Polarization of Ξ^- Hyperons Produced by 800-GeV Protons

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The polarization P_{Ξ^-} of Ξ^- hyperons produced by 800-GeV protons has been measured for x_F from 0.3 to 0.7 and p_T from 0.5 to 1.5 GeV/c. P_{Ξ^-} has a p_T dependence similar to that of the Λ but has a different x_F behavior. Also, an energy dependence of P_{Ξ^-} has been observed.

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Polarization of hyperons produced by high-energy protons has been found to be a universal phenomenon arising from strong interactions. Such polarization was discovered for the Λ [1] and has been measured to have comparable magnitude for the Ξ^0 [2], Ξ^- [3,4], Σ^+ [5], Σ^0 [6], and Σ^- [7] hyperons produced by protons. The kinematic dependence of this polarization has been most extensively studied for Λ's. Λ polarization P_Λ is approximately energy independent from 12 to 2000 GeV equivalent fixed-target energy [8]. It increases approximately linearly with both Feynman x, x_F, and transverse momentum, p_T. Above a p_T of about 1 GeV/c, Λ polarization appears to be independent of p_T but has a strong dependence on x_F [8,9]. Polarization data from other hyperons are of lower precision and do not span a wide enough kinematic range to independently determine their behavior. These data, however, appear to have a behavior consistent with that of the Λ [8]. Perturbative QCD does not predict such polarization in either magnitude or kinematic behavior [10], but is not thought to be applicable in the low-p_T region ($p_T < 4$ GeV/c) probed by the data. Phenomenological models that attempt to use the general properties of the color field give polarization results which depend only on the origin of the valence quarks and the spin structure of the hyperon [11–15]. Since these models were developed to explain the Λ-polarization data, it is necessary to test their validity by measuring the kinematic behavior of the polarization of other hyperons, as well as to investigate the general properties of this phenomenon.

We present polarization results which span a kinematic range of $0.3 < x_F < 0.7$ and $0.5 < p_T < 1.5$ GeV/c from a sample of 4.6×10^6 Ξ^-'s produced by 800-GeV protons at Fermilab. The decay chain $\Xi^- \to \Lambda + \pi^-$, $\Lambda \to p + \pi^-$ was detected. This is the first time that hyperon polarization, other than Λ polarization, has been measured at any energy above 400 GeV with a sufficient kinematic range to test the generality of conclusions drawn from P_Λ results.

An 800-GeV proton beam struck a 2-mm$\times$2-mm $\times$9-cm beryllium target to produce Ξ^-'s at a production angle on the order of 2 mrad. A parity-conserving component of the Ξ^- polarization would be perpendicular to the production plane defined by the direction of the proton beam and the Ξ^-, $\hat{\mathbf{k}}_p \times \hat{\mathbf{k}}_{\Xi^-}$. After passing through a dipole magnet ($M1$) the Ξ^-'s and decay products were detected by a charged-particle spectrometer which consisted of eight planes of silicon microstrip detectors (SSD's), nine multiwire proportional chambers (MWPC's), and two analyzing magnets to measure the momenta of the daughter particles. The apparatus is described elsewhere [16,17].

The Ξ^- polarization was found by measuring the polarization of the daughter Λ. These two quantities are related by [18]

$$\mathbf{P}_\Lambda = \frac{(\alpha_\Xi + \hat{\mathbf{\Lambda}}\cdot\mathbf{P}_\Xi)\hat{\mathbf{\Lambda}} + \beta_\Xi(\mathbf{P}_\Xi\times\hat{\mathbf{\Lambda}}) + \gamma_\Xi(\hat{\mathbf{\Lambda}}\times\mathbf{P}_\Xi)\times\hat{\mathbf{\Lambda}}}{1+\alpha_\Xi\hat{\mathbf{\Lambda}}\cdot\mathbf{P}_\Xi}, \qquad (1)$$

where α_Ξ, β_Ξ, and γ_Ξ are the decay parameters for the decay $\Xi^- \to \Lambda + \pi^-$, and $\hat{\mathbf{\Lambda}}$ is the direction of the Λ in the rest frame of the Ξ^-. In this analysis β_Ξ was taken to be zero [19], giving

$$\mathbf{P}_\Lambda = \frac{\gamma_\Xi\mathbf{P}_\Xi + [\alpha_\Xi + (1-\gamma_\Xi)\hat{\mathbf{\Lambda}}\cdot\mathbf{P}_\Xi]\hat{\mathbf{\Lambda}}}{1+\alpha_\Xi\hat{\mathbf{\Lambda}}\cdot\mathbf{P}_\Xi}. \qquad (2)$$

P_Λ was measured by examining the distribution of the proton in the rest frame of the Λ reached from the laboratory frame through the Ξ^- rest frame. The proton distribution is given by

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1+\alpha_\Lambda\mathbf{P}_\Lambda\cdot\hat{\mathbf{p}}), \qquad (3)$$

where α_Λ is the decay parameter for the $\Lambda \to p + \pi^-$ decay, and $\hat{\mathbf{p}}$ is the direction of the daughter proton in the Λ rest frame. In practice, this distribution was modified by

TABLE I. Polarization of Ξ^- as a function of momentum. The 1.3-mrad production angle was horizontal while the rest of the data come from vertical targeting.

Mean Ξ^- momentum (GeV/c)	Production angle (mrad) 1.3	1.7	2.1	2.7	2.5
255	...	-0.068 ± 0.029	-0.103 ± 0.025	-0.067 ± 0.027	-0.087 ± 0.020
290	...	-0.087 ± 0.011	-0.092 ± 0.010	-0.126 ± 0.011	-0.111 ± 0.008
330	...	-0.085 ± 0.007	-0.107 ± 0.006	-0.127 ± 0.008	-0.124 ± 0.005
365	...	-0.104 ± 0.005	-0.129 ± 0.005	-0.137 ± 0.006	-0.129 ± 0.004
405	-0.075 ± 0.017	-0.120 ± 0.005	-0.136 ± 0.005	-0.140 ± 0.007	-0.138 ± 0.004
445	-0.056 ± 0.013	-0.119 ± 0.006	-0.135 ± 0.006	-0.150 ± 0.008	-0.145 ± 0.006
480	-0.081 ± 0.014	-0.121 ± 0.008	-0.132 ± 0.009	-0.121 ± 0.013	-0.124 ± 0.008
520	-0.059 ± 0.023	-0.111 ± 0.012	-0.139 ± 0.015	-0.152 ± 0.025	-0.152 ± 0.014
560	...	-0.098 ± 0.025	...	...	-0.143 ± 0.030

the acceptance of both the spectrometer and the reconstruction algorithm. A hybrid Monte Carlo technique [20] was employed to determine the Λ polarization by correcting for the acceptance. The measured Λ polarization is the sum of the real polarization and any bias which results from uncorrected imperfections in the detection and reconstruction procedure. The polarization changes sign with the production angle while the bias, which is a property of the apparatus, does not. The bias is measured, and canceled, when data are taken at both positive and negative production angles.

To determine any residual systematic uncertainties, the polarization was measured using data sets with opposite fields of the analyzing magnets, which changes the correlation of the momentum of the Ξ^- decay products with their positions in the downstream part of the spectrometer. The agreement of the polarization measurements was excellent; χ^2 per degree of freedom was 0.9 for nine degrees of freedom. In addition, the parity-violating y component of the polarization was measured for the entire vertical-production-angle sample to check for possible measurement problems. It was found to be 0.0005 ± 0.0011, in good agreement with the expected value of zero. P_{Ξ^-} was stable to reasonable variations of the data-selection criteria to better than 0.5 standard deviation.

The Ξ^- polarization at the target can be found by correcting for the precession of the spin through the magnet $M1$. Defining a coordinate system with $\hat{\mathbf{z}}$ in the Ξ^- momentum direction, $\hat{\mathbf{y}}$ directed up, and $\hat{\mathbf{x}}=\hat{\mathbf{y}}\times\hat{\mathbf{z}}$, a polarization produced in the x-z plane would obey the following equations:

$$P_x(p)=P(p)\cos\phi+H\sin\phi\,, \qquad (4)$$

$$P_z(p)=P(p)\sin\phi+H\cos\phi\,, \qquad (5)$$

where $P_x(p)$ and $P_z(p)$ are the measured Ξ^- polarization components, $P(p)$ is the parity-conserving component of P_{Ξ^-} perpendicular to the production plane ($\hat{\mathbf{x}}$) at the target, H is the parity-violating component of the polarization in the direction of the Ξ^- momentum (helicity), and p is the Ξ^- momentum. The angle ϕ is the difference between the precession angle of the spin and momentum of the Ξ^-. It changes only with the magnetic field of $M1$.

The measurement of the Ξ^- helicity yielded $H=0.009 \pm 0.008$, consistent with zero as required by parity conservation in strong interactions. The x and y components of the bias were measured to be less than 1%, while that in the z direction was approximately 3% [16]. The measured values for P_{Ξ^-} are listed in Table I as a function of momentum with H constrained to be zero. The 1.3-mrad production angle was horizontal while the other production angles were vertical. These angles were measured to better than 0.08 mrad. The three different production-angle data sets, 1.7, 2.1, and 2.7 mrad, were selected from the vertical-production-angle data based on the reconstructed Ξ^- momentum vector. The results in the final column were selected from these data such that the average production angle would be precisely 2.5 mrad. This was done to facilitate a comparison with previous hyperon polarization results and is not independent of the 1.7-, 2.1-, and 2.7-mrad data sets.

Figure 1 shows the 2.5-mrad results compared to P_{Ξ^-}

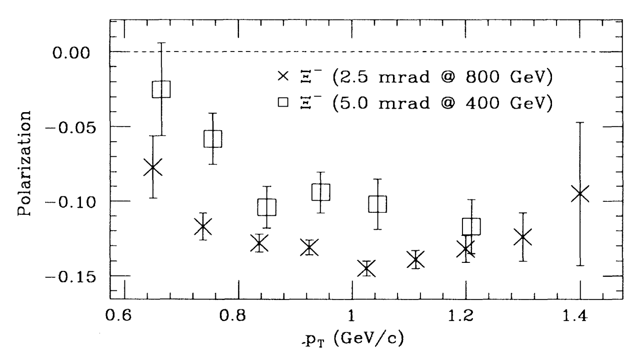

FIG. 1. P_{Ξ^-} from this experiment and an experiment using 400-GeV protons with a 5-mrad production angle (Ref. [3]). The data from the two experiments match in both x_F and p_T. Note the suppressed zero of the horizontal axis.

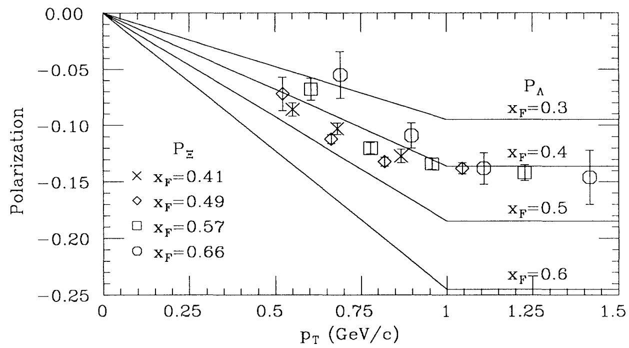

FIG. 2. P_{Ξ^-} as a function of p_T for contours of constant average x_F. The lines are a schematic representation of the behavior of the Λ polarization from $x_F = 0.3$ to $x_F = 0.6$, the same region as the P_{Ξ^-} results.

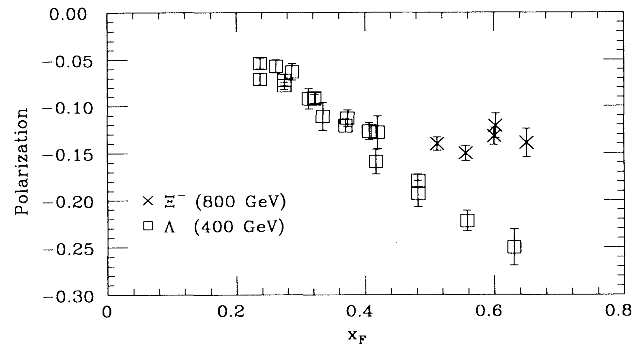

FIG. 3. Comparison of P_{Ξ^-} with P_Λ from another experiment (Ref. [9]) as a function of x_F. Only data with a p_T greater than 1 GeV/c are included.

measurements from an experiment with a 400-GeV proton beam and a 5.0-mrad production angle [3]. A direct comparison can be made with this experiment since its beam energy is half and its production angle is twice that of the present experiment. The data with the same p_T for the two experiments will also have the same x_F. The magnitude of P_{Ξ^-} at 800 GeV is consistently larger than that at 400 GeV, demonstrating that P_{Ξ^-} is energy dependent between 400 and 800 GeV. Since the polarization is a function of p_T, a systematic uncertainty in determining the production angle could account for the difference if that uncertainty were as large as 1.0 mrad in the 400-GeV experiment or 0.5 mrad in our experiment. In both cases it is significantly outside of the measurement uncertainty.

It is also obvious from Fig. 1 that P_{Ξ^-} does not continue to increase with p_T. The kinematic behavior of P_{Ξ^-} is shown in Fig. 2 as a function of p_T for different choices of x_F [16]. For reference, the lines in the figure represent the behavior of 400-GeV Λ polarization in this kinematic region [8,9]. In the range of x_F measured in this experiment, the Ξ^- polarization does not demonstrate the strong x_F dependence shown by P_Λ. The p_T behavior of P_{Ξ^-} is consistent with that of P_Λ, an approximately linear p_T dependence for small p_T, and independent of p_T above p_T of 1 GeV/c. Figure 3 illustrates the kinematic behavior of the polarization above p_T of 1 GeV/c. Here P_Λ increases linearly with x_F [9] but P_{Ξ^-} appears to be independent of x_F.

It is interesting to compare P_{Ξ^-} and P_{Ξ^0} since both Ξ^- and Ξ^0 production can be pictured as arising from the replacement of two valence quarks from an unpolarized proton by two s quarks. Figure 4 compares the 1.7-mrad Ξ^- results to 400-GeV P_{Ξ^0} measurements done at 3.5 mrad. These data match kinematically in x_F and p_T. The magnitude of P_{Ξ^-} appears to be consistently less than that of P_{Ξ^0} but the Ξ^0 uncertainties are large. Taking into account the energy dependence of Ξ^- polarization, this difference could be enhanced since $|P_{\Xi^-}|_{400\,\text{GeV}} < |P_{\Xi^-}|_{800\,\text{GeV}}$. Clearly, high-statistics 800-GeV Ξ^0 data are needed to make a definitive comparison.

This experiment has explored the behavior of the Ξ^- polarization as a function of beam energy, x_F, and p_T. The Ξ^- polarization has been compared to the behavior of the polarization of the Λ. While the sign and p_T dependence of these polarizations are similar, there are two significant differences. P_{Ξ^-} shows a definite energy dependence which does not appear to exist for P_Λ. However, measurements allowing for the direct comparison of p_T and x_F behavior at different energies have never been made for Λ's. Second, P_{Ξ^-} does not show the x_F dependence of the Λ data. Similar kinematic behavior might be expected since both P_Λ and P_{Ξ^-} arise from the process of producing strange quarks (1 or 2) and combining them with valence quarks (2 or 1) from an unpolarized proton to form the observed hyperon. Finally, the apparent difference between P_{Ξ^0} and P_{Ξ^-} is puzzling since both the

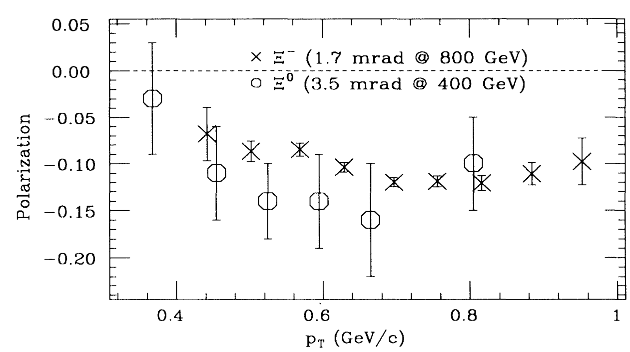

FIG. 4. Comparison of 800-GeV, 1.7-mrad P_{Ξ^-} data with 400-GeV, 3.5-mrad P_{Ξ^0} measured in a previous experiment (Ref. [21]). The data from the two experiments match in both x_F and p_T. Note the suppressed zero of the horizontal axis.

production mechanism and the initial and final states seem equivalent with respect to quark spin. Providing an explanation which accounts for the observed difference in the behavior of the Ξ^- polarization from that of the Λ and the Ξ^0 should lead to a better understanding of this phenomenon and perhaps the strong interaction in general.

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