Λ Production in e^+e^- Annihilation at 29 GeV

C. de la Vaissiere,[a] V. Luth,[b] G. S. Abrams, D. Amidei,[c] A. R. Baden, T. Barklow, A. M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, D. L. Burke, F. Butler, J. W. Dillon,[d] J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber,[e] L. G. Golding,[f] G. Hanson, J. Haggerty, D. Herrup, T. Himel, R. J. Hollebeek, W. R. Innes, J. A. Jaros, I. Juricic, J. A. Kadyk, S. R. Klein, A. J. Lankford, R. R. Larsen, B. W. LeClaire, M. E. Levi,[b] N. S. Lockyer,[g] C. Matteuzzi,[b] M. E. Nelson,[h] R. A. Ong, M. L. Perl, B. Richter, M. C. Ross, P. C. Rowson, T. Schaad, H. Schellman, W. B. Schmidke, P. D. Sheldon, G. H. Trilling, J. M. Yelton, D. R. Wood, and C. Zaiser

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 18 February 1985)

The production of Λ hyperons in e^+e^- annihilation has been measured as a function of their total momenta, transverse momenta, and the event thrust. The total production rate is $0.213 \pm 0.012 \pm 0.018$ Λ or $\bar{\Lambda}$ per hadronic event. The observation of correlations in rapidity and angles for events with two detected Λ decays supports fragmentation models with local baryon-number compensation.

PACS numbers: 13.65.+i, 13.30.Eg

The knowledge of the particle composition of the hadronic final states produced in e^+e^- annihilation is important for the understanding of the fragmentation of quarks and gluons. Baryons, both strange and nonstrange, are produced at a substantial rate,[1-4] but so far little is known about their production mechanism. In particular, it is important to determine if baryon number is compensated locally or globally. In this Letter, we report measurements of the inclusive production of Λ hyperons[5] at the c.m. energy of $E_{\text{c.m.}} = 29$ GeV. The production relative to the thrust axis is studied in terms of the transverse momentum of the Λ and the thrust of the events. For events with two detected Λ decays, correlations are given in terms of the relative rapidity, angles, and orientation in the plane transverse to the thrust axis.

The measurements are based on data recorded by the Mark II detector at the e^+e^- storage ring PEP at Stanford Linear Accelerator Center over a period of three years. The total sample corresponds to an integrated luminosity of 205 ± 8 pb^{-1}. The properties of the detector and the selection criteria for hadronic events have been described elsewhere.[6,7] The charged-particle trajectories are reconstructed in two concentric cylindrical drift chambers which operate in a solenoidal field of 2.3 kG. In the plane transverse to the beam, momenta p (GeV/c) are measured with a resolution of $\delta p/p = [(0.010p)^2 + (0.025)^2]^{1/2}$ (the trajectories are not constrained to include the interaction point).

Only events with at least five charged particles and the total energy exceeding $0.25E_{\text{c.m.}}$ are included in this analysis. These particles are required to have momenta transverse to the beam of more than 100 MeV/c, and polar angles Θ with $|\cos\Theta| < 0.75$. After these cuts 67 500 events are retained, containing small contaminations due to $\tau^+\tau^-$ production [$(2.0 \pm 0.5)\%$], e^+e^- scattering events [$(1.5 \pm 0.5)\%$], two-photon processes [$(1.5 \pm 0.8)\%$], and beam-gas interactions [$(1.0 \pm 0.5)\%$]. None of these background processes contributes significantly to Λ or $\bar{\Lambda}$ production.

Candidates for the decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ are selected by the following procedure:

(1) All pairs of trajectories of oppositely charged particles are subjected to a vertex fit in three dimensions.

(2) All pairs with an effective mass $M(p\pi)^0$ in the mass interval between 1.088 and 1.144 GeV/c^2 are retained.

(3) Projecting each track onto the plane transverse to the beam, the closest distance between the particle trajectory and the average beam position has to exceed 2 mm for the pion and 1 mm for the proton. This cut reduces the background dramatically. For a 1-GeV/c momentum track the average error on this impact parameter is 150 μm, while the rms beam size is 65 ± 15 μm vertically and 480 ± 10 μm horizontally.

(4) In the same transverse plane, the Λ-candidate momentum vector is required to project back to the beam to within 5 mm.[8]

(5) Decays of Λ's with momenta less than 0.5 GeV/c are not included, because of low acceptance and large backgrounds.

(6) Since particle identification is not used, the background under the Λ mass peak is still appreciable after the above cuts, roughly 45% when averaged over all momenta. Additional background rejection is

achieved from measured distributions in five quantities: the impact parameters of the π, proton, and Λ; the distance Δz between the two trajectories at the intersection; and the $\cos\xi$, where ξ is the angle of the proton relative to the Λ momentum in the rest frame of the Λ. The probability distribution for these five quantities for both real Λ's and background are determined from the Monte Carlo simulation as well as the experimental distributions. A cut on the product of the five ratios of probability functions for signal and background removes 60% of the background with only a small [(4 ± 2)%] loss in signal events.

The invariant-mass spectrum for the two-particle combinations which satisfy the cuts are shown in the inset of Fig. 1. The peak is centered at 1.116 ± 0.001 GeV/c^2 with a full width at half maximum of 7 ± 1 MeV/c^2. We consider as our signal region the mass interval 1.106–1.126 GeV/c^2 and estimate the background from the pair population in the mass intervals 1.088–1.098 GeV/c^2 and 1.134–1.144 GeV/c^2. After statistical subtraction of an estimated (8.5 ± 1.5)% K_s contamination, we find roughly equal numbers of Λ and $\bar{\Lambda}$, 1610 ± 46 in total, over a background of (14.7 ± 1.0)%.

The overall efficiency for the detection of Λ decays has been estimated by Monte Carlo simulation[9,10] of the production and decay of hyperons. The observed Λ mass resolution and its momentum dependence are well reproduced. The efficiency has a broad maximum of about 13% (including the branching ratio) between 1.5 and 4 GeV/c, decreases slowly at higher momenta, and falls rapidly below 1 GeV/c. The systematic uncertainties in the track and vertex finding of ± 8.5% (including changes in the drift-chamber performance over long periods of operation) have been estimated by detailed studies of the tracking algorithms, and the effect of changes in the Λ selection criteria on Monte Carlo simulations of signal and background, as well as the data.

The inclusive cross section for Λ production versus x_Λ is shown in Fig. 1. The errors presented include the statistical uncertainty of the data and the Monte Carlo simulation. Also shown is the prediction of the Lund model.[10] The shape is well reproduced, though at high x_Λ the model calculation is systematically high.

The extrapolation of the Λ yield below the momentum cutoff at 0.5 GeV/c is done by a fit to the invariant phase space. The fit requires the sum of the two exponential terms

$$\frac{E}{4\pi p^2}\frac{d\sigma}{dp} = a_1 \exp(-b_1 E) + a_2 \exp(-b_2 E),$$

where p and E refer to the Λ momentum and energy. The best fit gives $b_1 = 4.8 \pm 0.9$ GeV^{-1}, $b_2 = 0.83 \pm 0.03$ GeV^{-1}, and $a_2/a_1 = (1.2 \pm 0.2) \times 10^{-3}$, resulting in an estimate for the loss of (7.7 ± 2.2)%. For the total production cross section we obtain $\sigma(\Lambda) + \sigma(\bar{\Lambda}) = 89.8 \pm 5.2 \pm 9.5$ pb. The first error quoted is statistical, and the second systematic; it includes the uncertainty in the overall normalization of the hadronic event yield[7] of 6.5%. Normalization to the total hadronic cross section results in the Λ multiplicity of

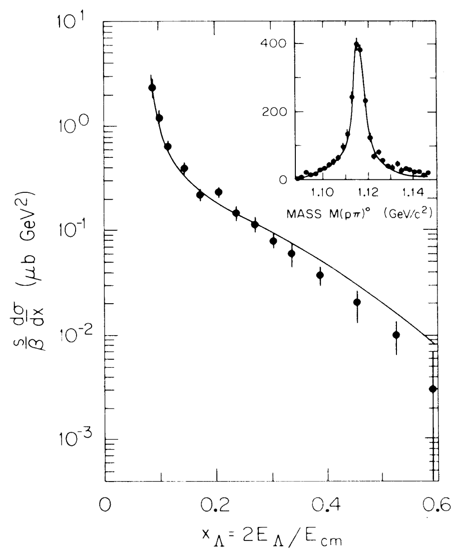

FIG. 1. Inclusive cross section for the sum of Λ and $\bar{\Lambda}$ vs $x_\Lambda = 2E/E_{\text{c.m.}}$, where E is the Λ energy. The curve represents the Lund model predictions. The inset gives the $M(p\pi)^0$ invariant-mass spectrum for the selected decays together with a curve which represents the resolution determined from Monte Carlo calculations.

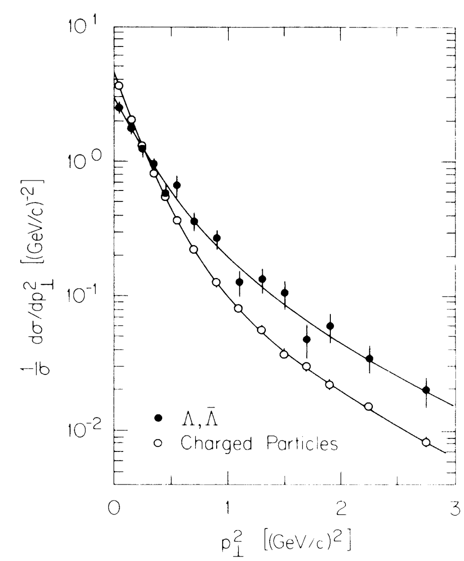

FIG. 2. Distribution of the transverse momentum squared for Λ hyperons and all charged particles, normalized to the total number of particles. The curves represent the empirical fit to the data described in the text.

$0.213 \pm 0.012 \pm 0.018$ per event.

In Fig. 2 we present the distribution of the transverse momentum relative to the thrust axis,[11] which is computed for all final-state particles in an event. The data are corrected for detection efficiency, and errors in the determination of the axis due to particle losses and initial-state radiation. The distribution has been fitted with the form

$$d\sigma/dp_\perp^2 = c_1 \exp(-p_\perp^2/2d_1^2) + c_2 \exp(-p_\perp^2/2d_2^2),$$

with $d_1 = 350 \pm 35$ MeV/c and $d_2 = 655 \pm 55$ MeV/c. The $p_\perp$ distribution for all charged particles is also shown in Fig. 2, together with a fit of the same form with $d_1 = 310 \pm 5$ MeV/c and $d_2 = 627 \pm 14$ MeV/c. While the fitted slopes are surprisingly similar for Λ and charged particles, the relative magnitude of the two Gaussian terms is quite different, namely, $c_2/c_1 = 0.17 \pm 0.08$ for Λ's and $c_2/c_1 = 0.063 \pm 0.008$ for all charged particles. The tail at higher $p_\perp$ is common to all particles. The low-$p_\perp$ enhancement in the charged-particle distribution can be attributed to the fact that most of them originate from decays of heavier resonances. In contrast, Λ's are expected to be produced directly in the fragmentation, or at least retain most of the momentum in baryon decay.

In terms of QCD, events with large thrust[11] are interpreted as two-jet fragments of quark-antiquark pairs, whereas low-thrust events are from the emission and fragmentation of additional hard gluons. In Fig. 3, the yield of hadronic events containing Λ's is compared to all hadronic events as a function of thrust. The errors are statistical; the relative efficiencies for the two samples vary by less than 30% below $T = 0.95$. There is a substantial increase in the Λ yield in the region below $T = 0.9$. This observation is interesting in the context of the threefold increase in the Λ/K ratio seen at the $\Upsilon(1S)$ resonance[4] which, according to QCD, decays predominantly into three gluons. Hence it appears that there is an enhancement in baryon production associated either with gluon fragmentation,[9,10] or with three-parton kinematics.[12]

For the understanding of the mechanism of baryon production, it is of prime importance to determine if baryon number is conserved locally or globally. In our sample there are 35 events with two detected Λ decays: 27 $\Lambda\bar{\Lambda}$ pairs, 3 $\Lambda\Lambda$ pairs, and 5 $\bar{\Lambda}\bar{\Lambda}$ pairs. We estimate the background to be 3.4 ± 1.5 events in each of the two samples, 60% of which is random, the rest due to K_s decays. Correlations between the two detected Λ's in each event are shown in Fig. 4. Here α refers to the opening angle between the pair, Δy represents the difference in rapidity, and $\Delta\phi$ refers to the difference in azimuthal angle ϕ defined in the projection transverse to the event thrust axis. The distributions for $\Lambda\bar{\Lambda}$ pairs differ from those expected for a Λ and a random hadron in the same event: The $\cos\alpha$ distribution is distinctly asymmetric, the forward-backward ratio being 18/9; there are eleven $\Lambda\bar{\Lambda}$ pairs within 40° of back-to-back, while four are expected for a uniform $\Delta\phi$ distribution. The eight pairs with equal baryon number are evenly distributed in $\cos\alpha$ and $\Delta\phi$ but within errors are also comparable with the $\Lambda\bar{\Lambda}$ pair distribution. A comparison with the results of a Monte Carlo simulation shows good agreement with the data. In this simulation it is assumed that the baryons in a pair are always adjacent in rank in the

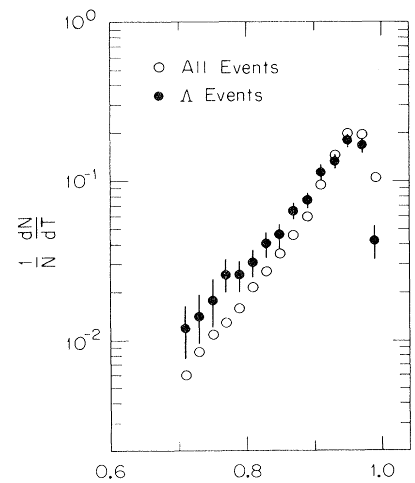

FIG. 3. Comparison of thrust distributions for all hadronic events and events with at least one Λ hyperon. The data are normalized to the total number of events in each sample. The errors are statistical only.

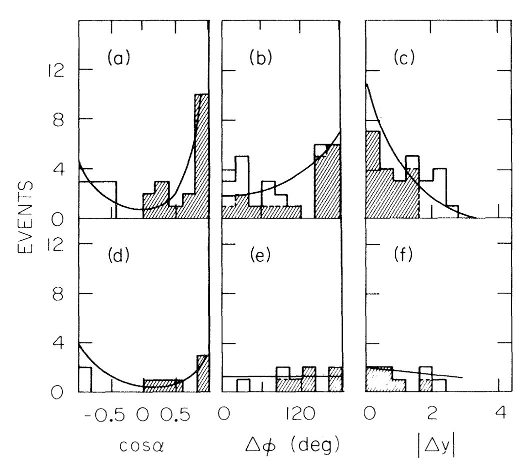

FIG. 4. Observed correlations for (a)–(c) $\Lambda\bar{\Lambda}$ pairs and (d)–(f) $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs. The variables are defined in the text. The curves represent the predictions of a fragmentation model with local compensation of baryon number. Events with $\cos\alpha > 0$ are shaded.

fragmentation, thus leading to a correlation in rapidity and azimuthal angle.[13] It should be noted that the distributions shown have not been corrected for efficiency or background; thus the data and Monte Carlo curves include background and the experimental error in the determination of the jet axis.

In summary, we have measured Λ and $\bar{\Lambda}$ differential and total cross sections using a very clean sample of 1610 ± 46 events. The total yield per hadronic event is $0.213 \pm 0.012 \pm 0.018$, a value that agrees well with the results of Bartel *et al.*[2] and Aihara *et al.*,[3] but is considerably below the results of Althoff *et al.*[14] of 0.31 ± 0.03. The differential-cross-section data follow the prediction of the Lund fragmentation model[10] reasonably well and are consistent with results from other experiments.

Enhanced Λ yields at large transverse momentum to the jet axis and in events with low thrust corroborate the evidence obtained from decays of the Υ resonance[4] that baryon production is enhanced in events that deviate from the two-jet topology. Events with a detected $\Lambda\bar{\Lambda}$ pair show correlations in angles and rapidity. For $\Lambda\bar{\Lambda}$ produced in the same jet we see evidence for a correlation in ϕ, an effect first observed by Bartel *et al.*[2] in $\Lambda\bar{p}$ pairs, but not confirmed by Brandelik *et al.*[1] or Aihara *et al.*[3] for $p\bar{p}$ pairs. More quantitative and detailed studies of the fragmentation leading to baryon production will require substantially more statistics.

This work was supported in part by the U. S. Department of Energy under Contract No. DE-AC03-76SF00515 and No. DE-AC03-76SF00098.

---

[a]Present address: Laboratoire de Physique Nucléaire et Haute Energies, Université Pierre et Marie Curie, Paris F-75230, France.

[b]Present address: CERN, CH-1211 Geneva 23, Switzerland.

[c]Present address: University of Chicago, Chicago, Ill. 60637.

[d]Present address: Xerox Park, Palo Alto, Cal. 94301.

[e]The Miller Institute for Basic Research in Science, Berkeley, Cal. 94720 (1984–1985).

[f]Present address: Therma Wave Inc., Fremont, Cal. 94539.

[g]Present address: University of Pennsylvania, Philadelphia, Pa. 19104.

[h]Present address: California Institute of Technology, Pasadena, Cal. 91125.

[1]R. Brandelik *et al.*, Phys. Lett. **94B**, 444 (1980), and **105B**, 75 (1981), and **130B**, 340 (1983).

[2]W. Bartel *et al.*, Phys. Lett. **104B**, 325 (1981).

[3]H. Aihara *et al.*, Phys. Rev. Lett. **52**, 577 (1984), and **54**, 274 (1985).

[4]M. S. Alam *et al.*, Phys. Rev. Lett. **53**, 24 (1984).

[5]We shall refer to Λ and $\bar{\Lambda}$ hyperons as Λ, since the analysis treats the decays in the same way.

[6]R. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981); J. Jaros, in Proceedings of the International Conference on Instrumentation for Colliding Beam Physics, edited by W. Ash, Stanford Linear Accelerator Center Report No. 250, 1982 (unpublished).

[7]J. Patrick *et al.*, Phys. Rev. Lett. **49**, 1229 (1982).

[8]This cut suppresses Λ's originating from the decays of long-lived hyperons. Given that Ξ^- decays contribute $\frac{1}{8}$ of all Λ's (Refs. 1 and 3), the total loss due to cascade production amounts to 6%. This is included in the efficiency calculation.

[9]A. Ali, E. Pietarinen, G. Kramer, and J. Willrodt, Phys. Lett. **93B**, 155 (1980); T. Meyer, Z. Phys. C **12**, 77 (1982).

[10]B. Anderson *et al.*, Phys. Lett. **85B**, 417 (1979), and Nucl. Phys. **B197**, 45 (1980), and Z. Phys. C **20**, 317 (1983). The curve in Fig. 1 was taken from Ref. 3.

[11]S. Brandt *et al.*, Phys. Lett. **12**, 57 (1964); E. Farhi, Phys. Rev. Lett. **39**, 1587 (1977).

[12]R. D. Field, Phys. Lett. **135B**, 203 (1984).

[13]A. Bartl, H. Fraas, H. R. Gerhold, and W. Majerotto, Phys. Rev. D **26**, 1061 (1982); A. Bartl *et al.*, Phys. Lett. **122B**, 427 (1983).

[14]M. Althoff *et al.*, Z. Phys. C **27**, 27 (1985).