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A measurement of the transverse polarization of Λ-hyperons produced in inelastic pN-reactions at 450 GeV proton energy

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Abstract. A study of the polarization of Λ hyperons produced in inelastic pN reactions induced by the 450 GeV proton beam from the CERN SPS has been performed with the NA48 detector. The Λ hyperons were detected at a fixed angle of 4.2 mrad in the momentum range from 50 GeV/c to 200 GeV/c. The polarization changes from -0.053 ± 0.034 to -0.298 ± 0.074 for a transverse momentum range of the Λ between 0.28 GeV/c and 0.86 GeV/c. The $\overline{\Lambda}$ polarization is consistent with zero.

1 Introduction

The polarization of Λ hyperons produced in inclusive reactions with unpolarized protons on unpolarized targets has been studied for more than 15 years. The polarization has been studied over a wide range of reaction energies and various production angles of the Λ's. An experiment at the CERN ISR has obtained a significant dependence of the polarization on the centre–of–mass energy from $\sqrt{s}$ =53 GeV to $\sqrt{s}$ =62 GeV [1], while fixed target experiments have shown no evidence for such dependence in the beam energy region from 13.3 GeV to 800 GeV [2–7]. The absolute value of the polarization has been found to grow approximately linearly with p_t and x_F at least in the region of $p_t < 1$ GeV/c and $x_F < 0.5$, where p_t and x_F are the transverse momentum and the fraction of the beam energy carried by the Λ, respectively.

Some theoretical models attempt to describe experimental data on polarization [8–10] but the polarization mechanism is still not understood.

In this letter we present a measurement of the polarization of Λ's produced by protons of 450 GeV in inclusive pN reactions at an angle of 4.2 mrad at the CERN SPS, using part of the NA48 detector [11–14].

2 Experimental setup and data taking

The neutral beam containing the observed Λ hyperons was produced on a 2 mm diameter, 400 mm long beryllium target by 450 GeV protons at a production angle of 4.2 mrad in the vertical plane [13,14]. These protons are split off from a high intensity SPS beam ($4{\cdot}10^{11}$ protons per spill) by channeling through a bent crystal [15], then transported and focussed by a series of four quadrupole magnets and deflected by two dipole magnets onto the target[1]. The target is followed by a 7.5 Tm dipole sweeping magnet (with magnetic field directed horizontally and perpendicular to the beam axis), packed with tungsten-alloy inserts (in which the protons not interacting in the target are absorbed) and a 1.5 m long collimator reaching from 4.5 to 6.0 m downstream of the target, containing a tapered hole. The beam defining aperture has a diameter of 3.6 mm at 4.8 m from the target. The exit of the collimator is covered by a vetocounter with a 11 mm thick lead converter in front. It is followed by a 89 m long evacuated tank and by a helium-filled tank which contains the magnetic spectrometer. Decays occurring in the upstream part of the vacuum tank are accepted. The outer diameter of each of the detectors is typically 2.5 m.

The analysis is based on data from a 40 h run in 1995 with a proton beam intensity of about 1×10^7 ppp hitting the target during the 2.4 s long SPS spill every 14.4 s.

The detector elements used for the polarization analysis were:

- A magnetic spectrometer with two drift chambers in front and one behind a dipole magnet that produces a 267 MeV/c transverse momentum kick; each drift chamber is composed of four double planes with staggered wires to resolve left-right ambiguities; the wire orientations in the four views are horizontal, vertical and at $\pm 45°$ with respect to the horizontal plane; the resolution of a coordinate in a single drift chamber is 110 μm and the mean momentum resolution of the three-chamber spectrometer is $\Delta p/p = 0.6\%$, giving a resolution on the Λ invariant mass from $\Lambda \to p\pi^-$ decays of 1.16 MeV/c^2;
- A sampling calorimeter made of iron plates and scintillator planes designed to measure hadronic showers with a readout in horizontal and vertical projections; a fast energy sum from the calorimeter is used in the trigger;
- A scintillator hodoscope located in front of the calorimeter to trigger on charged particles;
- A muon veto system consisting of three planes of plastic scintillator each preceded by an 80 cm thick iron wall.

A more complete description of the apparatus can be found elsewhere [11,12].

3 Event selection

Data for the polarization measurement were recorded with a two charged particle trigger. All events selected by the trigger should have at least two hits in two diagonally

[1] The possibility of the protons being slightly polarized (< 5 %) by their passage through the bent crystal of silicon has been considered in [16]

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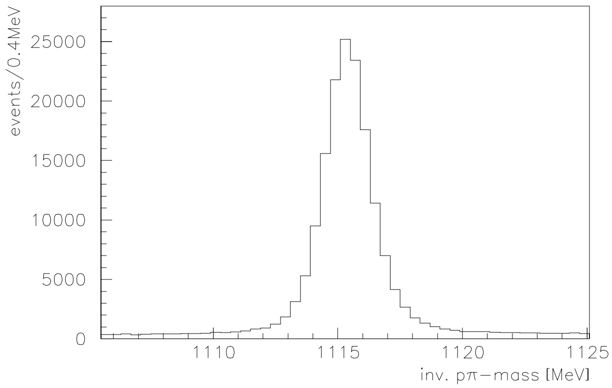

Fig. 1. Invariant mass distribution for $\Lambda \to p\pi^-$ hypothesis

opposite quadrants of the scintillator hodoscope, the energy deposit in the calorimeter had to be greater than 32 GeV, and both the vetocounter in the beam and the muon counters have been used in anticoincidence. After a full reconstruction of the events, the requirement that each event contain at least two charged tracks led to a sample of 4.1×10^5 events.

To be sure that the same trigger conditions have been required for data and Monte Carlo, a trigger requirement with more severe cuts has been used for the analysis. In this simulation exactly two reconstructed tracks hit the hodoscope in two diagonally opposite quadrants and the energy in the calorimeter was greater than 35 GeV. The following cuts have been applied to select the $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$ and $K_S \to \pi^+\pi^-$ decay candidates:

- The selected events must have exactly two tracks (one positive and one negative) with a reconstructed vertex in the interval from 6.07 m to 40 m downstream the target;
- The two tracks have to meet within 2.0 cm (closest distance of approach);
- The momentum of each track has to be greater than 10 GeV/c and the total momentum of both tracks has to be between 50 GeV/c and 200 GeV/c;
- The angle between the axis of the neutral beam and the total momentum vector of two tracks has to be less than 0.6 mrad to reject events coming from the collimator.

To select events consistent with a Λ, $\overline{\Lambda}$ or K_S decay the invariant mass of the two tracks was reconstructed under hypotheses of the decay into $p\pi^-$ (see Fig. 1), $\overline{p}\pi^+$ or $\pi^+\pi^-$, respectively. Events have been selected as $\Lambda(\overline{\Lambda}) \to p\pi^-(\overline{p}\pi^+)$ decays if the invariant mass was within 3.5 MeV/c^2 of the nominal $\Lambda(\overline{\Lambda})$ mass. $K_S \to \pi^+\pi^-$ events have been selected if the invariant mass was within 10 MeV/c^2 of the nominal K_S mass. $\overline{\Lambda} \to \overline{p}\pi^+$ decays which satisfy also the K_S mass hypothesis have been rejected to suppress background from K_S decays in the $\overline{\Lambda}$ data set. Events satisfying the Λ selection criteria have been rejected from the K_S sample.

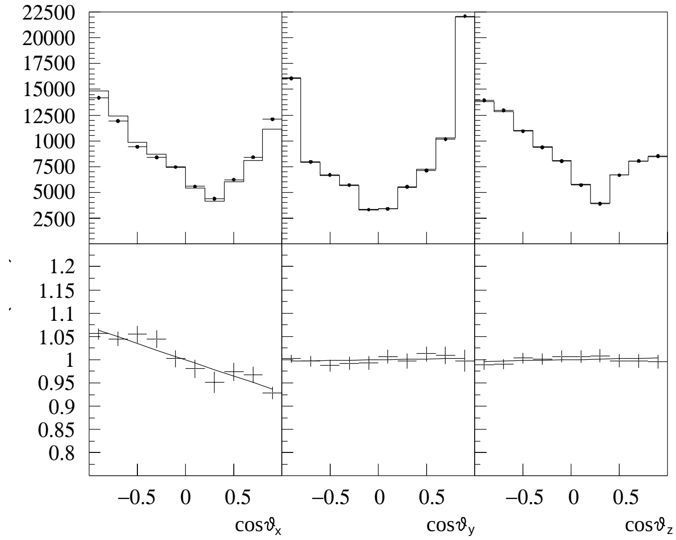

Fig. 2. $W(cos\theta_i)$ (points), $A(cos\theta_i)$ (histogram) and $R(cos\theta_i)$ distributions (lower half) for $i = x, y, z$

The number of $\Lambda \to p\pi^+$ events remaining after these cuts is 88039; in addition 8810 $\overline{\Lambda} \to \overline{p}\pi^+$ events have been selected. 219309 $K_S \to \pi^+\pi^-$ events have been selected to study detector geometry and systematic errors.

4 Polarization analysis and results

The coordinate system is defined for each event as follows. The horizontal $\hat{n}_x$ axis is a normal to the Λ production plane, $\hat{n}_x = \overrightarrow{p_{in}} \times \overrightarrow{p_\Lambda}/|\overrightarrow{p_{in}} \times \overrightarrow{p_\Lambda}|$, where $\overrightarrow{p_{in}}$ and $\overrightarrow{p_\Lambda}$ are the momentum vectors of the incident proton and the produced Λ, respectively. The $\hat{n}_z$ axis is along the direction of the produced Λ, $\hat{n}_z = \overrightarrow{p_\Lambda}/|\overrightarrow{p_\Lambda}|$; and the $\hat{n}_y$ axis is chosen to form a right-handed coordinate system, $\hat{n}_y = \hat{n}_z \times \hat{n}_x$. The Λ polarization $\overrightarrow{P}(P_x, P_y, P_z)$ is determined by the angular distribution of the decay proton in the Λ rest frame,

$$W(cos\theta_i) = A(cos\theta_i) \cdot (1 + \alpha P_i cos\theta_i) = A(cos\theta_i) \cdot R(cos\theta_i), \quad i = x, y, z, \tag{1}$$

where $cos\theta_i = \hat{n}_i \cdot \hat{k}$ ($\hat{k}$ is the direction vector of the decay proton), $\alpha = 0.642$ is the Λ -decay asymmetry parameter [17], and $A(cos\theta_i)$ is the acceptance of the apparatus which has been determined with a Monte Carlo simulation. The polarization components P_x, P_y and P_z correspond to a left-right decay asymmetry, an up-down decay asymmetry and a forward-backward asymmetry, respectively. According to parity conservation in the strong interaction, P_y and P_z should be equal zero if the incident proton beam was unpolarized. Thus the measurements of P_y and P_z were used for checking the systematic errors.

The $W(cos\theta_i)$ distributions together with the $A(cos\theta_i)$ (histogram) distributions for $i = x, y, z$ are shown in Fig. 2.

Table 1. The mean values of p_t, x_F and P_x measured in corresponding p_t intervals (systematic errors are presented following the statistical errors)

p_t interval [GeV/c]	p_t [GeV/c]	x_F	P_x
0.2 - 0.3	0.28 ± 0.02	0.13 ± 0.01	$-0.053 \pm 0.034^{+0.001}_{-0.019}$
0.3 - 0.4	0.36 ± 0.03	0.16 ± 0.01	$-0.066 \pm 0.018^{+0.007}_{-0.037}$
0.4 - 0.5	0.45 ± 0.03	0.21 ± 0.01	$-0.114 \pm 0.017^{+0.006}_{-0.021}$
0.5 - 0.6	0.54 ± 0.03	0.25 ± 0.01	$-0.155 \pm 0.025^{+0.010}_{-0.035}$
0.6 - 0.7	0.64 ± 0.03	0.30 ± 0.01	$-0.208 \pm 0.035^{+0.015}_{-0.039}$
0.7 - 1.0	0.86 ± 0.05	0.37 ± 0.02	$-0.298 \pm 0.074^{+0.026}_{-0.077}$

The acceptance corrected distribution $R(cos\theta_i)$ is fitted by a straight line to give the polarization

$$P_x = -0.109 \pm 0.012, \quad (2)$$

averaged over the experimental p_t and x_F ranges. The polarization measurements in the y and z directions, as expected, are consistent with zero: $P_y = 0.006 \pm 0.012$ and $P_z = 0.007 \pm 0.011$. In order to have an independent estimate of the systematic error on the polarization, the $cos\theta_x$ and $cos\theta_y$ distributions of the K_S sample have been analysed. Fits to the acceptance corrected distributions $R(cos\theta_i)$ give the polarizations $P_x = 0.010 \pm 0.009$ and $P_y = 0.003 \pm 0.009$ which are consistent with zero. The mean of the errors on P_z and P_y for the Λ decays, ± 0.011, has been taken as a measure of the systematic error in P_x (2). This error is consistent with those obtained for P_x and P_y for the K_S, where the physics polarization must be zero due to the kaon being a spinless particle.

The kinematic dependence of the polarization has been studied as a function of the transverse momentum p_t of the Λ relative to the proton beam line. Table 1 and Fig. 3 summarise the polarization results with statistical and systematic errors. The polarization systematic errors presented in Table 1 are the root mean square sums obtained by varying limits of the cuts used in the analysis. The combined errors are given by the error bars in Fig. 3.

The background in the Λ sample consisting of 0.8% misidentified $K_S \to \pi^+\pi^-$ events has no significant contribution to the measured polarization.

Finally, no polarization was observed for the selected $\overline{\Lambda}$ events:
$P_x = -0.014 \pm 0.037$.

Because of the fixed Λ production angle, a definite x_F value corresponds to each chosen p_t. Thus the polarization behavior presented in Fig. 3 reflects both p_t − and x_F − dependences. Some other fixed target experiment results [3, 5, 7] are presented in the same plot. They have been obtained at different beam energies and production angles of Λ's and consequently, represent different regions of x_F at the same p_t interval. Our data indicate a steeper dependence of the polarization on p_t than do the other experiments.

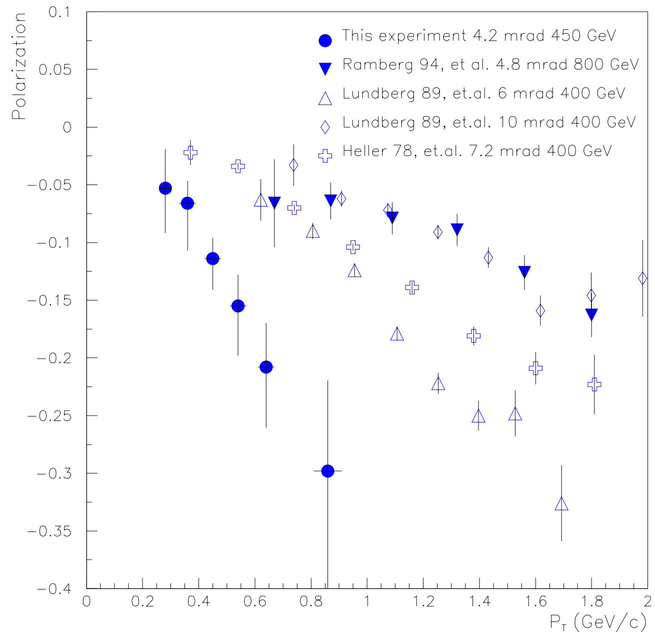

Fig. 3. Polarization versus p_t of the Λ samples involving both direct and indirect production (the statistical and systematic errors are added in quadrature for this experiment)

A fraction of the Λ's detected in all experiments comes from other hyperon decays. They are produced in, for example, decays like $\Xi^0 \to \Lambda\pi^0$ and $\Sigma^0 \to \Lambda\gamma$. Due to the experimental problems in distinguishing direct and indirect production, the polarization results are averaged over both production processes. To estimate the polarization of the directly produced Λ's, the polarization and rate of the indirectly produced Λ hyperons have to be known.

Λ's produced from $\Xi^0 \to \Lambda\pi^0$ decays have negative polarization like the Ξ^0 hyperon itself [18]. An analysis similar to that presented here [19] found 84 ± 8 $\Xi^0 \to \Lambda\pi^0$ decays giving an impurity of $(5.4 \pm 0.5)\%$ in the Λ sample due to this decay. This does not significantly change the measured polarization.

A theoretical calculation of the polarization of Λ's originating from $\Sigma^0 \to \Lambda\gamma$ decays gives a value related to the Σ^0 polarization, $P_\Lambda = -1/3 \cdot P_{\Sigma^0}$, which leads to a small positive Λ polarization [10]. Taking into account the rate of such Λ's (39 ± 4 %) measured at lower energies at BNL [20], it can be estimated that the absolute value of the polarization of directly produced Λ's is about 25% greater than the measured polarization in the Λ beam.

In spite of the fact that theoretical models [8–10] can be adjusted to explain large polarizations, a deeper understanding of the Λ polarization phenomenon is still lacking.

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