Polarization of Λ's and $\bar{\Lambda}$'s in pp, $\bar{p}p$, and K^-p Interactions at 176 GeV/c

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We have measured the polarization of Λ's in inclusive pp and K^-p reactions and of $\bar{\Lambda}$'s in $\bar{p}p$ interactions at a beam momentum of 176 GeV/c. Data were taken in the beam-fragmentation region with hyperon transverse momenta from 0.2 to 1.5 GeV/c. The $\bar{p}$-produced $\bar{\Lambda}$'s have the same magnitude and sign of polarization as the p-produced Λ's, whereas the Λ's from K^-p interactions are more highly polarized and in the opposite direction.

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Many recent experiments have shown that Λ, Σ, and Ξ hyperons produced in high-energy (proton equivalent laboratory momenta from 14 to 2000 GeV/c) pp and p-nucleus collisions are polarized.[1-3] These surprising observations cannot be explained by perturbative QCD,[4] but a number of *ad hoc* models have been constructed to fit the data.[5-7] In order to study the universality of this phenomenon we have measured the polarization of hyperons produced in reactions for which there is no published high-energy data: for Λ's produced in K^-p collisions[8] and for $\bar{\Lambda}$'s produced in $\bar{p}p$ interactions.[9]

Our experiment was performed at Fermilab in a 176-GeV/c secondary beam ($\Delta p/p \approx 7\%$ FWHM). The apparatus, shown in Fig. 1, included a differential Cherenkov counter (C) to tag the incident particle type and a beam spectrometer with magnets (B.S.M.) and beam (proportional) chambers, to give momentum analysis of the beam and to steer it onto a 73-cm-long liquid hydrogen target.[10] Changing the polarity of the beam-line magnets selected either the positive beam (mainly p's) or the negative which was 91% π^-, 6% K^-, and 3% $\bar{p}$.

A spectrometer made up of a large-aperture (1.25 m × 0.6 m) magnet, AM, with a transverse-momentum kick ≈ 0.2 GeV/c, flanked by four measurement stations, each with two planes of proportional wire chambers (PWC) and eight planes of drift chambers (DC), analyzed the decay products of the hyperons. A sweeper magnet helped remove low-energy charged particles from its aperture. A two-level trigger was used to select events for recording onto magnetic tape. The first required the presence of a valid beam particle, as signaled by the beam counters B1, B2, B3, C and the antihalo counter H, along with a hit in the I-counter hodoscope, indicating an interaction in the target. Counter B4 was used to veto noninteracting beam particles and diffractive processes. The second level, invoked only if the first level was satisfied, used a specially constructed trigger processor[11] to examine the pattern of hits in the eight PWC's to determine whether at least two charged tracks were present. The data acquisition cycle was initiated only if the second-level trigger was satisfied. With a typical beam rate of 3×10^5/sec, 500 triggers passed the first level and 50 the second. A total of 2.7 million triggers was recorded onto magnetic tape.

In addition to this interaction trigger a number of other triggers were recorded. These included straight-through beam tracks and decay muons illuminating the full aperture of the detector to provide continuous calibration of the apparatus.

Neutral-hyperon candidates were selected by requiring oppositely charged track pairs to originate in the

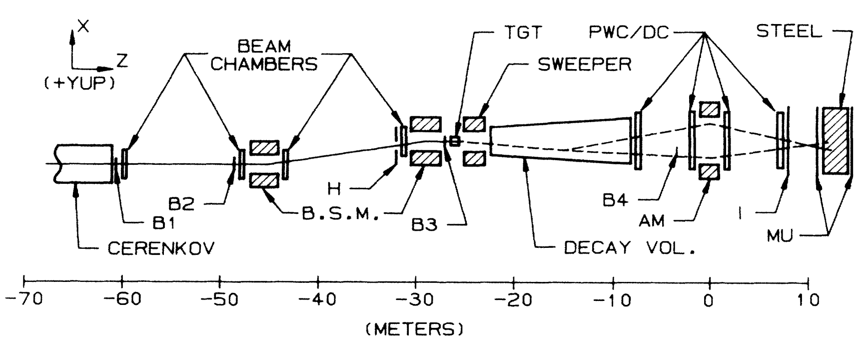

FIG. 1. Plan view of the experimental apparatus in the M-4 beam line at Fermilab. The x direction is not to scale.

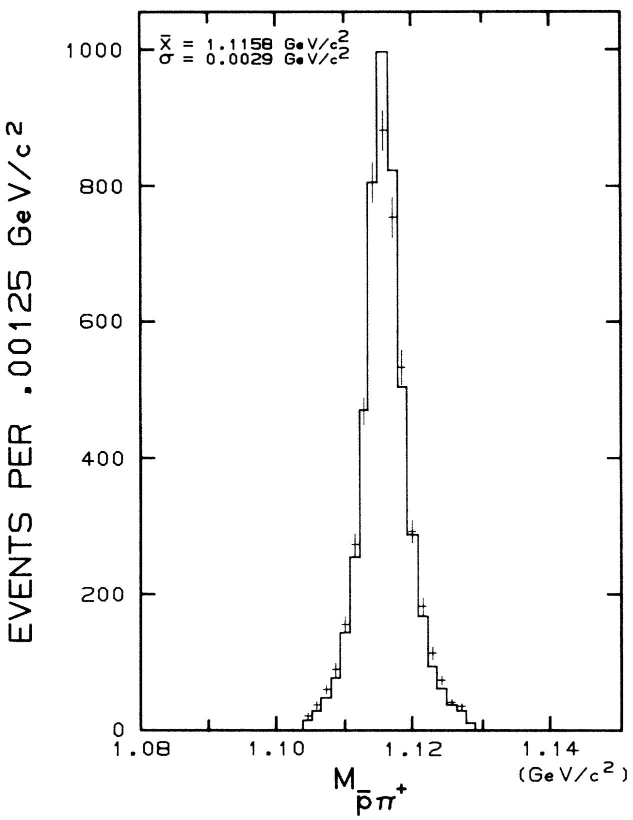

FIG. 2. Antiproton π^+ invariant mass from $\bar{p}+p \to \bar{\Lambda}+x$, with Monte Carlo prediction (solid line) superimposed.

decay volume (Fig. 1) and their momentum sum to intersect the beam track in the target. The surviving track pairs were fitted to the hypothesis $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$, and $K_S \to \pi^+\pi^-$. Events which satisfied both the Λ ($\bar{\Lambda}$) and K_S hypotheses were called Λ's ($\bar{\Lambda}$'s) and the consequences of this to the polarization measurement were estimated by the Monte Carlo program.

Representative of the resolution of the experiment and the level of background remaining after cuts is the $\bar{p}\pi^+$ effective-mass plot from the $\bar{p}p$ channel shown in Fig. 2. Superimposed is a prediction from the Monte Carlo program. The total number of events surviving each channel is given in the following table.

Channel	Events
$p \to \Lambda$	10480
$\bar{p} \to \bar{\Lambda}$	4800
$K^- \to \Lambda$	8250
$K^- \to K_S$	16685

The polarization analysis consists of extracting the parameters P_x, P_y, and P_z from a fit to the pion decay distribution in the hyperon rest frame:

$$dN/d\Omega = (4\pi)^{-1}[1+\alpha_\Lambda(P_x \sin\theta\cos\phi + P_y \sin\theta\sin\phi + P_z\cos\theta)],$$

where the z axis is chosen normal to the production plane ($\mathbf{p}_\Lambda \times \mathbf{p}_{\text{beam}}$), x is along the direction of the Λ, and y completes an orthogonal right-handed coordinate system. (For the $\bar{\Lambda}$ analysis $\alpha_{\bar{\Lambda}} = -\alpha_\Lambda$.) The quantity P_z is thus the only polarization allowed by parity conservation in the production process. This distribution is modified by the acceptance of the apparatus, the effect of which is to multiply it by a function $A(\theta,\phi)$. A detailed Monte Carlo program was written to calcu-

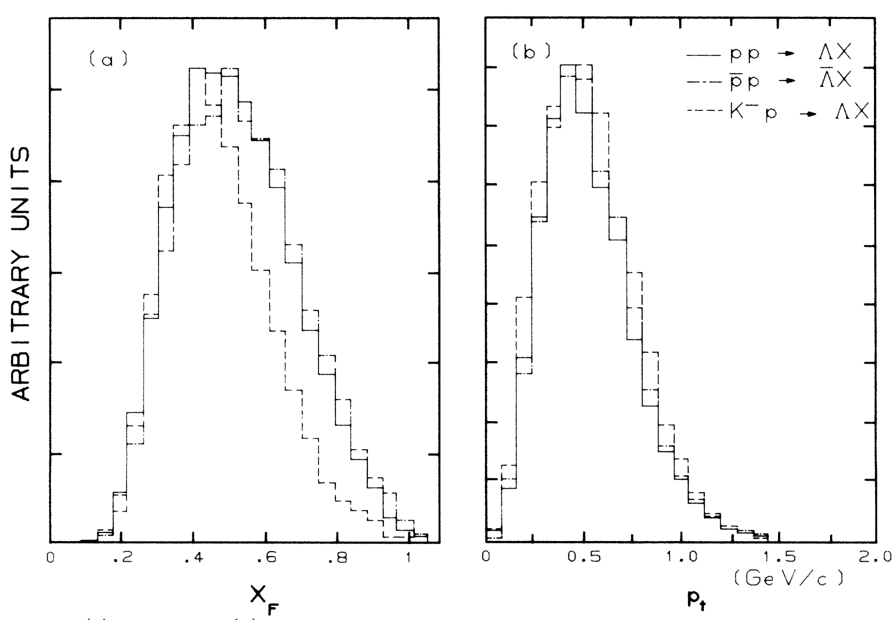

FIG. 3. Unweighted (a) x_F and (b) p_t event distributions for the reactions $p+p \to \Lambda+x$, $\bar{p}+p \to \bar{\Lambda}+x$, and $K^-+P \to \Lambda+x$.

TABLE I. Polarization results.

P_t bin (GeV/c)	P_t (GeV/c)	x_F	P_z	x_F bin	x_F	P_t	P_z
			$p \to \Lambda$				
0.00 – 0.40	0.29	0.42	−0.012 ±0.047	0.00 – 0.45	0.36	0.43	0.040 ±0.045
0.40 – 0.52	0.46	0.50	0.073 ±0.055	0.45 – 0.55	0.50	0.56	0.089 ±0.055
0.52 – 0.68	0.59	0.54	0.151 ±0.053	0.55 – 1.00	0.68	0.64	0.070 ±0.041
0.68 – 1.50	0.84	0.60	0.079 ±0.055				
			$\bar{p} \to \bar{\Lambda}$				
0.00 – 0.40	0.30	0.46	−0.026 ±0.070	0.00 – 0.45	0.36	0.41	0.055 ±0.069
0.40 – 0.52	0.47	0.53	−0.031 ±0.083	0.45 – 0.55	0.50	0.53	−0.064 ±0.081
0.52 – 0.68	0.59	0.56	0.117 ±0.076	0.55 – 1.00	0.70	0.61	0.174 ±0.056
0.68 – 1.50	0.85	0.63	0.173 ±0.080				
			$K^- \to \Lambda$				
0.00 – 0.40	0.28	0.39	−0.234 ±0.052	0.00 – 0.45	0.36	0.42	−0.326 ±0.043
0.40 – 0.52	0.46	0.46	−0.419 ±0.064	0.45 – 0.55	0.50	0.57	−0.466 ±0.057
0.52 – 0.68	0.60	0.50	−0.438 ±0.058	0.55 – 1.00	0.66	0.66	−0.470 ±0.052
0.68 – 1.50	0.85	0.57	−0.615 ±0.056				

late this function. Care was taken to include the correct distribution of beam phase space, self-consistent production distributions in angle and energy, proper decay distributions of the neutral particles, including K_S-K_L mixing, a complete specification of the experimental apparatus, and the precession of the Λ spin in the field of the sweeping magnet. Events satisfying the trigger were processed through the same set of programs as the data. The ratio of the number of surviving events to those generated is then the correction function.

A number of checks were made to test the Monte Carlo program and analysis programs to verify that the apparatus was properly modeled and that the analysis did not introduce any spurious asymmetries: (1) The lifetimes of the Λ, $\bar{\Lambda}$, and K_S were measured and found to be in good agreement with the world averages. (2) The "polarization" of K_S was measured and found to be consistent with zero for all three components. (3) The parity-forbidden P_x and P_y components of the polarization for Λ and $\bar{\Lambda}$ were found to be consistent with zero. (4) During the course of data taking, the direction of the field in both the sweeper and analysis magnets was periodically reversed and no difference in the measured polarizations between the two field directions was observed.

To make optimum use of the limited statistical power of this experiment, we present our results as a function of a single variable, either the Feynman x variable, x_F, or p_t, the transverse momentum. Figures 3(a) and 3(b) show the raw event distributions for the three reactions as functions of x_F and p_t, respectively. Table I summarizes our results for the average polarization in the three channels.

In Fig. 4 we plot the Λ polarization from $p \to \Lambda$, the Λ data of Ref. 1, and our polarization data from $\bar{p} \to \bar{\Lambda}$ vs p_t. Within statistics, the polarizations measured are the same.

Figure 5(a) shows our polarization data for $K^- \to \Lambda$ along with the data at 8.25 GeV/c [12] plotted versus p_t. Both experiments find the same polarization which is larger than that for the $p \to \Lambda$ channel and consistent with a linear dependence on p_t. The same data are plotted in Fig. 5(b) as a function of x_F along with the data from a number of experiments at lower energy.[13,14] The combined data show an energy independence from 8.25 to 176 GeV/c.

We have considered a number of sources of possible systematic errors and have estimated their effects on our measurements.

(1) The field in our sweeper magnet varied by ±5% over a portion of the spill. This changed the amount of the spin precession slightly but affected the measured polarization less than 1%.

(2) Possible misalignments in the apparatus have been computed to contribute a maximum of ±1.5% to the polarization.

(3) This experiment was not able to distinguish directly produced Λ's ($\bar{\Lambda}$'s) from the decay products

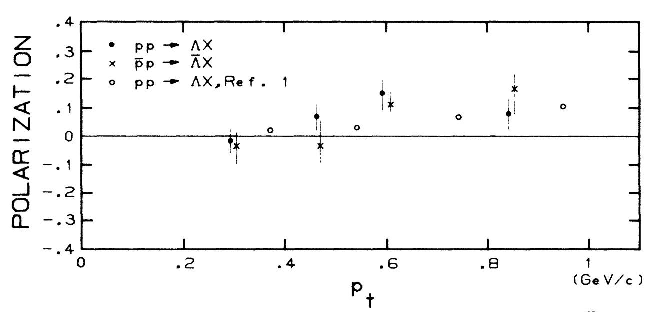

FIG. 4. Lambda polarization from $p+p \to \Lambda + x$, $\bar{\Lambda}$ polarization from $\bar{p}+p \to \bar{\Lambda}+x$, and the Λ polarization data from Ref. 3, plotted vs p_t.

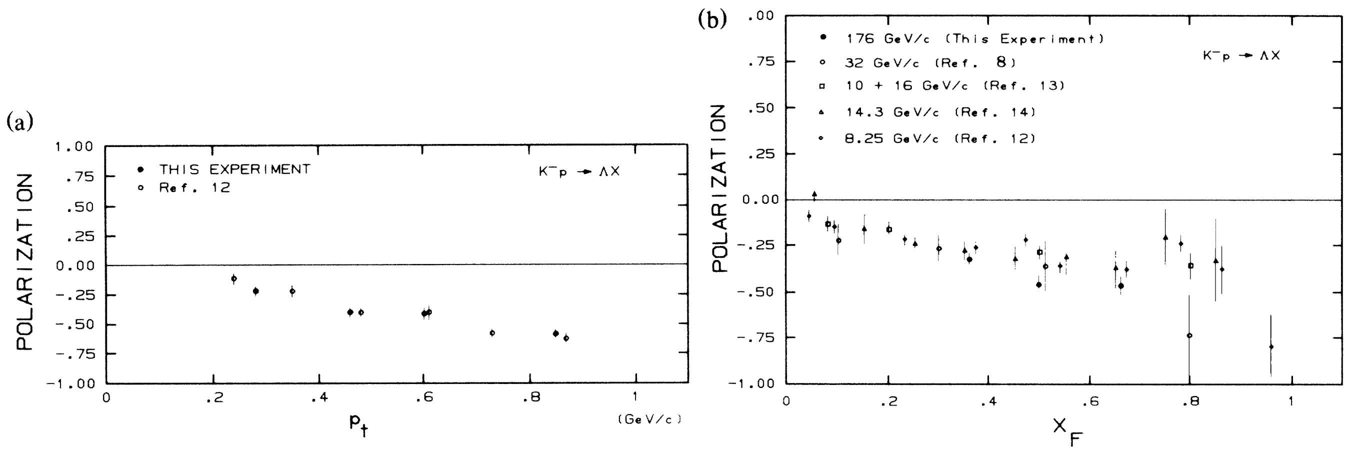

FIG. 5. (a) Lambda polarization from $K^- + p \to \Lambda + x$ and the 8.25-GeV/c data of Ref. 12 plotted vs p_t. (b) Lambda polarization from $K^- + P \to \Lambda + x$ and the data from Refs. 13 and 14 plotted vs x_F.

of directly produced Σ^0's ($\bar{\Sigma}$'s). For the proton-produced Λ's where the Σ^0 cross section and polarization data are available, we calculate a "prompt" Λ polarization 30% larger than our measurement.[15] This correction is not possible for the $K^- \to \Lambda$ or $\bar{p} \to \bar{\Lambda}$ data as the necessary cross-section and polarization data do not exist.

Our sample of Λ's and $\bar{\Lambda}$'s contains a background due to K_S's mentioned above. The relative proportions of these for the K^-, p, and $\bar{p}$ beams was $(11 \pm 1)\%$, $(1 \pm 1)\%$, and $(1 \pm 1)\%$, respectively. This contamination and its uncertainty have been explicitly taken into account in the Monte Carlo program and were found to have no statistically significant effect on the polarization.

No theoretical model proposed to date gives an adequate description of the existing data. DeGrand and Miettinen (Ref. 6) use the $p \to \Lambda$ and $p \to \Sigma^0$ polarization to fix two parameters and then correctly predict the polarization in the $p \to \Xi$ channel to be the same as the $p \to \Lambda$. While this model correctly predicts the sign of the $K^- \to \Lambda$ polarization it fails badly when it predicts the magnitude to be equal to that of $p \to \Lambda$.

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[1]L. G. Pondrom, Phys. Rep. **122**, 58 (1985).

[2]C. Wilkinson *et al.*, Phys. Rev. Lett. **46**, 803 (1981).

[3]K. Heller *et al.*, Phys. Rev. Lett. **51**, 2025 (1983).

[4]G. L. Kane, J. Pumplin, and W. Repko, Phys. Rev. Lett. **41**, 1689 (1978).

[5]B. Andersson, G. Gustafson, and G. Ingelman, Phys. Lett. **85B**, 417 (1979).

[6]T. A. DeGrand and H. I. Miettinen, Phys. Rev. D **24**, 2419 (1981).

[7]J. Szwed, Phys. Lett. **105B**, 403 (1981).

[8]The highest-energy polarization data in this channel are at 32 GeV/c from M. L. Faccini-Turluer *et al.*, Z. Phys. C **1**, 19 (1979).

[9]The highest-energy data in this channel are at 6 GeV/c by H. Becker *et al.*, Nucl. Phys. **B141**, 48 (1978).

[10]Details of the apparatus and the analysis can be found in H. Melanson, Ph.D. thesis, Michigan State University, 1985 (unpublished), and S. Gourlay, Ph.D. thesis, University of California, Davis, 1985 (unpublished).

[11]S. Gourlay, M. Melanson, and H. Kobrak, to be published.

[12]M. Baubillier *et al.*, Nucl. Phys. **B148**, 18 (1979).

[13]H. Grassler *et al.*, Nucl. Phys. **B136**, 386 (1978).

[14]H. Abramowicz *et al.*, Nucl. Phys. **B105**, 222 (1976).

[15]Lambdas resulting from polarized Σ^0 decays are polarized in a direction opposite to the parent Σ^0 with $\frac{1}{3}$ the magnitude. [See R. Gatto, Phys. Rev. **109**, 610 (1958)]. At lower energies, in both proton and K^- reactions, the Λ and Σ^0 production cross sections are consistent with the ratio

$$\sigma(\Sigma^0)/[\sigma(\Sigma^0)+\sigma(\Lambda)]=0.3.$$

The existing polarization data indicate that the Σ^0 polarization is opposite in sign to that of the Λ. [See E. C. Dukes, Ph.D. thesis, University of Michigan (unpublished).]