Λ Production in e^+e^- Annihilations at 29 GeV: A Comparison with Lund-Model Predictions

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This paper presents measurements of the inclusive production cross sections of Λ baryons in e^+e^- annihilations at $\sqrt{s} = 29$ GeV. The data sample corresponds to an integrated luminosity of 256 pb^{-1} collected with the High-Resolution Spectrometer at the SLAC storage ring PEP. Comparisons are made to the predictions of the Lund model. The data are well described with use of a strange-diquark suppression parameter, $(us/ud)/(s/d)$, of $0.89 \pm 0.10^{+0.56}_{-0.16}$, and the measured $\Lambda_c \rightarrow \Lambda + X$ branching ratio of $(23 \pm 10)\%$.

The inclusive cross sections for lambda (Λ) production in high-energy e^+e^- annihilations into hadrons have been measured by several experiments.[1-4] In this paper we present new results on Λ production from a large sample of data collected over a period of four years with the High-Resolution Spectrometer (HRS) at the SLAC e^+e^- storage ring PEP. The data, taken from an integrated luminosity of 256 ± 8 pb^{-1} at $\sqrt{s} = 29$ GeV, are compared to predictions of the Lund model[5] for the inclusive Λ differential cross sections as a function of fractional energy, $z = 2E_\Lambda/\sqrt{s}$, and rapidity, $y = \frac{1}{2}\ln[(E_\Lambda+p_\parallel)/(E_\Lambda-p_\parallel)]$.

In the Lund string model, baryons are produced when a quark and a diquark, members of neighboring pairs produced from the vacuum, are joined by a strong-force flux tube of sufficient energy. The production rate of baryons relative to mesons in the fragmentation chain is controlled, in this model, by a parameter that gives the relative probability of forming a diquark pair versus a quark pair. Physically, the diquark is pictured as an object of mass m that couples to the color field as a unit. The suppression of diquarks (and of heavy quarks) arises from a tunneling probability that is proportional to $\exp(-m^2/K^2)$, where $K \approx 250$ MeV. The production of a Λ is suppressed both because it is a baryon and because it contains a strange quark. The strangeness may come either from the quark or from the diquark. The ratio of strange-quark production to light-quark production, s/u, is a parameter of the model. Any additional suppression of strangeness in diquarks is specified by the parameter $\delta = (us/ud)/(s/d)$.

A second important source of Λ hyperons is the decay of charmed baryons. The shapes of the z and y differential cross sections are different for Λ hyperons coming from these two sources, and so their relative contributions can, in principle, be measured given sufficiently precise data.

The Λ particle is readily identifiable via its long-lived decay to $p\pi$. At PEP energies, the Λ and $\overline{\Lambda}$ are easily distinguished from one another because the proton must carry more momentum than the pion in the lab frame whenever the parent Λ has $z > 0.08$. Throughout this discussion we use "Λ" to refer to both the lambda hyperon and its antiparticle, and cross sections given for the "Λ" are the sums of the Λ and $\overline{\Lambda}$ values.

Features of the HRS detector[6] relevant to the present analysis include a fifteen-layer central drift chamber, with tracking layers spanning the radial distances from 21 to 103 cm, and covering 90% of 4π in solid angle, and a two-layer outer drift-chamber system at a radius of 190 cm, which covers 65% of 4π. Both chamber systems are contained within the 16.2-kG solenoidal magnetic field. The momentum resolution for tracks which pass through the outer drift-chamber layers is $\sigma_p = 2 \times 10^{-3}p^2$ (GeV/c).

The hadronic data sample was selected by a series of simple cuts,[7] which included the requirements of at least four charged tracks and a scalar sum of the momenta greater than 5.8 GeV/c. Events containing less than 7.0 GeV of charged-particle energy were required to have a total energy (including the energy in the electromagnetic shower counters) of at least 8.0 GeV.

The decays $\Lambda \to p\pi^-$ were identified through a series of cuts that favored neutral-track pairs coming from secondary decay vertices. The principal requirements were these: (a) Each track had to be well reconstructed, using at least 60% of the drift-chamber cells traversed. (b) For each pair of tracks, the one with the lower momentum was assumed to be the pion, and was required to miss the primary event vertex by at least 0.2 cm in the plane perpendicular to the beam direction. (c) The two decay tracks were required to intersect in that transverse plane at a radial distance of between 1.5 and 75.0 cm, and to pass within 2 cm of each other along the beam direction at this intersection point. (d) The reconstructed neutral momentum vector, when projected through the secondary vertex point, was required to come within 0.3 cm of the primary event vertex. (e) Vee candidates satisfying the above criteria were fitted to a three-dimensional secondary vertex. The χ^2 of this fit was required to be less than 10. (f) Vee candidates having an invariant mass within 10 MeV of the K^0 mass, when both tracks are interpreted as pions, were rejected.

These cuts produce an exceptionally narrow peak in the $p\pi$ mass spectrum, as shown in Fig. 1. The spatial resolution of the tracking chambers, and the small amount of material between the beam crossing point and the central drift chamber, combined with the high magnetic field, allow the extraction of a Λ sample with a good signal-to-noise ratio across a range of fractional energies that extends to $z = 0.8$. The signal in the high-z region is shown separately in Fig. 1(b).

The background distributions were determined from the data by reflecting the reconstructed momentum vector of all negatively charged tracks through the origin, 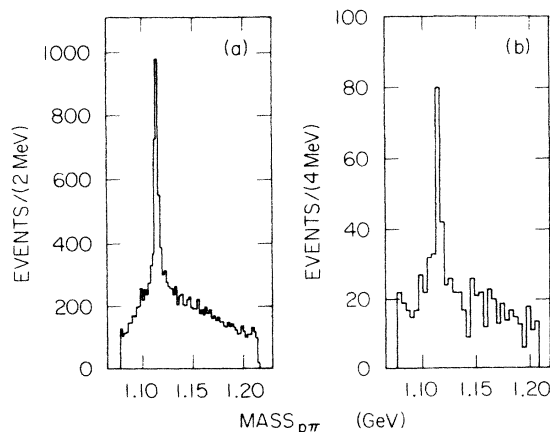and applying the same vee-finding analysis. These background vees produce a p-π mass spectrum whose shape agrees with that of the data in the regions away from the Λ mass peak. The distribution was normalized to give the proper number of events in the wings and subtracted from the data. The signal in Fig. 1(a) contains 1514 ± 85 Λ and 1407 ± 85 $\bar{\Lambda}$ events. Using Breit-Wigner forms to fit the peak regions,[8] we obtain central mass values of 1115.7 ± 0.1 MeV for the Λ and 1115.6 ± 0.1 MeV for the $\bar{\Lambda}$, in good agreement with world average values.[9] The widths (Γ) are found to be 5.0 ± 0.3 MeV for the Λ and 4.9 ± 0.3 MeV for the $\bar{\Lambda}$, in excellent agreement with Monte Carlo studies of the detector resolution. In determination of the inclusive distributions, the Λ signal was selected in the mass region between 1110.6 and 1120.6 MeV.

The detector acceptance was calculated as a function of z, with use of hadronic events simulated by a Monte Carlo program. The acceptance function peaks at $z = 0.25$, where 13% of $\Lambda \to p\pi^-$ decays are reconstructed; the overall acceptance for $\Lambda \to p\pi^-$ is 7.5%. The scaling cross section $(s/\beta)d\sigma/dz$, also corrected for the known branching ratio into $p\pi^-$,[9] is shown in Fig. 2 as a function of the fractional energy variable z. The statistical and systematic errors, which have been summed in quadrature in Fig. 2, are roughly equal in size. The systematic uncertainties include the background subtraction, acceptance correction, and luminosity determination. The results are in good agreement with earlier experiments[1-3] in the region of overlap. The HRS data at high z indicate a continuation of the previously observed exponential fall in the scaling cross section.

The Λ rapidity was calculated relative to a thrust

FIG. 1. Invariant-mass spectra resulting from oppositely charged track pairs satisfying the cuts described in text for (a) all z and (b) $0.4 < z < 0.8$. The higher-momentum track of the pair is interpreted as p ($\bar{p}$), the lower as π^- (π^+).
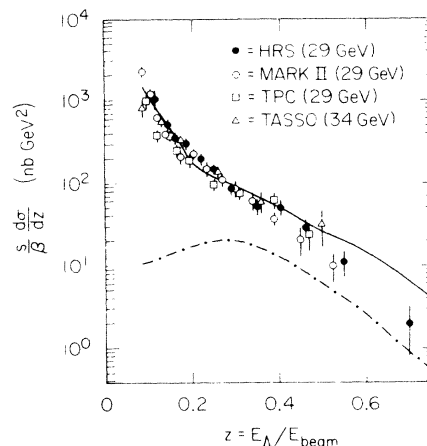

FIG. 2. Measurements of the scaling cross section, $(s/\beta)(d\sigma/dz)$, for inclusive Λ production. Data from the Mark II, TPC, and TASSO detectors are shown for comparison. The solid curve is given by the Lund Monte Carlo program, with $\delta = 0.89$ and a branching ratio for $\Lambda_c \to \Lambda + X$ of 23%. The dot-dashed curve represents the contribution from charmed-baryon decay.

axis, which was determined for each event by use of all well-measured charged tracks. Tracks tagged as coming from a K^0 or Λ decay were included in the thrust calculation as a single neutral track, constrained to a secondary vertex. Events in which the thrust axis was not well contained within the tracking volume were rejected from the data sample. The acceptance-corrected rapidity distribution is shown in Fig. 3.

The z and y distributions were fitted to the predictions of the Lund model, with the value of the strange-diquark suppression parameter δ varied from 0 to 1.5. The other important parameters of the model were set equal to the values $s/u = 0.34 \pm 0.03$, as determined from the HRS data on K^0, K^{*0}, and ϕ production,[10] and $qq/q = 0.078 \pm 0.005$, as determined from the baryon data of the TPC group.[11] The inclusive branching ratio (B) for $\Lambda_c \rightarrow \Lambda + K$ was fixed to the value $B = (23 \pm 10)\%$, as reported by Abe *et al.*[12] Fitting both the z and the y distributions, we obtain $\delta = 0.89 \pm 0.10$. These parameters give the solid curves in Figs. 2 and 3, both of which agree well with the data. The contributions from charmed-baryon decay alone are shown by the dot-dashed lines in Figs. 2 and 3. These distributions peak near $z = 0.3$ and $y = 2.0$, in contrast to the Λ particles coming from the fragmentation chain which populate the regions at low z and low rapidity.

The statistical and the systematic uncertainties in the data were both included in the χ^2 calculations and are reflected in the error of ± 0.10 on δ. This error, however, does not reflect the uncertainties in the other Lund parameters, qq/q and s/u, or in B. In order to reproduce the total inclusive cross section of the Λ, these parameters must satisfy the approximate relation

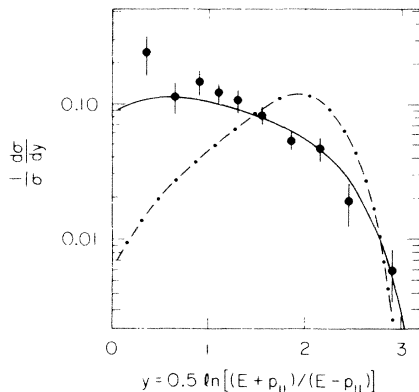$$\frac{qq}{q} \frac{s}{u} (1 + \delta) + C_1 B = \text{const},$$

where C_1 is a constant proportional to the total production rate for charmed baryons. This production rate has not been directly measured at PEP energies, and for this analysis it is taken to be $2 \times \frac{5}{11} (qq/q)$ charmed baryons per hadronic event. This is a reasonable but unsubstantiated assumption. Thus, although B is discussed as the parameter in question, one can regard the product $C_1 B$ as the true unknown.

Figure 4 shows the variation of δ with B, as determined from χ^2 fits to the z and y distributions of the Λ. The dashed lines represent the 1σ errors in δ for fixed B. The shapes of both the z and y distributions are best described with no contribution from charmed-baryon decay. The χ^2 of the fit steadily increases as one follows the band of best values from $B = 0\%$ to $B = 50\%$. If the experimental measurement[12] of B is included as a constraint in the fit, then the 1σ upper and lower bounds on δ are 1.45 and 0.80. On the basis of these considerations, and of the quoted uncertainties in qq/q and s/u, we assign an additional systematic error of $^{+0.56}_{-0.16}$ to the δ measurement.

As a further check, we note that the set of Lund parameters reported here implies a production of 0.024 Ξ^- particle per event, in good agreement with the measurements of 0.026 ± 0.012 Ξ^- per event by the TASSO group,[13] and 0.020 ± 0.009 Ξ^- per event by the TPC group.[11] A determination from these Ξ^- numbers alone yields $\delta = 0.88 \pm 0.39$.

An evaluation of δ can also be made from the cross section for events containing both a Λ and $\bar{\Lambda}$. There are 21 such events in the present data sample, with an estimated background of 3.3 ± 2.1 events, giving a mean multiplicity of $\langle n_{\Lambda \cdot \bar{\Lambda}} \rangle = 0.054 \pm 0.014 \pm 0.012$ pairs per hadronic event. The first error is statistical, the second systematic. This value, averaged with the TPC measurement[2] of $\langle n_{\Lambda \cdot \bar{\Lambda}} \rangle = 0.042 \pm 0.017 \pm 0.014$ and compared with the Lund-model prediction for
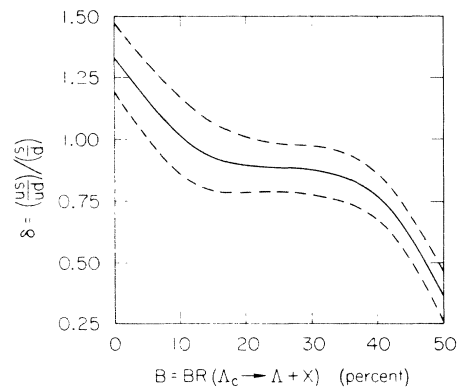
FIG. 3. The rapidity distribution, $(1/\sigma)(d\sigma/dy)$, for inclusive Λ production, where y is measured relative to the thrust axis. The solid curve is given by the Lund Monte Carlo program, with $\delta = 0.89$ and $B(\Lambda_c \rightarrow \Lambda + X) = 23\%$. The dot-dashed curve represents the contribution from charmed-baryon decay ($\times 10$).

FIG. 4. Best-fit values of the Lund strange-diquark suppression parameter δ as a function of the assumed inclusive branching ratio (B) for $\Lambda_c \rightarrow \Lambda + X$. The dashed lines represent 1σ errors in δ for fixed B.

$\langle n_{\Lambda-\bar{\Lambda}} \rangle$, leads to a value of $\delta = 0.77 \pm 0.35$. Both this measurement and the Ξ^--production measurement are in reasonable agreement with our previous result, but neither is precise enough to rule out the low-δ region.

In quoting a total Λ-production cross section, it is important to specify the correction made for the unobserved momentum region. In the range from $z = 0.1$ to 0.8, where a good signal is obtained, the ratio to the μ-pair point cross section is measured to be $R_\Lambda = 0.678 \pm 0.023 \pm 0.047$. From the solid curve of Fig. 2, the correction is 20.9%, which results in a total multiplicity of $\langle n_\Lambda \rangle = 0.220 \pm 0.007 \pm 0.022$ per event.[14]

In summary, the fits of the Lund model to the inclusive Λ data presented here show that very little extra suppression of the strange flavor is needed in diquark pair production over that already found for single-quark pair production. Previous analyses of inclusive Λ data have reported values for the Lund strange-diquark suppression parameter, δ, of 0.32[1] and 0.2.[2] These results were obtained with a version of the Lund Monte Carlo procedure[5] which yields a value of 50% for the inclusive branching ratio $\Lambda_c \rightarrow \Lambda + X$. Substantially better agreement with the present data is achieved when the recently measured value of $B = (23 \pm 10)\%$ is used, and a value $\delta = 0.89 \pm 0.10^{+0.56}_{-0.16}$ is obtained.

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[14]Using the Lund curve with $\delta = 0.3$ and $B = 50\%$ gives a total multiplicity of $\langle n_\Lambda \rangle = 0.214 \pm 0.007 \pm 0.021$, in good agreement with the values reported by the Mark II and TPC Collaborations.