Λ_c Production from e^+e^- Annihilation in the Υ Energy Region

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We have observed Λ_c baryons in nonresonant e^+e^- annihilation at energies around $\sqrt{s} = 10.5$ GeV through their decay to $\Lambda\pi^+\pi^+\pi^-$. We measure the branching fraction to be $(2.8 \pm 0.7 \pm 1.1)\%$. The momentum spectrum of the Λ_c is similar to that of charmed mesons, providing a constraint on models of charmed-quark hadronization.

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The study of baryon production in e^+e^- annihilation has become increasingly important in efforts to understand the hadronization process. The comparison of the production rate of baryons, three-parton objects, reveals an important aspect of the dynamics of hadronization. Comparison of charmed baryons and mesons produced in e^+e^- annihilation is particularly interesting since they are leading particles; that is, they contain the primary charmed quark produced in the $e^+e^- \to c\bar{c}$ reaction and are less affected by decays from higher-mass hadrons.

In an experiment using the CLEO detector[1] at the Cornell Electron Storage Ring (CESR), we have measured the production of Λ_c baryons[2] through their decay to $\Lambda\pi^+\pi^+\pi^-$. We present results on the production rate times branching ratio for this decay mode and compare the Λ_c's momentum spectrum with that of charmed mesons in order to discriminate between various models of baryon hadronization. These include diquark models[3] in which a quark combines with a diquark produced from the vacuum to make a baryon, and independent-quark-production models,[4] in which baryons are made of quarks independently produced from the vacuum.

We identify Λ_c's (and $\bar{\Lambda}_c$'s) by reconstructing the invariant mass of $\Lambda\pi^+\pi^+\pi^-$ (and $\bar{\Lambda}\pi^-\pi^-\pi^+$) combinations. Hereafter, mention of a Λ_c production or decay process also implies the charge conjugate. The data sample is from an integrated luminosity of 18 pb^{-1} at center-of-mass energies below the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.2$–10.5 GeV), 40 pb^{-1} at the $\Upsilon(4S)$ ($\sqrt{s} = 10.58$ GeV), and 71 pb^{-1} at energies above the $\Upsilon(4S)$ ($\sqrt{s} = 10.6$–11.2 GeV). Λ_c's which might originate from the decay of B mesons from the $\Upsilon(4S)$ will not contribute to our sample since we demand a minimum Λ_c momentum which is above the maximum allowed for B decay.

For this analysis, only the inner tracking chambers of the CLEO detector were used. These include a three-layer proportional chamber surrounded by a seventeen-layer drift chamber, both enclosed in a solenoidal magnetic field of 10 kG. This leads to a charged-particle momentum resolution of $\Delta p/p \approx 1.0\% \times p$ (p in GeV/c).

We search our standard hadronic event sample[1] for Λ's decaying to $p\pi^-$, using procedures for identifying Λ's which have been described before.[5] For each pair of oppositely charged tracks we required that (a) the momentum of each of the tracks exceed 100 MeV/c, (b) the decay vertex be more than 8 mm from the primary e^+e^- annihilation vertex in the plane perpendicular to the beam direction, and (c) the momentum of the Λ candidate exceed 300 MeV/c. Figure 1 shows the mass spectrum of our Λ candidates. We define as Λ's those candidates within 5 MeV/c^2 of the correct Λ mass which are not consistent with being a K_S^0 decay. Our efficiency for finding a Λ is approximately 10%.

We combine each Λ with three other charged tracks which are assumed to be pions. We demand that the cosine of the angle between each of the charged tracks and the Λ direction be greater than -0.4 in order to eliminate the random combinatorial background from the other quark jet. There is also a momentum cut of $p > 2.5$ GeV/c on the Λ_c candidate to further reduce background. We calculate the invariant mass for two cases: $\Lambda\pi^+\pi^+\pi^-$ ("right charge") and $\Lambda\pi^-\pi^-\pi^+$ ("wrong charge"). We refer to the first case as right charge because it has the correct baryon number and charge for a Λ_c.

Figures 2(a) and 2(b) display the invariant-mass distributions for the right- and wrong-charge combinations, respectively. There is an enhancement at a mass of about 2.275 GeV/c^2 in the right-charge distribution and no similar peak in the wrong-sign one. The size of this signal was determined by fitting the two distributions simultaneously with a single background polynomial function plus a Gaussian functional form. The position, width, and size of the peak were allowed to vary. The result of the fit is shown as the curves in Figs. 2(a) and 2(b). The size of the peak is 108 ± 28 events, with a fitted mass of 2.277 ± 0.011 GeV/c^2. Monte Carlo calculations indicate a decrease of 10 MeV/c^2 in the apparent mass due to dE/dx energy loss of charged particles traversing the beam pipe and inner proportional chamber. After we apply this correction the resulting mass is $2.287 \pm 0.011 \pm 0.005$ GeV/c^2, in good agreement with the known Λ_c mass.[6] The second error in the mass measurement is a systematic one due to uncertainties in the magnetic field normalization and the aforementioned dE/dx correction.

The full width at half maximum (FWHM) of the enhancement is 94 ± 25 MeV/c^2, somewhat larger than the 50-MeV/c^2 FWHM estimated from Monte Carlo

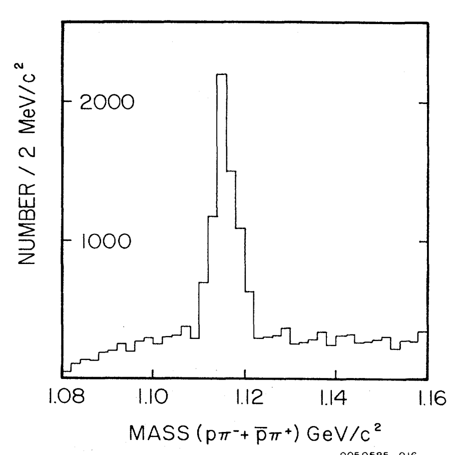

FIG. 1. The $p\pi^- + \bar{p}\pi^+$ invariant mass for Λ candidates.

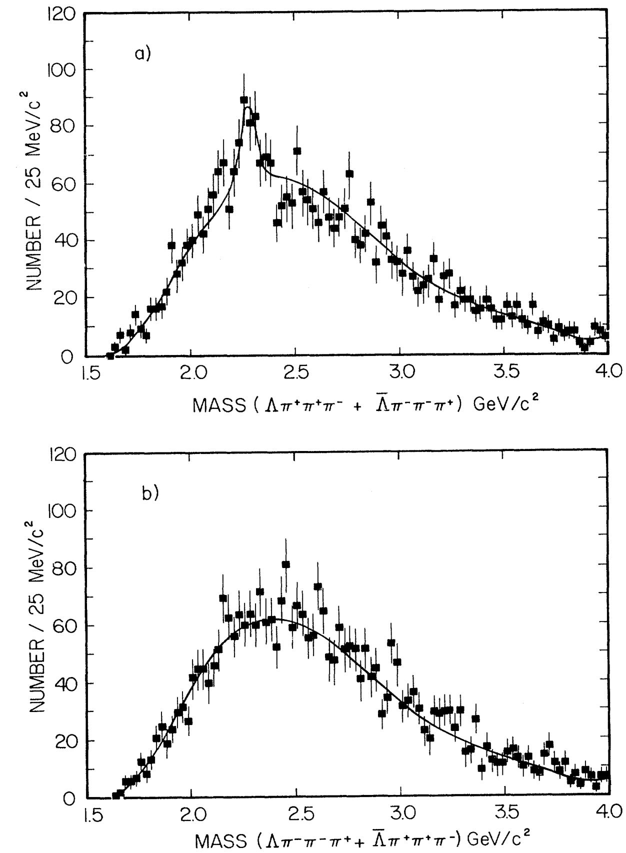

FIG. 2. (a) The $\Lambda\pi^+\pi^+\pi^-$ $(+\bar{\Lambda}\pi^-\pi^-\pi^+)$, "right-charge," invariant mass with the background plus Gaussian fit overplotted. (b) The $\Lambda\pi^-\pi^-\pi^+$ $(+\bar{\Lambda}\pi^+\pi^+\pi^-)$, "wrong-charge," invariant mass with the background fit overplotted.

calculations.[7] If we use 50 MeV/c^2 for the FWHM in the fit, we obtain a signal of 70 ± 17 events; we include this uncertainty due to the signal width in the systematic error on the Λ_c production rate.

We present the Λ_c momentum distribution in terms of the scaled momentum variable $x = P(\Lambda_c)/P_{\max}$, where $P_{\max}$ is the maximum possible momentum of the Λ_c. The x distribution is found for candidates that are within 50 MeV/c^2 of 2.275 GeV/c^2. In order to minimize the errors in subtracting the wrong-sign distribution from the right-sign one, we fitted the number of wrong-sign events by a smooth function of x. The fitted wrong-sign value for each x bin was then subtracted from the number of right-sign events at that value of x. We then correct these events by the Λ_c detection efficiency which was determined as a function of x by a Monte Carlo calculation. The efficiency rises rapidly from zero at $x = 0.2$ and is constant over the x range of 0.3–1.0, with a value of

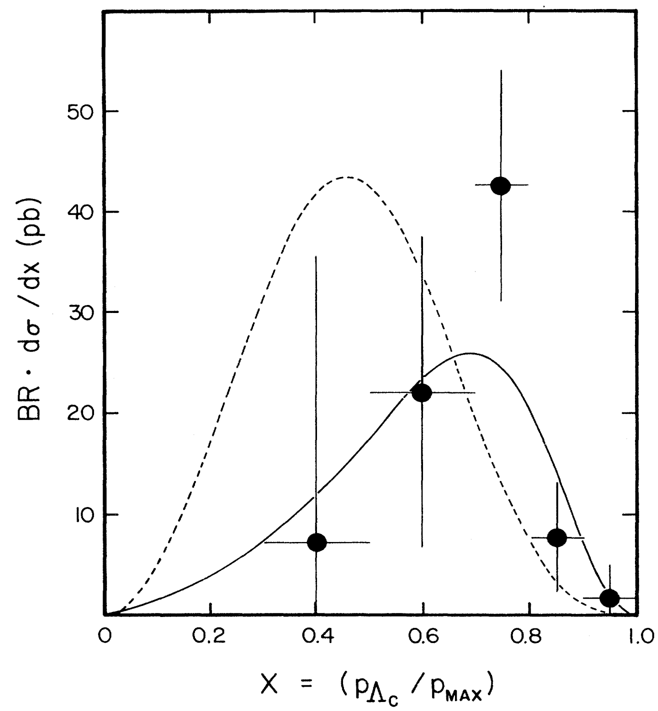

FIG. 3. The branching fraction $B(\Lambda_c \to \Lambda\pi^+\pi^+\pi^-)$ times the differential cross section $d\sigma/dx$ for Λ_c production. The solid curve is a theoretical prediction of Peterson *et al.* (Ref. 9), while the dashed curve is the prediction of DeGrand (Ref. 11).

$(5.9 \pm 0.4)\%$.

Figure 3 shows the resulting branching fraction times differential cross section for $e^+e^- \to \Lambda_c \to \Lambda\pi^+\pi^+\pi^-$. The spectrum peaks at large values of x, reminiscent of the spectrum for continuum production of charmed mesons.[8] This is in sharp contrast to the exponentially falling differential cross sections for hadrons like Λ's and K_S^0's.[5] This "hard" spectrum is expected since the Λ_c carries the original charmed quark produced from the e^+e^- annihilation.

The solid curve in Fig. 3 represents the formula of Peterson *et al.*[9] for the fragmentation function of mesons containing a heavy quark. The functional form is $x^{-1}[1 - 1/x - \epsilon/(1-x)]^{-2}$, where $\epsilon = (m_{\rm sp}^2 + P_T^2)/m_c^2$, $m_{\rm sp}^2$ is the mass squared of the spectator system, m_c^2 is the mass squared of the charmed quark, and P_T is the transverse momentum of the spectator relative to the charmed-quark direction. We have set $\epsilon = 0.14$ which gives the best fit to our D^* x spectrum[10] in order to study differences between these data and the meson case. As is evident, this form provides a good fit to the Λ_c data, yielding a χ^2 of 4.0 for four degrees of freedom. If we allow ϵ to be a free parameter we obtain $\epsilon = 0.21 \pm 0.08$.

We have also plotted as a dashed curve in Fig. 3 a formula suggested by DeGrand[11] as a hadronization function for charmed baryons. It is a generalization of the one for mesons, modified to include the independent production of two quark-antiquark pairs from the vacuum. We again fix the value for ϵ to be the same as in the meson case, that is, 0.14, which yields a χ^2 of 9.7 for four degrees of freedom. If we allow ϵ to vary, we obtain $\epsilon = 0.02 \pm 0.01$, which is too small to agree with reasonable values of the spectator quarks' masses.

The x dependence of Λ_c hadronization is sensitive to the underlying dynamics, and we have used these two formulations to compare the spectrum expected from a one-step diquark approach (Peterson formula) with a two-step, independent-quark-production model (DeGrand formula). The Peterson formula fits the data better, lending support to models in which baryons are formed by combination of a quark with an effective two-quark bound state (a diquark).

To measure the total number of Λ_c's produced, we use the Peterson formula with $\epsilon = 0.14$ to correct for the unseen part of the spectrum (a correction of 39%). After dividing by the total continuum cross section,[12] we find the yield of Λ_c's per hadronic event which decay into $\Lambda\pi^+\pi^+\pi^-$ to be $0.0044 \pm 0.0011 \pm 0.0015$, where the errors are statistical and systematic, respectively.[13]

If we assume that 40% of the continuum hadronic events are due to $c\bar{c}$ production then there is 0.8 c $(+\bar{c})$ quark per hadronic event. Therefore, the number of Λ_c's per charmed quark which decay into $\Lambda\pi^+\pi^+\pi^-$ is $0.0055 \pm 0.0014 \pm 0.0019$. If we use the estimate from MARK II data[14] that there is 0.2 Λ_c produced per c quark, we find the branching fraction for $\Lambda_c \rightarrow \Lambda\pi^+\pi^+\pi^-$ to be $(2.8 \pm 0.7 \pm 1.1)\%$. We have included a 20% uncertainty on the number of Λ_c's produced per c quark in the systematic error.

In summary, we have measured for the first time the Λ_c fragmentation function and found it to be very similar to that of charmed mesons. Its shape is more consistent with predictions from diquark fragmentation models than from independent-quark-production models when ϵ is fixed by charmed-meson data. We have also made the first measurement of the $\Lambda_c \rightarrow \Lambda\pi^+\pi^+\pi^-$ branching fraction.

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[12]Because the data were collected at energies both above and below B-meson threshold, we calculate the average "continuum" cross section by taking the cross section below the $\Upsilon(4S)$ and extrapolating it to higher energies accounting for the $1/s$ dependence; therefore, the "continuum" cross section does not include $e^+e^- \rightarrow b\bar{b}$ events.

[13]Our systematic error comes from adding in quadrature uncertainties in the reconstruction efficiency, including the error in the signal width (30%), uncertainties in the size of the background subtraction (10%), and uncertainty in the size of the extrapolation of x to 0 (15%).

[14]In Ref. 11, DeGrand uses the observed step in baryon production in e^+e^- annihilation at Λ_c threshold, as reported by Abrams *et al.*, Ref. 2, to obtain this estimate.