Study of Λ^0 Polarization in Four Different Exclusive pp Reactions at 27.5 GeV/c

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We have measured the x_F and P_T dependence of the polarization of Λ^0 hyperons produced in exclusive final states $pp \to p\Lambda^0K^+\pi^+\pi^-$, $pp \to p\Lambda^0K^+\pi^+\pi^-\pi^+\pi^-$, $pp \to p\Lambda^0K^+\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, and $pp \to p\Lambda^0K^+\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ at 27.5 GeV/c. We present an empirical parametrization for Λ^0 polarization as a function of x_F and P_T: $\mathcal{P} = (-0.443 \pm 0.037)x_F P_T$ for $-1 \le x_F \le 1$ and $0 \le P_T \le 1.8$ GeV/c. This parametrization is independent of the final state and provides a good description of the data. We note that the mechanism responsible for Λ^0 polarization appears to be independent of the production mechanism. [S0031-9007(99)09536-8]

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The discovery that Λ^0 hyperons are produced polarized in high energy pp collisions [1] has posed an interesting puzzle for theories of particle production. This discovery, and subsequent observations that other hyperons are produced polarized as well [2], challenges the assumption that spin plays no role in high energy multiparticle production. Since multiparticle processes involve many final state particles and a correspondingly large number of amplitudes, it had been thought that coherent interference of spin-dependent amplitudes was precluded in these processes. However, the existence of polarization, which implies coherent interference of at least two spin-dependent amplitudes, may suggest that only a few spin-dependent amplitudes are involved in producing hyperons.

Although extensive experimental [3] and theoretical [4] efforts have addressed the polarization phenomenon during the past 20 years, an understanding of the mechanism responsible for polarization remains elusive. Various models that have been proposed do not fit the data well and tend not to have predictive power [4]. One of the impediments to understanding this fundamental process may be that most polarization measurements of hyperons in high energy collisions are based on inclusive measurements, in which a hyperon is included in a sample regardless of other particles produced in the collision. Exclusive measurements of specific final states, on the other hand, involve fewer amplitudes and provide a means to gain insight into the polarization phenomenon that is inaccessible to inclusive measurements. For example, the largest measured value for Λ^0 polarization comes from an analysis of $pp \to p\Lambda^0K^+$ events [5], in which the polarization is observed to increase to a value of -0.62 ± 0.04 as a function of the invariant mass of the diffractive Λ^0K^+ system.

In this paper, we present exclusive measurements from a study of Λ^0 polarization in a high statistics sample of the reactions

$$pp \to p\Lambda^0K^+\pi^+\pi^-, \tag{1}$$

$$pp \to p\Lambda^0K^+\pi^+\pi^-\pi^+\pi^-, \tag{2}$$

$$pp \to p\Lambda^0K^+\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-, \tag{3}$$

$$pp \to p\Lambda^0K^+\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-. \tag{4}$$

This sample consists of fully reconstructed events in which all final state particles are measured and identified. A previous measurement has been published [6] for events belonging to reaction (2). We have reanalyzed these events for this paper to include them in our study of four specific final states.

The data for this study were recorded at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory in experiment E766, described in detail elsewhere [7–9]. A beam of 27.5 GeV/c protons interacted in a 30.5 cm long (5% interaction length) liquid-hydrogen target. The charged particles that were produced by pp interactions and those that resulted from the decays of short-lived particles were detected and measured in a six-station drift-chamber magnetic spectrometer. The momentum of the beam particle was measured in a separate spectrometer [10]. The data were reconstructed using a special computational system [11].

A detailed description of the event selection can be found elsewhere [7]. Here we mention details relevant only to the present analysis. Our data sample yielded $\sim 3 \times 10^6$ exclusive events. All of the events in this sample satisfied a kinematic constraint requiring that the initial and final 4-momentum be balanced, and additional constraints requiring conservation of charge, strangeness, and baryon number [9]. Events belonging to the specific final states selected for the Λ^0 polarization measurements had to satisfy three additional requirements: (i) events were required to have one and only one vertex separated from the interaction vertex of the beam proton, (ii) the invariant mass of the separated vertex with a proton and a pion as the daughter particles had to be consistent with the mass of the Λ^0, and (iii) events belonging to reactions (1), (2), (3), and (4) were required to have six, eight, ten, and twelve *charged* particles, respectively.

A verification of the procedure used to measure Λ^0 polarization was performed by measuring the polarization of K_S^0's produced in the reactions

$$pp \to ppK_S^0K^+\pi^-, \qquad (5)$$

$$pp \to ppK_S^0K^+\pi^-\pi^+\pi^-, \qquad (6)$$

$$pp \to ppK_S^0K^+\pi^-\pi^+\pi^-\pi^+\pi^-, \qquad (7)$$

$$pp \to ppK_S^0K^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-. \qquad (8)$$

Events belonging to reactions (5), (6), (7), and (8) were required to satisfy the same selection criteria as events belonging to reactions (1), (2), (3), and (4), respectively, except that the invariant mass of the separated vertex (with two pions as the daughter particles) had to be consistent with the mass of the K_S^0.

The numbers of exclusive events satisfying our selection criteria are 5421, 51 195, 48 195, and 14 582 for reactions (1), (2), (3), and (4), and 4623, 47 352, 46 057, and 13 037 for reactions (5), (6), (7), and (8), respectively. Backgrounds for reactions (1)–(4) due to the kinematic ambiguity between Λ^0's and K_S^0's are small because (i) the mass resolution is excellent (the standard deviation of the Λ^0 mass distribution is 0.5 MeV$/c^2$ [8]) and (ii) an exclusive event must satisfy the additive conservation laws for charge, strangeness, and baryon number. Backgrounds from mismeasured, nonexclusive events are $\leq$5% [9], and the requirement of 4-momentum balance reduces the background from events with $\Sigma^0 \to \Lambda^0 + \gamma$ decays to less than 2% (as determined by a Monte Carlo study).

In our study of Λ^0 polarization we explore the dependence of the polarization on the kinematic variables P_T and x_F [12] in each of the four final states (1), (2), (3), and (4). The variables are defined as follows: P_T is the Λ^0's transverse momentum with respect to the incident beam proton; and x_F is defined by $x_F = \frac{P_Z}{P_{Z\max}}$, where P_Z is the longitudinal momentum of the Λ^0 in the pp center of mass frame with the Z axis parallel to the direction of the beam proton, and $P_{Z\max}$ is the maximum value P_Z could have in this reference frame.

The angular distribution of the proton from the $\Lambda^0 \to p\pi^-$ decay in the Λ^0 rest frame is

$$dN/d\Omega = N_0(1 + \alpha \mathcal{P} \cos\theta), \qquad (9)$$

where N_0 is a normalization constant, α is the decay asymmetry parameter (0.642 ± 0.013) [13], and $\mathcal{P}$ is the polarization. The angle θ is defined as the angle between the direction of the daughter proton from the decay of the Λ^0 and the normal of the Λ^0 production plane, $\hat{n} \equiv \frac{\vec{P}_{\text{beam}} \times \vec{P}_\Lambda}{|\vec{P}_{\text{beam}} \times \vec{P}_\Lambda|}$, where $\vec{P}_{\text{beam}}$ and $\vec{P}_\Lambda$ are the beam proton and Λ^0 momentum vectors, respectively.

Since Λ^0 polarization is odd in x_F [6,14], we combine the data from $x_F > 0$ and $x_F < 0$ by multiplying $\cos\theta$ by the sign of x_F to improve the statistical power of our polarization measurements. Both our results and the following discussion are presented in terms of $|x_F|$.

To analyze the data, $\mathcal{P}$ is parametrized as a function of x_F and P_T: $\mathcal{P} = \mathcal{P}(x_F, P_T)$. The parameters of this function are determined using the maximum likelihood method [13], with Eq. (9) as the probability distribution for having dN protons in a solid angle of $d\Omega$.

Without a theory for Λ^0 polarization the function $\mathcal{P}(x_F, P_T)$ must be determined empirically. For the maximum likelihood analysis we have chosen a function that represents the simplest bilinear combination of x_F and P_T:

$$\mathcal{P}_1(x_F, P_T) = -a x_F P_T\,. \qquad (10)$$

We have also investigated other functions with different P_T dependences by expressing $\mathcal{P}(x_F, P_T)$ as a power series expansion in P_T, but we do not find any other function with a solution that is significantly better than the solution we find for Eq. (10). Using Eq. (9), we define the probability for the extended likelihood as a function of $\cos\theta$ as

$$P_{\text{ex}}(\cos\theta) = C_0 A(1 + \alpha \mathcal{P} \cos\theta), \qquad (11)$$

where C_0 is a normalization constant and A is the acceptance determined by a Monte Carlo analysis. The acceptance correction is symmetric in $\cos\theta$; therefore, our final results are presented without an acceptance correction. We determine the parameter a in Eq. (10) for each of the reactions numbered (1)–(4), and for the combined sample by minimizing the negative log of the extended likelihood. The results from this analysis are presented in Table I, which shows that, within errors, the dependence of Λ^0 polarization on x_F and P_T is independent of the reaction. Furthermore, the polarization for the combined sample is consistent with the results for the individual reactions. Using the value for the combined sample from

TABLE I. The values of parameter a in Eq. (10) as found by the maximum likelihood analysis for each reaction (1)–(4) and for the combined sample.

Reaction	a
1	0.390 ± 0.079
2	0.490 ± 0.051
3	0.366 ± 0.064
4	0.515 ± 0.143
All combined	0.443 ± 0.037

Table I, we write the Λ^0 polarization function as

$$\mathcal{P}(x_F, P_T) = (-0.443 \pm 0.037) x_F P_T \tag{12}$$

for $-1 \leq x_F \leq 1$ and $0 \leq P_T \leq 1.8$ GeV$/c$.

We verify the data analysis procedure using samples of exclusive events belonging to reactions (5), (6), (7), and (8), which contain a K_S^0 instead of a Λ^0. These events are subjected to the same polarization analysis to see if the analysis introduces a net polarization. The measured polarization for K_S^0's is found to be consistent with zero.

A Monte Carlo analysis is used to study possible systematic effects, caused by spectrometer acceptance and resolution, that might bias the Λ^0 polarization measurements. The Monte Carlo sample is generated with unpolarized Λ^0's using a model for reactions (1)–(4) that faithfully reproduces all kinematic distributions [9]. This sample of events is subjected to the same analysis programs and cuts used for the data. The numbers of Monte Carlo events that survive the analysis cuts for reactions (1), (2), (3), and (4) are 34 110, 236 078, 176 638, and 38 622, respectively. These events are combined into a single sample of 316 314 events by preserving the same relative number of events observed for each reaction in the data. The measured polarization for this Monte Carlo sample, which is generated with zero polarization, is found to be consistent with zero.

In a second analysis that makes a direct comparison to data, Monte Carlo events are weighted by $(1 + \alpha \mathcal{P} \cos\theta)$ with $\mathcal{P} = -0.443 x_F P_T$, based on Eq. (12). The resulting $\cos\theta$ distributions, in bins of $|x_F|$ and P_T, are shown in Fig. 1. The Monte Carlo distributions are shown as histograms (solid line) with the data distributions superimposed as data points with error bars. Figure 1 shows that the Λ^0 polarization in the Monte Carlo is in good agreement with the data. Figure 1 also shows that the $\cos\theta$ distributions are not quite linear, due to detector acceptance, and that these acceptance induced variations in $\cos\theta$ are reproduced by the Monte Carlo.

The dynamics of Λ^0 hyperon production in reactions (1)–(4) varies dramatically from one reaction to the next [9]; the Λ^0's in these reactions have very different x_F and P_T distributions. However, using a maximum likelihood analysis, we find the same dependence (within errors) of Λ^0 polarization on x_F and P_T for each of the four reactions. For these reactions, Λ^0 polarization can be described as $\mathcal{P} = (-0.443 \pm 0.037) x_F P_T$ for $-1 \leq x_F \leq 1$ and $0 \leq P_T \leq 1.8$ GeV$/c$. We conclude that the mechanism responsible for Λ^0 polarization is independent of the production mechanism for the final states we have measured.

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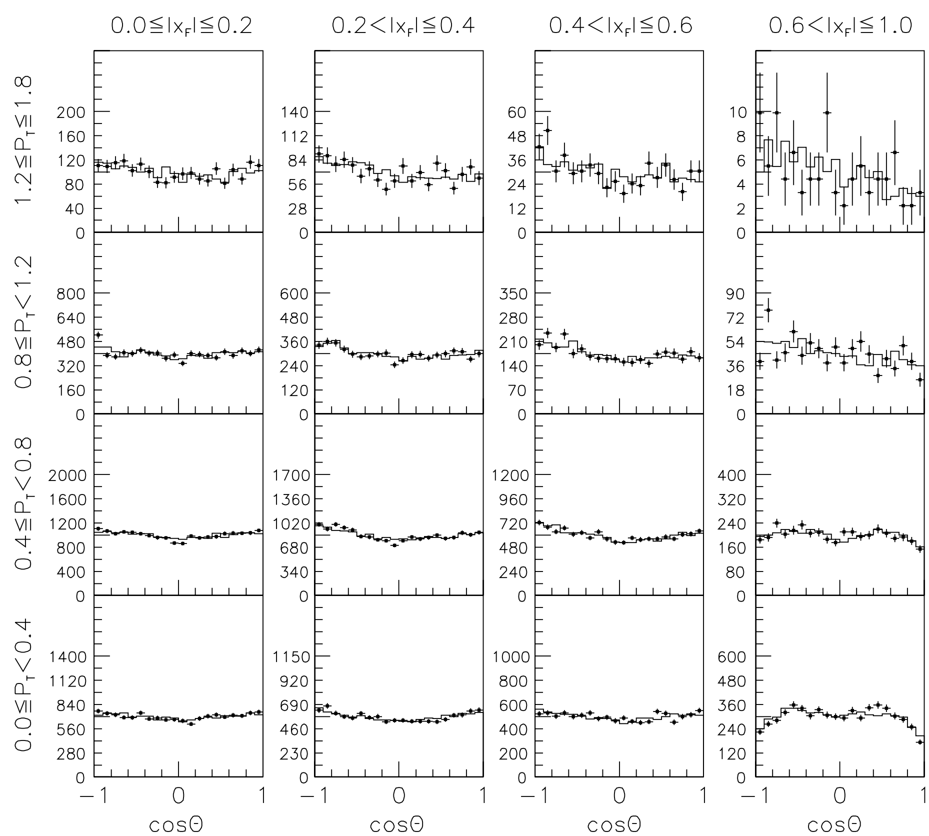

FIG. 1. The $\cos\theta$ histograms in bins of $|x_F|$ and P_T for all events belonging to reactions (1)–(4). Monte Carlo distributions are shown as histograms with solid lines. Data distributions are superimposed as data points with error bars.

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