Polarization of Λ and $\bar{\Lambda}$ Produced by 800-GeV Protons

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Abstract

We have measured the polarization of Λ and $\bar{\Lambda}$ hyperons produced by 800 GeV protons on a Be target at a fixed targeting angle of 4.8 mrad. Comparison with previous data at 400 GeV production energy and twice the targeting angle shows no significant energy dependence for the Λ polarization. This is in striking contrast to the energy dependence found for Σ^+ and Ξ^- polarizations. We find no evidence for $\bar{\Lambda}$ polarization at 800 GeV.

Although it has been known for more than 15 years that some hyperons are produced with a significant polarization in hadroproduction experiments, there is still no generally accepted mechanism[1–4] that can explain the pattern of polarizations. The recent discovery[5,6] that the anti-hyperons $\bar{\Xi}^+$ and $\bar{\Sigma}^-$ are produced polarized upsets the idea[7] that the pattern might be explained by a valence quark model. One author has suggested[4] that this discrepancy might arise from a difference in polarization between hyperon production at 400 GeV and 800 GeV. Recently, evidence has been presented[6,8] that both Ξ^- and Σ^+ hyperon polarizations differ significantly between 400 GeV and 800 GeV. Previous to these observations, it appeared[3] that high energy hyperon polarization was a function only of the hyperon transverse momentum (p_T) and the fraction of beam energy carried by the final state hyperon (x_F). The dependence of Λ polarization on these variables has been well measured[9] at 400 GeV. An ISR experiment[10] at center of mass energies of $\sqrt{s} = 53$ and $\sqrt{s} = 62$ GeV suggests a substantial polarization increase with energy. Direct comparison is not possible, however, because of large statistical uncertainties as well as differing kinematic conditions and production processes (proton-Be *vs* proton-proton reactions). In this letter, we present the first measurements of Λ and $\bar{\Lambda}$ polarization in fixed target hadroproduction at 800 GeV. In a direct comparison with 400 GeV data, we find no significant polarization difference. We also find no evidence for $\bar{\Lambda}$ polarization at this energy.

The data discussed in this letter were obtained by Fermilab Experiment 799. A secondary neutral hadron beam, including Λ hyperons, was produced by a primary 800 GeV proton beam incident on a Be target. The targeting angle was fixed at 4.8 mrad in the horizontal plane. Since we could not vary the production angle, the Λ spin direction was reversed by altering its precession angle in our beamline magnets.

Collimators, lead absorbers, and 4 sweeping magnets were used to create two neutral beams, separated vertically by an angle of 1.2 mrad. After the last sweeping magnet, located approximately 55 meters from the target, $\Lambda \rightarrow p\pi^-$ decays could occur without the final state particles being swept out of the beamline. The Λ polarization is perpendicular to the production plane, along (or opposite) the $\vec{p_P} \times \vec{p_\Lambda}$ direction. (For this analysis, we define the $\vec{p_P} \times \vec{p_\Lambda}$ direction to be the +Y axis. The neutral beamline is the +Z axis, and the origin of coordinates is at the production target.) The sweeping magnets all had magnetic fields in the horizontal (X) direction producing a precession of the Λ spin in the Y-Z plane. By altering the field strength and polarity of *just one* sweeping magnet, the Λ spin precession was changed from $0°$ (0.0 ± 0.3 T-m total field integral) to $180°$ (16.0 ± 0.3 T-m). The accepted value[13] of the Λ magnetic moment was used in calculating the required field strength. The field of this magnet was changed approximately every run, typically 8 hours. The data set used for this analysis spans 109 runs. Figure 1 shows the locations of the sweeping magnets and detector elements along the beamline.

The decay region for $\Lambda \rightarrow p\pi^-$ decays extended from Z = 55 m to Z = 160 m. The acceptance for upstream decays was limited by a rectangular collimator at Z = 85 m and by the upstream beam pipe. The spectrometer began at Z = 160 m. The main spectrometer components were 4 drift chambers for charged particle tracking and a lead glass calorimeter for electromagnetic particle identification. Each drift chamber contained 2 X-measuring views and 2 Y-measuring views of wire planes, with each plane giving single hit resolution of approximately 100 μm. The wire spacing in the drift chamber planes was 12.7 mm, with one plane in each view offset from the other by half a wire spacing. There were 2 drift chambers on either side of an analyzing magnet whose integral transverse momentum kick was 200

MeV/c. The observed momentum resolution from the spectrometer was $(\sigma_p/p)^2 = (5 \cdot 10^{-3})^2 + (1.4 \cdot 10^{-4} p)^2$, where p is the momentum of the track in GeV/c. The calorimeter gave an average electron energy resolution of 4.5% for this experiment. To veto events which had additional decay products outside the acceptance of the drift chambers and calorimeter, there were veto counters at periodic stations in the region downstream of 120 meters from the target. Two hodoscopes upstream of the lead glass array were used to form the trigger for charged particles. The detector is described in greater detail elsewhere.[11]

At the first level, the $\Lambda \to p\pi^-$ trigger required 2 hits in each trigger counter bank (rejecting events with 3 or more hits in both trigger banks) and the absence of energy in the various veto counters. At the second level, the trigger selected high momentum forward particles by comparing X-view hits in the central 10 wires of the drift chambers with patterns stored in a high-speed lookup memory module. The deflection of the selected particles by the spectrometer magnet was less than or equal to 1 wire. A further requirement of the trigger was that the number of drift chamber hits be consistent with a two track decay.

For this analysis, events with two reconstructed tracks in both the X and Y views and with the lower momentum track pointing toward a calorimeter cluster of energy $E > 0.5$ GeV were retained. Cuts were made to ensure good quality tracks matched to a vertex. The drift chamber hits associated with the two tracks were also required to satisfy the trigger conditions. The two tracks were required to be of opposite sign, with the higher momentum track being positively (negatively) charged for the Λ ($\bar{\Lambda}$) sample. The lower momentum track was required to be at least 1.2 cm from the nearest calorimeter beam hole to ensure good particle identification.

Figure 2a shows the proper lifetime (τ_Λ) distribution for the data in the Λ decay sample. As can be seen, the distribution is essentially flat beyond 10 lifetimes. This long-lived tail is correlated with a calorimeter response consistent with an electron signal ($E/p = 1$). These events are background from the decay $K_L \to \pi e \nu_e$ (Ke3). The level of this background is the same for the two polarization settings. Cuts of $\tau_\Lambda < 10$ and $E/p < 0.8$ were imposed on the data sample, reducing the Ke3 background to well below 1%. To ensure that each event was consistent with a Λ or $\bar{\Lambda}$ decay, the invariant mass of the two tracks was calculated, with the higher momentum track assumed to be a proton and the lower momentum track a pion. This reconstructed mass, $m_{p\pi}$, was required to be within 15 MeV/c^2 of the nominal[13] Λ mass, 1115.6 MeV/c^2. The reconstructed momentum transverse to the Λ line of flight from the target was required to be less than 45 MeV/c. Figure 2b shows the $m_{p\pi}$ distribution before and after the cuts on τ_Λ, E/p and transverse momentum. The number of Λ decay events passing all of the cuts is 379247, of which 186146 events have 0° polarization precession. The number of $\bar{\Lambda}$ events is 11464, of which 5522 have 0° precession. There were approximately equal numbers of events in each beam.

Another source of background is $K^\circ \to \pi^+\pi^-$ decays with the positive pion misidentified as a proton. An estimate can be made of the level of this background from the sidebands of the invariant mass spectrum: $15 < |m_{p\pi} - m_\Lambda| < 30$ MeV/c^2. A clear pion-pion mass peak is evident at the neutral kaon mass, 498 MeV/c^2. The number of K° decays in the mass sidebands that pass all other cuts is then an estimate of the background under the Λ mass peak itself. We estimate the background from K° decays to be 0.4% (6.4%) for the Λ ($\bar{\Lambda}$) sample.

The Λ polarization was determined by first splitting our data into two oppositely polarized samples and then calculating the direction cosines $[cos\theta_x, cos\theta_y, cos\theta_z]$

of the pion momentum vector in the Λ rest frame. For a sample of decays where the Λ has an average polarization $\vec{\mathbf{P}}$, the normalized direction cosine distribution[12] is

$$f_{\pm}(cos\theta_i) \propto A(\cos\theta_i)[1 \pm \alpha_\pi P_i cos\theta_i] \tag{1}$$

for $i = x,y,z$. The currently accepted value[13] of the pion asymmetry parameter in $\Lambda \to p\pi^-$ decay is $\alpha_\pi = -0.642 \pm 0.013$. The function $A(cos\theta_i)$ describes the experimental acceptance for Λ decays as a function of the pion direction cosine. The quantity $f_+(cos\theta_i)$ $[f_-(cos\theta_i)]$ is the fraction of the 0° $[180^\circ]$ precession sample with a given value of $cos\theta_i$. Then the antisymmetric ratio:

$$R(cos\theta_i) = \frac{(f_+ - f_-)}{(f_+ + f_-)} = \alpha_\pi P_i cos\theta_i \tag{2}$$

has a slope with respect to $cos\theta_i$ which gives the asymmetry $\alpha_\pi P_i$, from which the polarization component P_i is obtained. As long as the acceptance of the detector does not vary rapidly with time, it does not enter this calculation of the polarization because it cancels in the ratio. Backgrounds will reduce the calculated value of polarization by a factor of (1 + B/S), where B/S is the ratio of background events to signal events. An analysis of $K_L \to \pi^+\pi^-\pi^\circ$ decays, taken simultaneously with the Λ data, shows that these kaon decays are not affected by the magnet settings. It is assumed that the kaon decays comprising our background are likewise unaffected. All polarization results presented have been corrected for background.

Figure 3 shows a comparison between the pion direction cosine distributions for the two magnet settings. As can be seen, the pairs of distributions are essentially identical in the X and Z directions. In the Y direction, however, the two distributions are clearly different, showing the effect of the Λ polarization on the pion decay distribution. Also shown in Figure 3 are plots of the ratio defined in Equation 2.

Linear fits to these graphs give average asymmetries of $\alpha_\pi P_X = -0.0002 \pm 0.0037$, $\alpha_\pi P_Y = 0.0639 \pm 0.0028$, and $\alpha_\pi P_Z = 0.0071 \pm 0.0028$. The slight deviation from zero of the average Z polarization has been thoroughly investigated, and no known acceptance biases contributed to it. The data were split into separate groups of runs to look for time dependence. No significant run-to-run variation in the calculated Λ asymmetries was found.

The Λ data were divided into energy bins, and the polarization was calculated for each bin. Results for P_Y are shown in Table 1. There was not enough $\bar{\Lambda}$ data to determine polarizations for separate energy subsamples. The entire $\bar{\Lambda}$ data sample was analyzed using the method discussed above. A value of $< P_Y >= 0.014 \pm 0.027$ was obtained. This sample had an average $\bar{\Lambda}$ energy of 252 GeV and an average transverse momentum of 1.22 GeV/c.

Our bias canceling analysis in combination with frequent polarization reversals by magnetic precession effectively eliminated most sources of systematic error. To check this we calculated P_X and P_Y for each Λ energy bin and obtained values consistent with zero to within two standard deviations. We also verified that there was no significant polarization difference between events from the upper beam and the lower beam. There was likewise no significant polarization difference between upstream ($Z < 85$ m) and downstream ($Z > 85$ m) decays. Since these subsamples differed substantially in acceptance, this clearly indicates that detector acceptance effects do not significantly impact our polarization results.

The uncertainty in the accepted value[13] of α_π gives rise to a 2% polarization scale uncertainty. The 0.3 T-m uncertainty in our precession field integral would give rise to an 0.2% *underestimate* of the lambda polarization value. These are to be compared to our relative statistical error, which is 10% or greater for each energy bin. We have taken the view that the observed overall Z asymmetry of 0.0071 provides an absolute upper limit on acceptance systematics and have conservatively assigned a corresponding systematic error for each energy bin. We also assign an uncertainty to the background estimates of 20% of their size. These systematic errors were combined in quadrature with the statistical uncertainty for each energy bin to obtain the error values given in Table 1.

Figure 4 shows the variation of Λ polarization with production transverse momentum. On this same graph, comparable data[9] from Fermilab Experiment 555 has been superimposed. These data had a targeting angle of approximately 9.6 mrad, twice our targeting angle, and a proton beam energy of 400 GeV, half our energy. The target material for this data and for ours was Be. For a given value of p_T, the E555 data have the same x_F value as the data presented here, and are therefore directly comparable. No significant change in Λ polarization is seen between the two production energies of 400 and 800 GeV. This contrasts markedly with the situation for Ξ^- hyperons, where polarization differences are as large as a factor of two, with the 800 GeV data having the greater polarization.[8] Polarizations at these energies for Σ^+ hyperons also differ by as much as a factor of two, but with the 800 GeV data having the lower polarization.[6]

In conclusion, we have determined the polarization of Λ hyperons produced by 800 GeV protons at a fixed targeting angle of 4.8 mrad. Comparing our values with those determined previously for production at 400 GeV and a targeting angle of 9.6 mrad, we find no significant energy dependence in Λ polarization at these energies. This is in clear contrast to the energy dependence observed for both Ξ^- and Σ^+ polarizations at these same energies. We also find no significant $\bar{\Lambda}$ polarization at 800 GeV. These results emphasize the still puzzling nature of the polarization pattern in hadroproduction of hyperons.

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Table 1: Polarization of Λ hyperons produced at 800 GeV. The errors are statistical and systematic combined. The negative sign for P_Y indicates that the polarization vector is *opposite* to $\vec{p_P} \times \vec{p_\Lambda}$ which defines the positive Y axis.

Energy Range (GeV)	Number of Events	Average Energy (GeV)	p_T (GeV/c)	x_F	P_Y
100-150	6308	137.5 $\pm$ .1	0.67	0.172	-0.066$\pm$0.038
150-200	50344	180.5 $\pm$ .1	0.87	0.226	-0.064$\pm$0.016
200-250	104902	226.2 $\pm$ .1	1.09	0.283	-0.079$\pm$0.014
250-300	101896	273.7 $\pm$ .1	1.32	0.342	-0.089$\pm$0.014
300-350	64629	322.5 $\pm$ .1	1.56	0.403	-0.126$\pm$0.015
350-400	31999	371.5 $\pm$ .1	1.80	0.465	-0.163$\pm$0.019
400-800	19123	444.2 $\pm$ .3	2.15	0.556	-0.198$\pm$0.023

References

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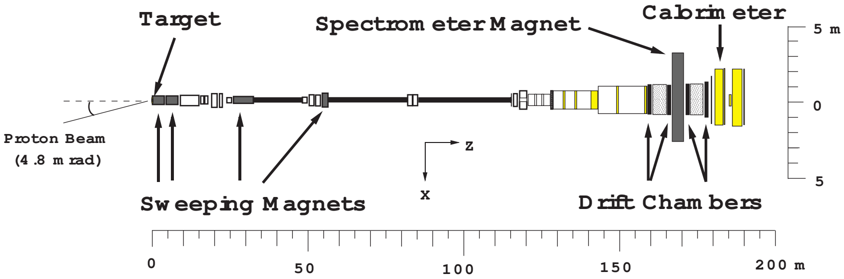
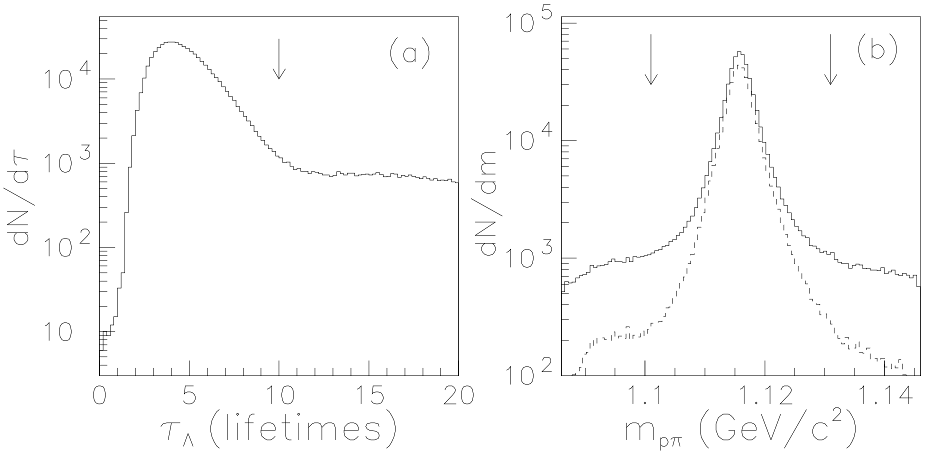
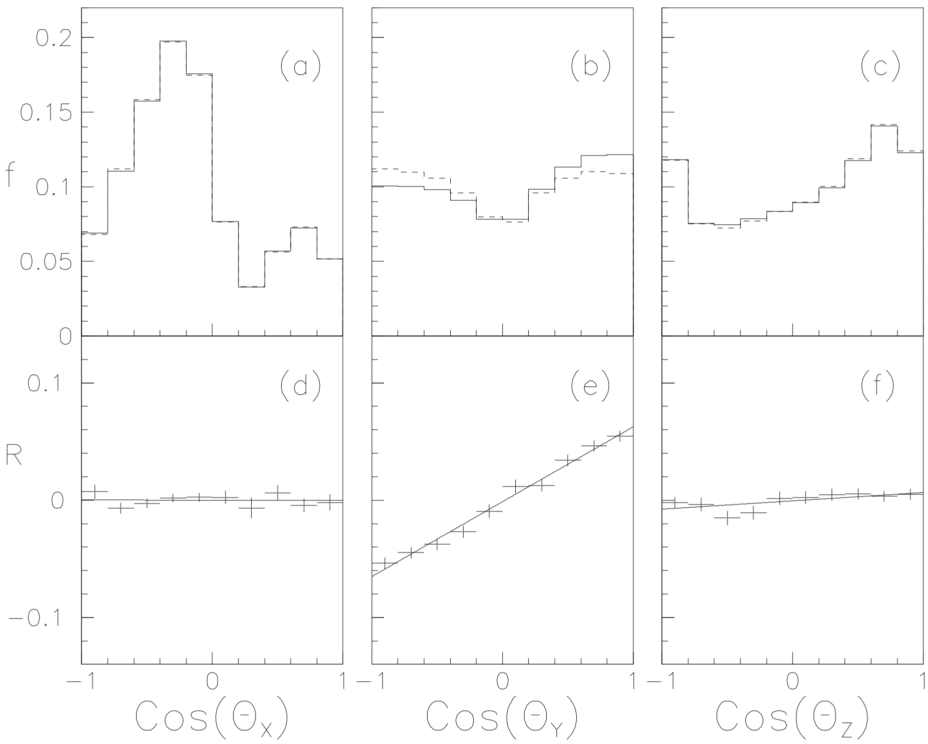


1. Plan view of the Fermilab Meson Center beamline showing the locations of the sweeping magnets and detector elements.

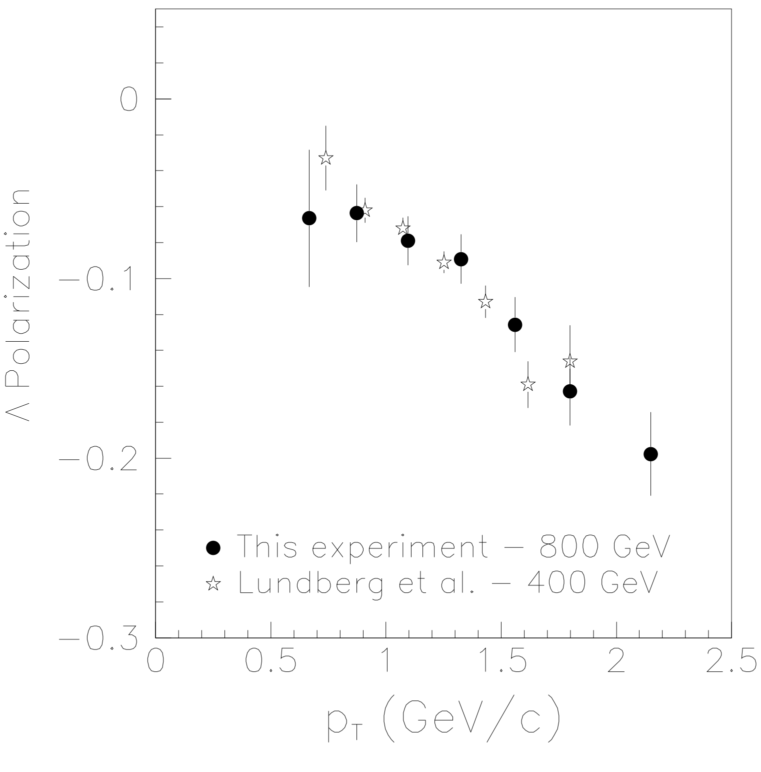
Figures



2. For the Λ decay sample discussed in the text, (a) is the number of proper lifetimes, τ_Λ, from the target to the event vertex, and (b) is the reconstructed $p\pi^-$ mass in GeV/c^2. The solid line is before cuts on τ_Λ, E/p and transverse momentum. The dashed line is after the cuts. The arrows indicate cut values.



3. Normalized direction cosine distributions $f_{\pm}(cos\theta_i)$ in the (a) X, (b) Y, and (c) Z directions. Solid lines are f_+ and dashed are f_-. Graphs (d), (e), and (f) show the ratio $R(cos\theta_i)$ defined in Equation 2. Error bars are statistical only.



4.Lambda polarization *vs* production transverse momentum (p_T). For comparison, data for 400 GeV production (Ref. 10) are also shown.