquark production or the production of multiple intermediate mesons between a baryon and antibaryon. Neither the JETSET nor the HERWIG model produces events of the type observed, although both might be adapted to include one or both of the above processes. JETSET does produce $N_{c1} M \bar{N}_{c2}$ events, where M is a single meson, often a vector decaying into two or three pions, but the event characteristics are far from consistent with the data. Multiple intermediate meson processes occur naturally in the UCLA model, which also predicts an enhanced $\Lambda_c^+ \Lambda_c^- X$ fraction due to events of this type, with suppressions of kaons and vector mesons. The version of the UCLA model used does not describe the observed events in detail, having an average of only 1.8 intermediate mesons with a distribution peaked at low values, but the results presented here should encourage development of this and other relevant models.

In summary, we isolate a sample of 649 ± 35 $e^+ e^- \rightarrow c\bar{c}$ events containing both a Λ_c^+ and a Λ_c^- with high momentum in opposite hemispheres, and study these events in detail. The number of events is estimated to be about 4 times that expected if the leading c and \bar{c} hadron types are uncorrelated, confirming an observation by the CLEO Collaboration. Taking advantage of the particle identification capabilities of the *BABAR* detector and the

large data sample, we are further able to establish that almost all of these events contain no additional baryons. They do contain 2.6 ± 0.2 additional charged intermediate mesons on average, and events with zero additional mesons do not contribute significantly. Our event sample exhibits distributions of momentum, angle, rapidity, and c baryon type similar to those in typical hadronic events, but contains fewer kaons and vector mesons. This is direct evidence for a new class of multihadron events, in which baryon number is conserved by a leading baryon and antibaryon, rather than locally along the hadronization chain.

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