Study of Λ^0 Polarization in $pp \to p\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-$ at 27.5 GeV

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We measured the polarization of 51 195 Λ^0's produced in the specific reaction $pp \to p\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-$ with 27.5 GeV/c protons incident on a liquid hydrogen target. Because the reaction was measured completely, the polarization was studied versus the following: x_F (-1 to $+1$), Λ^0 transverse momentum (0 to 1.32 GeV/c), correlations with the momentum vectors of the other particles in the reaction, and the invariant mass of combinations of particles in the final state. The dependence of the polarization on these variables does not always agree with theoretical expectations.

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Ever since the discovery that Λ^0 hyperons are produced with significant polarization in high energy collisions [1–3], there has been a major effort to understand the source of the polarization phenomenon. Experiments have established several general features of the phenomenon and have found that other hyperons are also polarized when produced in high energy collisions [4–7]. Although theoretical models have been developed which fit some of the data, these models fail to present a complete picture of the underlying physical processes and often lack predictive power [8–10]. Since the source of hyperon polarization remains elusive, studies are needed of as many aspects of Λ^0 polarization as possible in the hope of shedding light on this important process. It is interesting that most Λ^0 polarization experiments have utilized inclusive Λ^0 production; i.e., all the Λ^0's emerging from the high energy collisions are used. No attempt is made to distinguish the specific reaction which produced a given Λ^0 or to determine the contribution of Λ^0's from a particular final state to the polarization of the Λ^0 sample. Recognizing that studies of specific reactions might provide new insight in this field, we began an experimental program to investigate several exclusive Λ^0 production reactions. The decision to move in that direction was buoyed by the publication of enhanced polarization in one final state [11] and by theoretical suggestions that the behavior of other particles [9,12] produced with the Λ^0 might hold important clues. In this paper, we report the first results of that program—a high statistics study of the particular reaction

$$pp \longrightarrow p\Lambda^0 K^+\pi^+\pi^-\pi^+\pi^-. \quad (1)$$

The data were amassed at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratories in experiment E766, described in detail elsewhere [13–15]. A beam of 27.5 GeV/c protons interacted in a 12-in.-long liquid hydrogen target. Charged particles from the interaction were detected and measured in a precision spectrometer containing six minidrift chamber modules (11 264 instrumental wires) in the magnetic field of a large aperture (6 ft wide $\times$ 4 ft high $\times$ 8 ft deep) magnet. The average $\int B\,dl$ of the magnet was 1.17 T m (350 MeV/c). The incoming proton beam momentum vector was measured in a separate spectrometer [16]. Direct particle identification was provided by a 96 element atmospheric pressure Freon 114 threshold Cherenkov counter and two scintillator counter hodoscopes yielding time-of-flight and pulse height information. In a two week exposure, more than 3×10^8 high multiplicity interactions were recorded. The event sample was reconstructed using a specially constructed computational system [17].

The narrow wire spacing (2.0 to 3.5 mm) of the drift chambers, the $\sim$150 μm accuracy of the spatial measurements, and the redundancy afforded with four views per drift chamber module proved sufficient to allow accurate track reconstruction with as many as 20 particles in the final state. The momentum resolution of the spectrometer $\Delta p(\mathrm{FWHM})/p$ was $0.01 + 0.0016p$ GeV/c. For further

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details of the spectrometer, the triggering systems, and the reconstruction algorithms, see Ref. [13].

In order for an event to be a candidate for the completely measured or exclusive sample, the magnitude of the vector sum of the final state momenta transverse to the beam proton had to be ≤ 100 MeV$/c$ and the sums of the difference of the particle energy (E) and longitudinal momentum (P_L) in the initial and final states had to agree within ± 30 MeV$/c$, i.e., $|\sum(E - P_L)_{\text{initial}} - \sum(E - P_L)_{\text{final}}| \leq 30$ MeV$/c$. Our sample yielded $\sim 3 \times 10^6$ exclusive events. The specific channels of interest for this measurement had to satisfy several additional requirements: (i) Since the $\Lambda^0 \to p\pi^-$ decay was used to identify and select Λ^0's, the number of charged particle tracks, in the final state, had to equal 8. (ii) Only one vertex separated from the interaction point of the beam proton was allowed. (iii) The invariant mass of the separated vertex had to be consistent with either a Λ^0 if the event was a candidate for reaction (1) or a K_s^0 if the event was a candidate for the reaction

$$pp \longrightarrow ppK_s^0K^+\pi^+\pi^-\pi^-. \tag{2}$$

Backgrounds for any exclusive event sample from mismeasured, nonexclusive events are $\leq 5\%$. The kinematic ambiguity between Λ^0's and K_s^0's is small because (a) the mass resolution of the spectrometer is excellent—the standard deviation of the Λ^0 mass distribution is 0.5 MeV—and (b) an exclusive event must satisfy the additive conservation laws such as baryon number, strangeness, and charge. The exclusive event samples selected for this measurement are 51 195 events of reaction (1) and 23 459 events of reaction (2).

The Λ^0 polarization $\mathcal{P}$ is determined using the expression [15]

$$dN/d\Omega = N_0(1 + \alpha\mathcal{P}\cos\theta), \tag{3}$$

where $dN/d\Omega$ is the angular distribution of the proton from the Λ^0 decay in the Λ^0 rest frame, N_0 is a normalization constant, and the asymmetry parameter α is 0.642 ± 0.013 [18]. The angle θ is between the direction of the proton from the decay of the Λ^0 and the normal to the production plane $\hat{n}$. $\hat{n} \equiv \vec{P}_{\text{beam}} \times \vec{P}_\Lambda/|\vec{P}_{\text{beam}} \times \vec{P}_\Lambda|$, where $\vec{P}_\Lambda$ and $\vec{P}_{\text{beam}}$ are the momentum vectors of the Λ^0 and the incident beam proton, respectively.

The polarization for a Λ^0 sample was determined by histogramming the distribution of the proton directions in 20 equal sized bins in $\cos\theta$ and by using a least squares fit of the distribution by a straight line in $\cos\theta$ [see Eq. (3)]. The uncertainty in the polarization is statistical only.

We have chosen to present the determination of the polarization without correction for the acceptance of the spectrometer in $\cos\theta$ since the acceptance is flat in that variable. In order to insure that this procedure was reasonable, we determined the acceptance with Monte Carlo techniques with moderate statistics and performed the corrections on a bin-by-bin basis after binning in $\cos\theta$. The polarization results were identical within statistics to the ones calculated without the acceptance correction, although the uncertainties in the polarization results were increased due to the finite Monte Carlo statistics.

The procedure to extract the polarization was also checked as follows: (a) A sample of exclusive events of reaction (1) was generated using a Monte Carlo calculation which faithfully simulates all aspects of the spectrometer. The Λ^0's in this sample were generated with a specific polarization, including dependencies on different kinematic variables. These Monte Carlo events were analyzed as though they were data and the polarization was extracted. The polarization of this sample was identical, within statistical uncertainties, with the known polarization of the sample. The agreement between the known polarization and that calculated from the Monte Carlo events was excellent whether or not the distributions were corrected for spectrometer acceptance. (b) The sample of exclusive events containing a K_s^0—instead of a Λ^0—was subjected to the same polarization analysis. The polarization of the K_s^0 was found to be zero (as expected) for every possible subset of the K_s^0 sample, demonstrating that the observed polarization is independent of our analysis procedures.

In order to compare with inclusive measurements, the Λ^0 polarization as a function of P_T, the transverse momentum of the Λ^0 with respect to the incident proton beam, was determined for the entire sample. Within errors, the polarization for this total sample averages to zero. This initially surprising result is due to the facts that our detector has uniform acceptance in Feynman x, x_F, and that the polarization of the final state of Λ^0 in pp collisions is antisymmetric in x_F by virtue of rotational invariance. The total sample was then divided into two pieces on the basis of the sign of the x_F of the Λ^0 and the results are plotted in Fig. 1(a). Since our sample has roughly equal numbers of events in each subsample and since the polarizations in each subsample differ only in sign, the observation of zero average polarization in the total sample is understandable. Combining the subsamples with the appropriate change of sign, we find excellent agreement with the inclusive results shown in Fig. 1(b). When fit with a linear dependence on P_T, we find for $x_F > 0$, $\mathcal{P} = (-0.250 \pm 0.067)P_T + (0.063 \pm 0.041)$ ($\chi^2/N_{\text{DOF}} = 1.04$); for $x_F < 0$, $\mathcal{P} = (0.147 \pm 0.056)P_T + (-0.007 \pm 0.033)$ ($\chi^2/N_{\text{DOF}} = 1.04$); and for the combined samples, $\mathcal{P} = (-0.189 \pm 0.042)P_T + (0.029 \pm 0.025)$ ($\chi^2/N_{\text{DOF}} = 1.68$).

We then studied the x_F dependence of the polarization. The average polarization for events in six x_F bins from -1.0 to $+1.0$ is shown in Fig. 2(a). Both the $x_F > 0$ and $x_F < 0$ bins have approximately the same number of events and roughly the same distribution. The average polarization is roughly linear in x_F [average $\mathcal{P} = (-0.20 \pm$

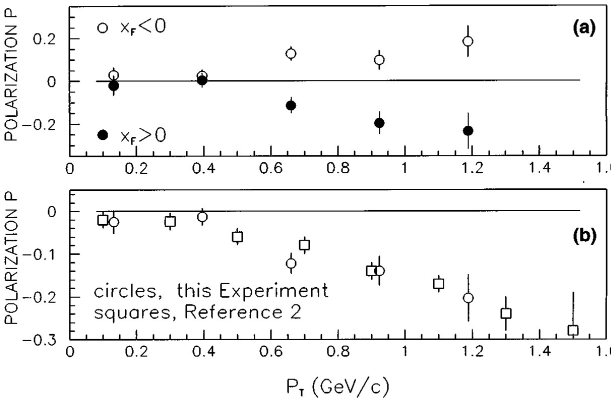

FIG. 1. (a) Λ^0 polarization, splitting the sample into $x_F < 0$ and $x_F > 0$. (b) The $x_F < 0$ sample polarization has been multiplied by -1 and combined with the $x_F > 0$ sample.

$0.06)x_F + (-0.032 \pm 0.018)$, $\chi^2/N_{\mathrm{DOF}} = 0.247$]. The average polarization changes sign at $x_F \cong 0$.

The polarization data were examined for possible correlations with respect to the directions of other particles in the final state, the proton and the K^+. There is a theoretical suggestion [9] that the s and $\bar{s}$ quarks in the final state move in opposite directions, causing Λ^0 polarization. This model can be investigated by searching for correlations between the polarization and the motions of the Λ^0 (s quark) and the K^+ ($\bar{s}$ quark). For this analysis, we took the direction of K^+ (Λ^0) as the direction of $\bar{s}$ quark (s quark). The sample was divided based on whether the K^+ and Λ^0 were in the same c.m. hemisphere or in opposite hemispheres. The polarizations were calculated correcting the sign of the polarization for the sign of x_F. The polarizations were identical, inside statistical errors, in the two $K^+\Lambda^0$ hemispheres; see Fig. 2(b). This result differs from the theoretical suggestion in Ref. [9].

The polarization was determined in the subset in which the Λ^0 and p have opposite signs of x_F. For Λ^0's within this subset which have $x_F < 0$, $\mathcal{P} = (0.185 \pm 0.070)P_T + (-0.013 \pm 0.039)$; $\chi^2/N_{\mathrm{DOF}} = 1.39$. For Λ^0's within this subset which have $x_F > 0$, $\mathcal{P} = (-0.291 \pm 0.068)P_T + (0.082 \pm 0.041)$; $\chi^2/N_{\mathrm{DOF}} = 1.03$. These results are within 2 standard deviations of the results in which no conditions on the relative $\Lambda^0 p$ directions were imposed. Figure 2(c) shows Λ^0 polarization combining appropriately the $x_F > 0$ and $x_F < 0$ subsamples.

When the p and the Λ^0 have the same sign of x_F the polarization is consistent with zero [$\mathcal{P} = (0.041 \pm 0.096)P_T + (0.026 \pm 0.060)$, $\chi^2/N_{\mathrm{DOF}} = 0.38$]. This result is dominated by the fact that ~75% of these Λ^0's have $|x_F| < 0.3$. Since the magnitude of the polarization is linear in x_F of the Λ^0, the small polarization is expected.

We also investigated Λ^0 polarization as functions of the invariant mass $M(\Lambda K)$, $M(\Lambda K \pi^+ \pi^-)$, and $M(\Lambda K \pi^+ \pi^- \pi^+ \pi^-)$. In this analysis, the sign of the Λ^0 polarization was appropriately treated for the sign of the Λ^0 x_F. We observed the following.

(a) Λ^0 polarization is roughly linear with $M(\Lambda K)$, decreasing from zero at $M(\Lambda K) = 1.63$ GeV to -0.16 at $M(\Lambda K) = 2.47$ GeV; see Fig. 3(a). The linear fit is $\mathcal{P} = (-0.185 \pm 0.068)M(\Lambda K) + (0.30 \pm 0.14)$, $\chi^2/N_{\mathrm{DOF}} = 0.0023$. These results agree with those observed [11] in the $pp \rightarrow p\Lambda K$ reaction at higher energies, for masses between 1.6 and 2.4 GeV, Fig. 3(a). We cannot comment on the large polarization seen at 2.8 GeV.

(b) Λ^0 polarization is roughly linear with $M(\Lambda K \pi^+ \pi^-)$, decreasing from zero at $M(\Lambda K \pi^+ \pi^-) = 2.75$ GeV to -0.16 at $M(\Lambda K \pi^+ \pi^-) = 3.75$ GeV; see Fig. 3(b). The linear fit is $\mathcal{P} = (-0.170 \pm 0.057)M(\Lambda K \pi^+ \pi^-) + (0.475 \pm 0.187)$, $\chi^2/N_{\mathrm{DOF}} = 0.073$.

(c) Λ^0 polarization is roughly linear with $M(\Lambda K \pi^+ \pi^- \pi^+ \pi^-)$, decreasing from zero at $M(\Lambda K \pi^+ \pi^- \pi^+ \pi^-) = 3.9$ GeV to -0.14 at $M(\Lambda K \pi^+ \pi^- \pi^+ \pi^-) = 5.1$ GeV; see Fig. 3(c). The linear fit is $\mathcal{P} = (-0.154 \pm 0.048)M(\Lambda K \pi^+ \pi^- \pi^+ \pi^-) + (0.63 \pm 0.22)$, $\chi^2/N_{\mathrm{DOF}} = 0.55$.

In general, a measurement of Λ^0 polarization may depend on whether the Λ^0 is produced directly in the interaction or is the decay product of a particle or resonance. This difficulty might be a problem for inclusive studies. In the following, we show that such problems are greatly reduced with the exclusive sample.

(a) The number of Λ^0's which are the results of the $\Sigma^0 \rightarrow \Lambda^0 \gamma$ decay is quite small. In order for an event to

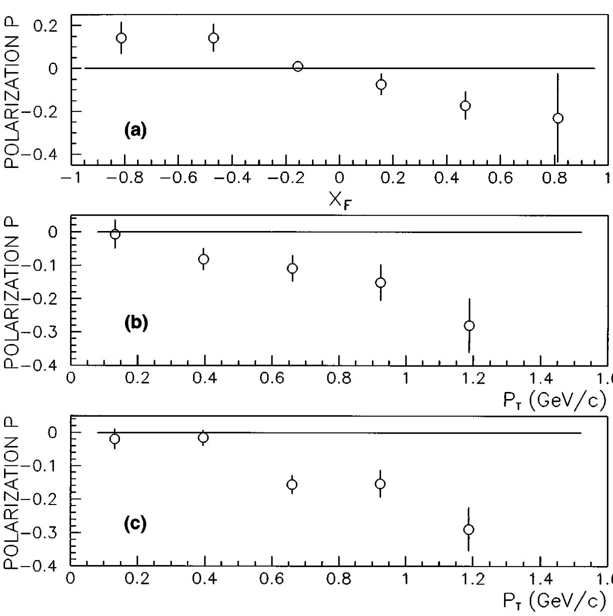

FIG. 2. (a) Λ^0 polarization as a function of x_F. (b) Λ^0 polarization, Λ^0 and K^+ are in opposite hemispheres. (c) Λ^0 polarization, Λ^0 and p are in opposite hemispheres. In (b) and (c), the $x_F < 0$ sample polarization has been multiplied by -1 and combined with the $x_F > 0$ sample.

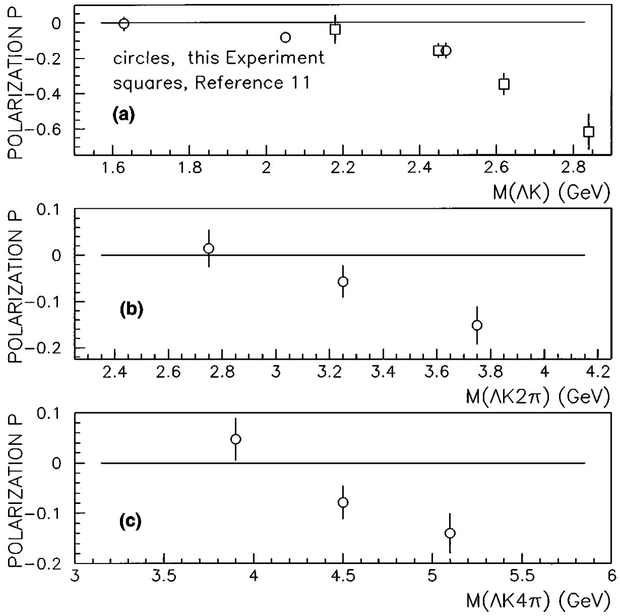

FIG. 3. Λ^0 polarization as a function of (a) $M(\Lambda K)$, (b) $M(\Lambda K \pi^+ \pi^-)$, (c) $M(\Lambda K \pi^+ \pi^- \pi^+ \pi^-)$.

be a candidate for an exclusive reaction, there are stringent demands on both the conservation of longitudinal and transverse momenta for the entire event. These requirements allow only a small fraction of $\Sigma^0 \to \Lambda^0 \gamma$ decays with an undetected γ to fake reaction (1). Using Monte Carlo techniques we estimate that only 3.4% of the Λ^0 sample could come from Σ^0 decay. The fraction of Λ^0's from Σ^0 decay is further reduced by a factor of 3 to 1.1% when the requirements on those momentum sums are tightened. We analyzed the Λ^0 polarization after those tighter cuts were applied. No statistically significant changes in the polarization results were found in that smaller sample.

(b) Contributions from decays of resonances are not large. By examining $\Lambda^0 \pi^+$ and $\Lambda^0 \pi^-$ invariant mass distributions, we determined that $\Sigma^{*+}(1380)$ and $\Sigma^{*-}(1380)$ production and decay accounted for roughly 4.5% of the Λ^0's each. No statistically significant differences in the Λ^0 polarization were observed when Σ^* resonances were excluded.

In conclusion, this measurement of Λ^0 polarization in an exclusive reaction has provided detailed information on the kinematic dependencies of that polarization. That detail poses a challenge to future models of the polarization phenomenon, especially where the experimental results differ from current theoretical expectations.

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