Polarization of Ξ^0 and Λ Hyperons Produced by 400-GeV/c Protons

K. Heller
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455

and

P. T. Cox,[(a)] J. Dworkin, and O. E. Overseth
Department of Physics, University of Michigan, Ann Arbor, Michigan 48109

and

L. Pondrom, R. Grobel,[(b)] R. Handler, M. Sheaff, and C. Wilkinson
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

and

T. Devlin, L. Deck,[(c)] K. B. Luk,[(d)] R. Rameika,[(e)] and P. Skubic[(f)]
Department of Physics, Rutgers, The State University, Piscataway, New Jersey 08854

and

G. Bunce
Accelerator Division, Brookhaven National Laboratory, Upton, New York 11973
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The polarization of Ξ^0 and Λ hyperons produced by 400-GeV protons interacting with a beryllium target has been measured in the projectile fragmentation region. The Ξ^0 polarization agrees in sign, magnitude, and kinematic behavior with that of Λ. The target dependence of these Ξ^0 and Λ polarizations was also investigated with use of Cu and Pb targets.

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There is a growing body of evidence that polarization is an important effect which must be explained by any theory of high-energy particle production. The polarization of Λ hyperons produced by the fragmentation of protons has been observed for proton energies between 14 and 2000 GeV.[1-3] In similar experiments Σ^+ hyperons are produced with polarization opposite to the Λ's[4] while protons[5] and $\bar{\Lambda}$'s[3] are not polarized. It appears that the strange quark, s, is either produced polarized or is polarized as it combines with the proton fragment.[3,6] The sign of the resulting hyperon polarization can be determined by the spin-flavor structure of its quark wave function. In Ξ^0 production where two s quarks are added to the projectile fragment, one thus expects the same polarization as the Λ with a similar kinematic behavior. Models of particle production in which polarization arises from the interference of resonances[7] would not automatically predict a similarity of the Λ and Ξ^0 polarizations.

This experiment measured, for the first time, the kinematic behavior of the polarization of Ξ^0 hyperons produced by high-energy protons. In order to make a direct comparison between Ξ^0 and Λ polarization 565 125 Λ's and 204 989 Ξ^0's produced by 400-GeV protons incident on a beryllium target were collected in the same apparatus. Additional data with copper and lead targets were used to determine the effect of the target nucleus on the polarization. This data set consisted of 130 545 (114 506) Λ and 42 274 (37 343) Ξ^0 events from the Cu (Pb) target.[8] Finally the data from all targets were combined to search for a parity-nonconserving helicity in the production of Ξ^0 or Λ hyperons.

These measurements result from the analysis of data taken by use of the neutral hyperon beam and spectrometer at Fermilab. Other measurements using these same data have been reported previously.[9-11] Details of the apparatus, triggering, and data selection will be found in those references. The incident proton beam was deflected in the vertical plane to give angles of 0, ± 3.5, ± 7.2, and ± 9.8 mrad between the protons and the collimator axis defining the neutral beam. The acceptance of the collimator was ± 0.5 mrad. A right-handed coordinate system was defined by the collimator axis ($+\hat{z}$ downstream), the vertical magnetic field of the collimator ($+\hat{y}$ upwards), and $\hat{x} = \hat{y} \times \hat{z}$. Any parity-allowed polarization would be perpendicular to the production plane defined by $\hat{k}_p \times \hat{k}_H = \hat{x}$, where $\hat{k}_p$ is the proton momentum direction and $\hat{k}_H$ is that of the hyperon. A parity-nonconserving helicity would be along $\hat{k}_H = \hat{z}$ at production. The polarization which precesses in the collimator magnetic field is a vector sum of the parity-allowed component P and the helicity, h. Six different magnetic fields (± 13.46, ± 10.41, ± 8.93 T m) gave precession angles as large as 150° for Λ's and 300° for Ξ^0's. The combination of different precession angles and positive and negative production angles allowed the determination of the original direction of the hyperon polarization as well as the measurement and elimination of any apparatus-induced asymmetries.

The Λ was detected via the charged products of decay $\Lambda \to p\pi^-$ while the Ξ^0 detection relied on the decay chain $\Xi^0 \to \Lambda\pi^0$, $\Lambda \to p\pi^-$, $\pi^0 \to \gamma\gamma$. The Λ trigger was a subset of the Ξ^0 trigger. In both cases the proton and π^- momenta were measured with use of a multiwire-proportional-chamber spectrometer. The γ energies were measured using a lead-glass Cerenkov counter array and their positions by MWPC's preceded by two radiation lengths of lead.

The polarizations of both the directly produced Λ's and Ξ^0's were measured by observing the asymmetry of the daughter proton direction, in the Λ rest frame. The technique of always analyzing the Λ decay asymmetry capitalized on the highly efficient and well understood acceptance of the apparatus for $\Lambda \to p\pi^-$,[12] and avoided possible distortions due to Ξ^0 acceptance. For the decay $\Xi^0 \to \Lambda\pi^0$, the Λ polarization is given by

$$\vec{P}_\Lambda = [(\alpha_\Xi + \hat{\Lambda}\cdot\vec{P}_\Xi)\hat{\Lambda} - \beta_\Xi(\hat{\Lambda}\times\vec{P}_\Xi) - \gamma_\Xi\hat{\Lambda}\times(\hat{\Lambda}\times\vec{P}_\Xi)]/(1+\alpha_\Xi\hat{\Lambda}\cdot\vec{P}_\Xi), \tag{1}$$

where $\hat{\Lambda}$ is the direction of Λ in the Ξ^0 rest frame, $\vec{P}_\Xi$ is the polarization of the Ξ^0, $\vec{P}_\Lambda$ is the polarization of the Λ in the Λ rest frame reached by a boost from the Ξ^0 rest frame, and α_Ξ, β_Ξ, and γ_Ξ are the decay parameters for the mode $\Xi^0 \to \Lambda\pi^0$. If the β_Ξ term is ignored,[13] Eq. (1) can be written as

$$\vec{P}_\Lambda = [\alpha_\Xi\hat{\Lambda} + \gamma_\Xi\vec{P}_\Xi + (\vec{P}_\Xi\cdot\Lambda)(1-\gamma_\Xi)\hat{\Lambda}]/(1+\alpha_\Xi\hat{\Lambda}\cdot\vec{P}_\Xi), \tag{2}$$

where the large constant term $\gamma_\Xi\vec{P}_\Xi$ is isolated. Since α_Ξ is known,[10] and $\gamma_\Xi > 0$,[14] the terms in Eq. (2) can be evaluated as a function of the unknown polarization vector $\vec{P}_\Xi$ for each event. A trial value of $\vec{P}_\Xi$ ($\vec{P}_\Xi'$) was obtained from the approximation $\vec{P}_\Lambda \simeq \alpha_\Xi\hat{\Lambda} + \gamma_\Xi\vec{P}_\Xi'$. The components of the trial vector were then substituted into the small terms (everything except $\gamma_\Xi\vec{P}_\Xi$) in Eq. (2). Subsequent iterations were not necessary.

The parity-allowed polarization and the helicity at production were determined by fitting the measured hyperon polarization by the equations

$$P_x(p,\theta,t) = B_x(p) + P(p,\theta,t)\cos\omega + h(p,|\theta|,t)\sin\omega, \quad P_z(p,\theta,t) = B_z(p) + P(p,\theta,t)\sin\omega + h(p,|\theta|,t)\cos\omega.$$

Parity-allowed polarization, P, is a function of the hyperon momentum (p), production angle (θ), and target (t). P is constrained to reverse sign with production angle. The helicity, h, is also a function of p, θ, and t. The helicity, however, would not change sign with production angle reversal. B_x and B_z represent apparatus-induced asymmetries ("biases") which were a function only of spectrometer variables. The precession angle, ω, depended only on the collimator field integral and the magnetic moment, μ, of the hyperon, $\omega = (2\mu/\hbar c\beta)\int B\,dl = (18.30)\mu\int B\,dl$ for ω in degrees, μ in nuclear magnetons, $\int B\,dl$ in tesla meters, and $\beta = 1$. The hyperon magnetic moment, μ, determined from this fit agreed with that reported earlier using a slightly different analysis technique.[11] For the results quoted here μ was fixed to be the best measured value for Λ and Ξ^0.[11,15] The biases also agreed with those displayed previously.[10]

The resulting P_Λ and P_{Ξ^0} for the Be target are given in Table I as a function of p and θ. The 0 mrad data were consistent with zero for each p. For Be at $\theta = 0$ mrad, $\bar{P}_\Lambda = 0.04 \pm 0.04$ at $\bar{p} = 165$ GeV/c and $\bar{P}_\Xi = -0.03 \pm 0.01$ at $\bar{p} = 200$ GeV/c. Figure 1 compares P_Λ and P_{Ξ^0} for the most precise data set (7.2 mrad, Be target). Also shown are Λ data from an earlier experiment with the same proton energy, t, and θ.[3] There is good agreement between the two experiments and no significant difference between the P_Λ and P_{Ξ^0}.

Earlier experiments which obtained data at one fixed angle were not able to separate the behavior of P_Λ into a transverse (p_T) and longitudinal ($x = 2P_L^{\mathrm{cm}}/\sqrt{s}$) dependence. Indications were P_Λ depended mainly on p_T but only weakly on x.[3] More sensitive experiments have observed that P_Λ increases with increasing x.[16,17] Figure 2 shows P_Λ and P_{Ξ^0} as a function of p_T for the different θ. There is clear evidence from both data sets that

TABLE I. Be target data. Ξ^0 and Λ polarization as a function of hyperon production angle in mrad and momentum in GeV/c.

p	$\theta = 3.5$	$\theta = 7.2$	$\theta = 9.8$
		Ξ^0 polarization	
105	-0.03 ± 0.06	-0.07 ± 0.02	-0.06 ± 0.03
130	-0.11 ± 0.05	-0.10 ± 0.02	-0.10 ± 0.03
150	-0.14 ± 0.04	-0.10 ± 0.02	-0.15 ± 0.04
170	-0.14 ± 0.05	-0.13 ± 0.03	-0.26 ± 0.07
190	-0.16 ± 0.06	-0.14 ± 0.04	...
220	...	-0.18 ± 0.06	...
230	-0.10 ± 0.05	...	...
		Λ polarization	
75	-0.20 ± 0.12	-0.07 ± 0.03	-0.04 ± 0.04
90	-0.03 ± 0.04	-0.06 ± 0.01	-0.09 ± 0.02
110	-0.08 ± 0.03	-0.07 ± 0.01	-0.09 ± 0.02
130	-0.07 ± 0.02	-0.10 ± 0.01	-0.12 ± 0.02
150	-0.05 ± 0.02	-0.13 ± 0.01	-0.12 ± 0.03
170	-0.04 ± 0.03	-0.11 ± 0.02	-0.12 ± 0.05
190	-0.11 ± 0.03	-0.13 ± 0.03	-0.02 ± 0.09
220	...	-0.21 ± 0.03	...
240	-0.16 ± 0.02	...	...
270	...	...	...

P at smaller θ is systematically larger than that of the larger θ at the same p_T. This confirms for Λ and establishes for Ξ^0 that P is an increasing function of x as well as p_T.

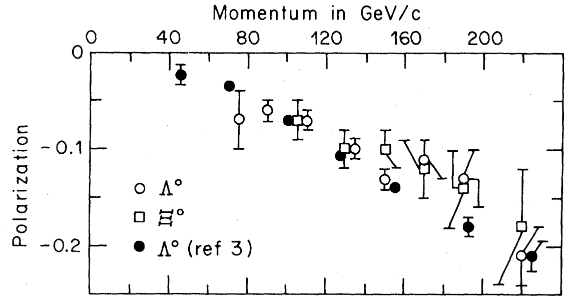

FIG. 1. Λ and Ξ^0 polarizations from this experiment compared as a function of momentum. Also shown is the Λ polarization from Ref. 3.

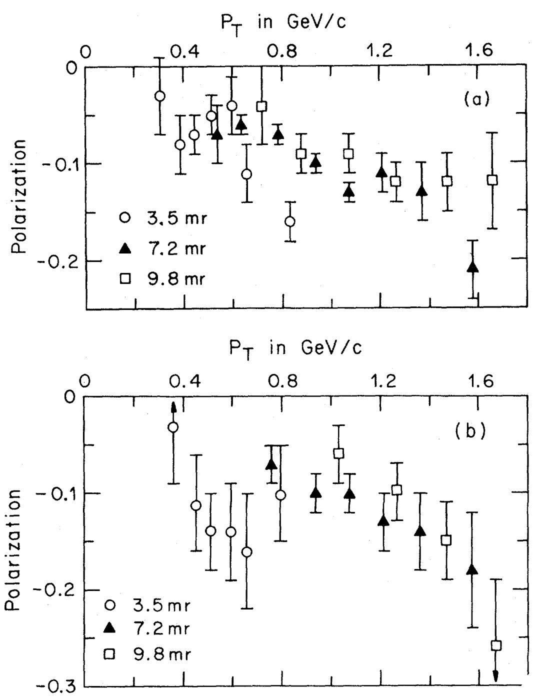

FIG. 2. Hyperon polarization for each production angle as a function of p_T. (a) Λ; (b) Ξ^0.

A previous experiment in which Λ's were produced by 28-GeV protons observed decreased P_Λ from a Be target as compared to a hydrogen target.[2] Because of our limited statistics, the data at each θ were combined to give a single value of P for each target. The Cu ($A = 63$) and Pb ($A = 207$) data were also combined to compare with those from Be ($A = 9$). Figure 3 shows this combined P as a function of p_T. The magnitude of P_Λ decreases with A in agreement with Ref. 2. P_{Ξ^0} has larger errors and, while showing no such behavior, is not inconsistent with the Λ data.

The helicity was measured for both Ξ^0 and Λ production. Data for all t, p, and θ were combined, giving the results $h_{\Xi^0} = 0.014 \pm 0.007$, $h_\Lambda = 0.001 \pm 0.004$. These results show no parity non-

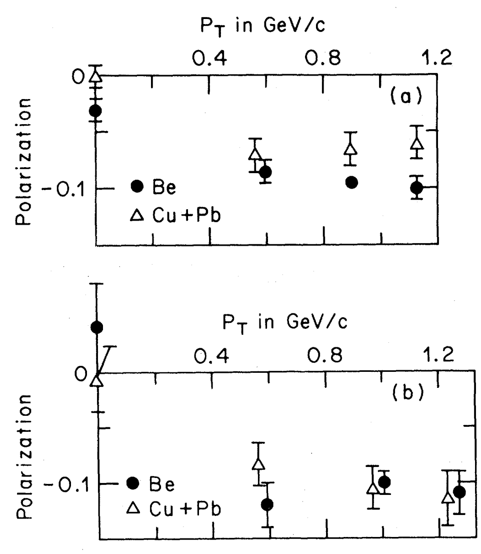

FIG. 3. Hyperon polarization for Be-target data compared to the combination of Cu- and Pb-target data. (a) Λ; (b) Ξ^0.

conservation occurring in the production process and, in the case of the Λ, agree with a previous result.[3] Subsets of the data as functions of θ or p also revealed no parity nonconservation.

This experiment has shown that Λ's and Ξ^0's produced by 400-GeV protons have polarization with similar kinematic behavior. It is reasonable to assume that the underlying mechanisms which gives this effect are also similar. The polarization is a function of x as well as p_T. P_Λ decreases with the atomic number of the target. Finally, no evidence for a parity-nonconserving helicity was observed for either Λ or Ξ^0 production.

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[a]Present address: CERN, CH-1211, Geneve 23, Switzerland.

[b]Present address: Salomon Bros., Inc., New York, N.Y. 10004.

[c]Present address: Max Planck Institut für Physik, München-40, Germany.

[d]Present address: University of Washington, Seattle, Wash. 98195.

[e]Present address: Fermilab, P.O. Box 500, Batavia, Ill. 60510.

[f]Present address: University of Oklahoma, Norman, Okla. 73019.

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