

## Production Polarization and Magnetic Moment of $\Xi^+$ Antihyperons Produced by 800-GeV/c Protons

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(Received 27 April 1990)

The polarization of  $\Xi^+$  hyperons produced by 800-GeV/c protons in the inclusive reaction  $p + \text{Be} \rightarrow \Xi^+ + X$  has been measured. The average polarization of the  $\Xi^+$ , at a mean  $x_F = 0.39$  and  $p_t = 0.76$  GeV/c, is  $-0.097 \pm 0.012 \pm 0.009$ . The magnetic moment of the  $\Xi^+$  is  $0.657 \pm 0.028 \pm 0.020$  nuclear magneton.

PACS numbers: 13.88.+e, 13.40.Fn, 13.85.Ni, 14.20.Jn

In 1976 it was shown<sup>1</sup> that  $\Lambda$  hyperons are substantially polarized when they are produced in the reaction  $p + \text{Be} \rightarrow \Lambda + X$ . Similarly, polarization of comparable magnitude has been found in the production of  $\Sigma^0$ ,  $\Sigma^+$ ,  $\Sigma^-$ ,  $\Xi^0$ , and  $\Xi^-$  hyperons.<sup>2</sup> The polarization of  $\bar{\Lambda}$ 's produced by protons has been found to be consistent with zero.<sup>3</sup> Models based on the recombination of valence quarks in the projectile with quarks from the sea to form the hyperon<sup>4</sup> have been used to explain the qualitative behavior shown by the data. These models also predict zero polarization for particles that have no valence quarks in common with the incoming particle.

We have discovered that  $\Xi^+$ 's produced by protons have a polarization approximately equal to that of the  $\Xi^-$ . The presence of a significant polarization for the  $\Xi^+$  makes possible the first measurement of the magnetic moment of an antihyperon.

This experiment was performed in the Proton Center beam line at Fermilab. A plan view of the experiment is shown in Fig. 1. An 800-GeV/c proton beam was incident on a  $2 \times 2 \times 92\text{-mm}^3$  beryllium target with vertical production angles of  $\pm 2.4$  mrad. By comparing the transverse-momentum ( $p_t$ ) distributions of the detected particles at each angle, the relative difference of the two targeting angles was determined to be less than 0.06 mrad. A secondary beam of charged particles was defined by a curved collimator through the magnet  $M1$ . With a field integral,  $\int B dl$ , of 15.35 Tm,  $M1$  was used to transmit positively charged particles with momenta in the range from 240 to 450 GeV/c and to precess the spin of the particles. Negatively charged particles were selected by reversing the magnetic field. A polarization perpendicular to the production plane would be precessed in the  $x$ - $z$  plane by  $M1$ . A  $y$  component of the

polarization would violate parity conservation in strong interactions.

In this experiment the decay sequences of interest were  $\Xi^+ \rightarrow \bar{\Lambda}\pi^+$ ,  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$  and  $\Xi^- \rightarrow \Lambda\pi^-$ ,  $\Lambda \rightarrow p\pi^-$ . The charged particles were detected with a spectrometer consisting of scintillation counters  $S1$ ,  $S2$ ,  $V1$ ,  $V2$ , and  $M$ , silicon strip detectors  $SSD1$ – $SSD8$ , multiwire chambers  $C1$ – $C9$ , and analyzing magnet  $M2$  that provided a transverse bending power of 1.5 GeV/c in the horizontal plane. For the  $\Xi^+$  run, the magnetic field of  $M2$  bent  $\pi^+$ 's to the  $-x$  direction and  $\bar{p}$ 's to the  $+x$  direction. The trigger required a signal from counters  $S1$  and  $S2$  with no signal from the veto counters  $V1$  and  $V2$ . The pulse height from the multiplicity counter  $M$  was required to be greater than that corresponding to

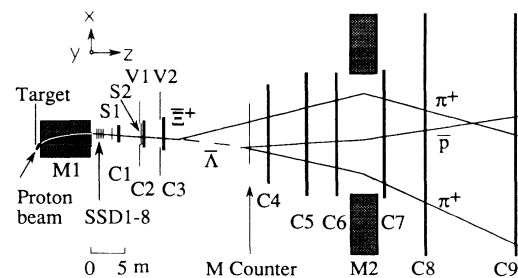


FIG. 1. Plan view of the experiment. Note that the transverse dimensions have been exaggerated.  $SSD1$ – $SSD8$ ,  $C1$ – $C3$ , and  $C4$ – $C9$  have 0.1-, 1-, and 2-mm pitch, respectively. The SSD's are grouped into four pairs of  $x$  and  $y$  planes. The  $y$  axis is in the production plane and out of page in this figure,  $z$  is along the axis of the charged beam through the spectrometer, and the  $x$  axis is in the horizontal plane to form a right-handed coordinate system.

two ( $M_{\min}$ ) but less than five ( $\bar{M}_{\max}$ ) minimum-ionizing particles. Downstream of  $M2$ , at least one hit on the right-hand side ( $-x$ ) of  $C8$  and one hit on the left-hand side of  $C9$  were required. Thus the final trigger was

$$\Xi^+ = S1 \cdot S2 \cdot \bar{V}1 \cdot \bar{V}2 \cdot M_{\min} \cdot \bar{M}_{\max} \cdot C8R \cdot C9L.$$

For the  $\Xi^-$  run, the fields of  $M1$  and  $M2$  were reversed and the same trigger was applied. No distinction was made between the  $\Xi^+$  and  $\Xi^-$  in the reconstruction and polarization analysis. In the following discussions,  $\Xi$  indicates both  $\Xi^-$  and  $\Xi^+$ .

From the measured momenta of the three charged tracks, invariant masses,  $m_{p\pi}$  and  $m_{\Lambda\pi}$ , were calculated under the hypotheses  $\Xi \rightarrow \Lambda\pi$  and  $\Lambda \rightarrow p\pi$ . A good  $\Xi$  candidate was required to have  $m_{p\pi}$  within  $\pm 10$  MeV/ $c^2$  ( $\pm 5\sigma$ ) of the  $\Lambda$  mass,<sup>5</sup> and  $m_{\Lambda\pi}$  within  $\pm 12$  MeV/ $c^2$  ( $\pm 5\sigma$ ) of the  $\Xi$  mass after constraining  $m_{p\pi}$  to the  $\Lambda$  mass. The reconstructed momentum of the  $\Xi$  was required to trace back to within 5.5 mm of the target center to eliminate collimator-produced background. At this stage,  $K^+ \rightarrow \pi^+\pi^+\pi^-$  decays were the dominant background of the  $\Xi^+$  sample; the contamination of  $\Omega^-$  and  $K^-$  decays in the  $\Xi^-$  sample was negligible. All  $K^+$  background events were eliminated by requiring  $m_{3\pi}$ , reconstructed under the  $K^+ \rightarrow 3\pi$  hypothesis, to be greater than 510 MeV/ $c^2$ . This cut also removed about 0.5% of the real  $\Xi^+$ 's. After all software cuts, which were the same for  $\Xi^+$  and  $\Xi^-$ , the backgrounds were estimated to be less than 1%. Figure 2 shows the reconstructed masses of 70 000  $\Xi^+$ 's and 122 000  $\Xi^-$ 's before applying the  $m_{\Lambda\pi}$  cut.

The polarization vector of the daughter  $\Lambda$ ,  $\mathbf{P}_\Lambda$ , in the  $\Lambda$  rest frame can be related to that of the parent  $\Xi$ ,  $\mathbf{P}_\Xi$ , in the  $\Xi$  rest frame as follows:<sup>6</sup>

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

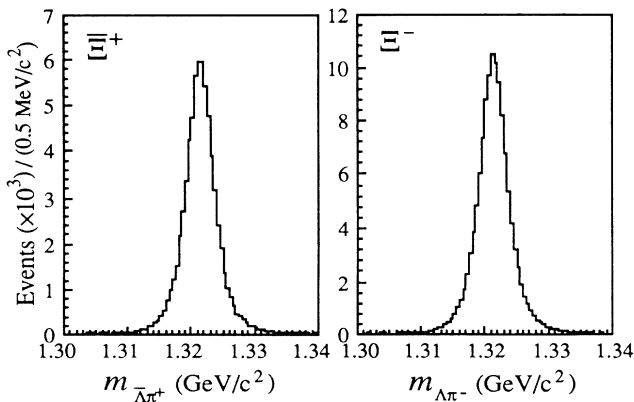


FIG. 2.  $\Lambda\pi$  invariant-mass distributions of the  $\Xi^+$  and  $\Xi^-$  samples after all software cuts except the  $m_{\Lambda\pi}$  cut.

where  $\hat{\Lambda}$  is the unit vector along the  $\Lambda$  momentum in the  $\Xi$  rest frame,  $\alpha_\Xi = -0.456 \pm 0.014$ ,  $\gamma_\Xi = 0.890 \pm 0.007$ , and  $\beta_\Xi$  was taken to be zero.<sup>5</sup> The distribution of the protons in the  $\Lambda$  rest frame with respect to a coordinate axis  $i$  ( $x$ ,  $y$ , or  $z$ ), parallel to the corresponding laboratory axis, has the form

$$I(\theta_i) = \frac{1}{2} (1 + \alpha_\Lambda P_{\Lambda_i} \cos\theta_i), \quad (2)$$

where  $\alpha_\Lambda = 0.642 \pm 0.013$ ,<sup>5</sup>  $\cos\theta_i$  is the direction cosine of the proton, and  $P_{\Lambda_i}$  is given in Eq. (1).

The distribution of the protons as a function of  $\cos\theta$ , as given in Eq. (2), was modified by the acceptance and the resolution of the apparatus. In Figs. 3(a) and 3(b) we compare the observed  $\cos\theta_x$  distributions for positive and negative production angles for both  $\Xi^+$  and  $\Xi^-$  decays. In this figure, the positive-angle data were normalized to the negative-angle data. There were 32 000 (38 000)  $\Xi^+$ 's and 62 000 (60 000)  $\Xi^-$ 's for the positive (negative) angle in our data samples. The differences in the  $\cos\theta_x$  distributions between the two angles show an unambiguous polarization signal for both  $\Xi^+$  and  $\Xi^-$ . As a check, 42 000 (48 000)  $K^+ \rightarrow \pi^+\pi^+\pi^-$  events for the positive (negative) production angle, collected concurrently with the  $\Xi^+$ 's, were reconstructed with the  $\pi^-$  and a randomly chosen  $\pi^+$  to form a "particle,"  $Q$ . The  $\cos\theta_x$  distributions of the  $\pi^-$  in the  $Q$  rest frame are shown in Fig. 3(c). As expected, no difference was observed between the angles since  $K^+$  is a spin-0 particle.

A Monte Carlo technique based on the measured kinematic quantities of each event was used to generate isotropic  $\Lambda$  decays to unfold the acceptance from the asymmetries of the proton distributions.<sup>7</sup> The asymmetry measured in this way consists of two parts: the real polarization signal and the bias. The bias was due to difficulties in reconstructing narrow-opening-angle events that were not totally reproduced in the Monte Carlo simulation. Thus the bias was independent of the production angle. The measured asymmetries  $A_i$  can be written as

$$A_i(\pm) = \pm \alpha_\Lambda P_{\Lambda_i} + B_i \approx \pm \alpha_\Lambda \gamma_\Xi P_{\Xi_i} + B_i, \quad (3)$$

where  $B_i$  is the bias and  $(\pm)$  refers to the positive and negative production angles.<sup>8</sup> The sum of the asymmetries gives the bias. If the difference of the measured asymmetries is taken, the bias term drops out and the polarization signal can be extracted. The measured biases for the full sample were  $B_x = 0.009 \pm 0.007$  ( $0.013 \pm 0.005$ ),  $B_y = 0.001 \pm 0.007$  ( $0.002 \pm 0.005$ ), and  $B_z = 0.030 \pm 0.008$  ( $0.026 \pm 0.006$ ) for the  $\Xi^+$  ( $\Xi^-$ ). The average  $y$  component of the polarization for the  $\Xi^+$  ( $\Xi^-$ ) was  $-0.016 \pm 0.011$  ( $0.005 \pm 0.009$ ) which is consistent with zero as required by parity conservation.

With these polarized samples of  $\Xi$ 's, we measured the magnetic moments  $\mu_\Xi$ . The precession angle of the polarization in  $M1$ ,  $\phi$ , relative to the  $\Xi$  momentum is given

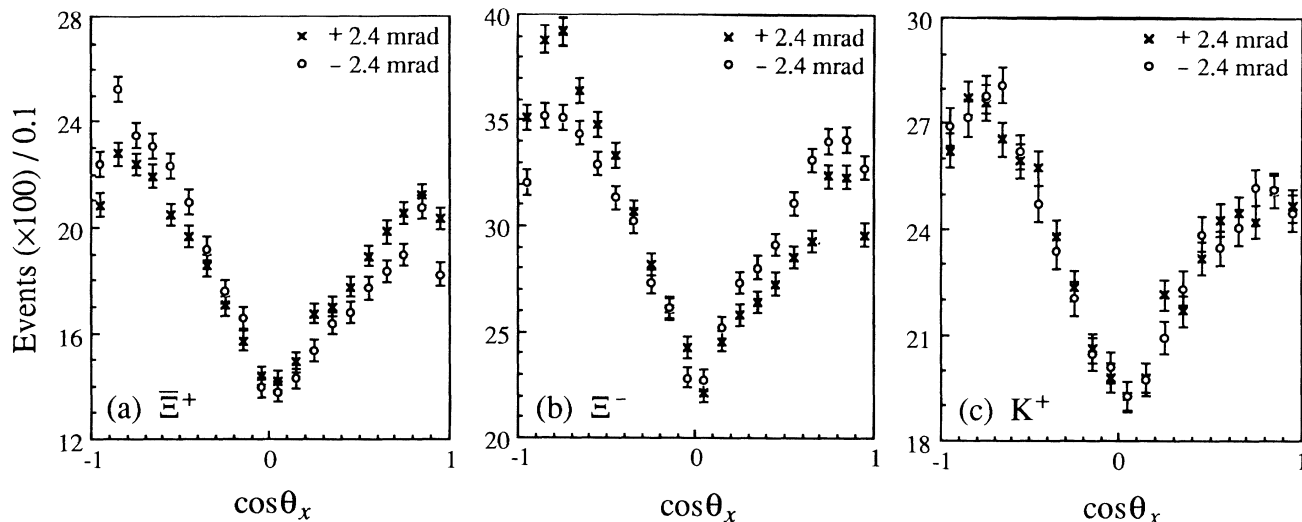


FIG. 3. Comparison of  $\cos\theta_x$  distributions for positive and negative production angles for (a)  $\bar{p}$  from  $\Xi^+$ , (b)  $p$  from  $\Xi^-$ , and (c)  $\pi^-$  from  $K^+$  decay. Note that these figures have a suppressed zero in order to emphasize the difference between the two angles.

by

$$\phi = \frac{2}{\beta} \left[ \mu_{\Xi} - \frac{q_{\Xi}}{2m_{\Xi}c} \right] \int B dl, \quad (4)$$

where  $q_{\Xi}$  and  $m_{\Xi}$  are the charge and mass of the  $\Xi$ , respectively, and  $\beta = v/c \approx 1$  in this experiment. From the measured asymmetries, the magnetic moment and the polarization at the target were calculated by a least-squares method.<sup>9</sup> The fit of the  $\Xi^+$  ( $\Xi^-$ ) data gave a  $\chi^2$  of 3.6 (1.3) for 2 degrees of freedom. Table I gives the fitted asymmetry,  $\alpha_{\Lambda\gamma\Xi}P_{\Xi}$ , and the polarization of  $\Xi^+$  and  $\Xi^-$  at the target as a function of momentum. Both  $\Xi^+$  and  $\Xi^-$  have negative polarizations<sup>10</sup> and, within uncertainties, the magnitudes are equal. Figure 4 shows that the polarization of the  $\Xi^-$  is consistent with the previous  $\Xi^-$  results at 400 GeV/c and a production angle of 5 mrad.<sup>2</sup> In general, comparisons must be made by matching both  $x_F$  and  $p_t$ . In this case, events from each data set have essentially the same  $x_F$  at a given  $p_t$  since the production angle of the 400-GeV/c data is almost twice that of the 800-GeV/c data. The  $\Xi^+$  polarization data are also shown in Fig. 4. The magnetic moment of the  $\Xi^-$  was determined to be  $-0.674 \pm 0.021$  nuclear magnetons (n.m.) in agreement with the world average.<sup>5</sup> For the  $\Xi^+$ , the magnetic moment was found to be

$$0.657 \pm 0.028 \text{ n.m.}^{11}$$

Systematic uncertainties in the polarization and  $\mu_{\Xi}$  were estimated by studying the change in the results when software cuts were varied. By far, the largest uncertainty, comparable to the statistical uncertainty, came from varying the cut on the  $\Lambda$  decay angle. We estimated the systematic errors to be 0.01 and 0.02 n.m. for the polarization and  $\mu_{\Xi}$ , respectively.

We have found that  $\Xi^+$ 's produced by 800-GeV/c protons are polarized with an average polarization of  $-0.097 \pm 0.012 \pm 0.009$  at  $\langle x_F \rangle = 0.39$  and  $\langle p_t \rangle = 0.76$  GeV/c. For comparison, the  $\Xi^-$  polarization was measured to be  $-0.102 \pm 0.012 \pm 0.010$  at  $\langle x_F \rangle = 0.41$  and  $\langle p_t \rangle = 0.78$  GeV/c. The near equality of the  $\Xi^+$  and  $\Xi^-$  polarizations calls into question models of hyperon polarization which predict zero polarization for all antihyperons. In addition, the observed  $\Xi^+$  polarization allows us to make the first measurement of the  $\Xi^+$  magnetic moment, and we obtain  $\mu_{\Xi^+} = 0.657 \pm 0.028 \pm 0.020$  nuclear magnetons.

This work was supported in part by the U.S. DOE and the NSF. K.B.L. was partially supported by a DOE Outstanding Junior Investigator award. We would like to thank L. Pondrom for lending wire chambers to this experiment. The support of the Fermilab staff was

TABLE I. The fitted asymmetry  $\alpha_{\Lambda\gamma\Xi}P_{\Xi}$  and polarization of the  $\Xi^+$  and  $\Xi^-$  at target as a function of momentum  $p$ .

$p_{\Xi^+}$ (GeV/c)	$\alpha_{\Lambda\gamma\Xi^+}P_{\Xi^+}$	$P_{\Xi^+}$	$p_{\Xi^-}$ (GeV/c)	$\alpha_{\Lambda\gamma\Xi^-}P_{\Xi^-}$	$P_{\Xi^-}$
277	$0.057 \pm 0.012$	$-0.099 \pm 0.021$	283	$-0.068 \pm 0.009$	$-0.119 \pm 0.015$
312	$0.034 \pm 0.011$	$-0.060 \pm 0.020$	323	$-0.050 \pm 0.008$	$-0.087 \pm 0.015$
357	$0.076 \pm 0.011$	$-0.132 \pm 0.020$	373	$-0.056 \pm 0.009$	$-0.098 \pm 0.015$

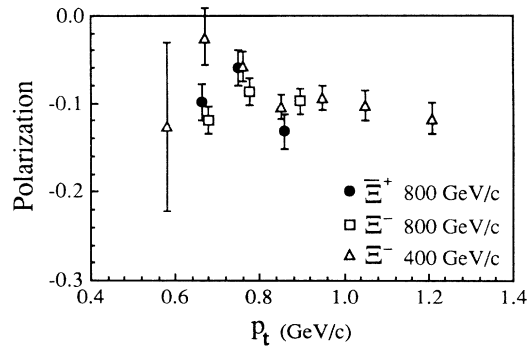


FIG. 4. Comparison of the  $\Xi^+$  and  $\Xi^-$  polarization from this experiment with that of the  $\Xi^-$  data taken at 400 GeV/c and a production angle of 5 mrad. (See Rameika *et al.*, Ref. 2.)

essential to its completion. Important contributions from M. Shupe, K. Thorne, P. Border, M. Groblewski, and G. Eblin are gratefully acknowledged.

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<sup>6</sup>Particle Data Group, M. Aguilar-Benitez *et al.*, Phys. Lett. **170B**, 154 (1986).

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<sup>10</sup>Positive polarization was defined as long  $\mathbf{p}_{\text{beam}} \times \mathbf{p}_{\text{hyperon}}$  at the target.

<sup>11</sup>The precession angle  $\phi$  had an ambiguity of  $m\pi$ , where  $m=0, \pm 1, \dots$ , since it was measured only with one  $\int B dl$ . This ambiguity was resolved by taking the solution which gave  $|\mu_{\Xi^+}|$  closest to  $|\mu_{\Xi^-}|$ , as given in Ref. 5, with  $m=0$ . The other two closest solutions of  $\mu_{\Xi^+}$  were 0.014 and 1.295 n.m.