Polarization and Magnetic Moment of the $\Sigma^+$ Hyperon

C. Wilkinson, (a) R. Handler, B. Lundberg, (b) L. Pondrom, and M. Sheaff

Physics Department, University of Wisconsin, Madison, Wisconsin 53706

P. T. Cox, (c) E. C. Dukes, (d) J. Dworkin, (e) and O. E. Overseth

Department of Physics, University of Michigan, Ann Arbor, Michigan 48109

A. Beretvas, L. Deck, (f) T. Devlin, K. B. Luk, (g) R. Rameika, (g) and R. Whitman (h)

Department of Physics and Astronomy, Rutgers—The State University, Piscataway, New Jersey 08854

and

K. Heller

School of Physics and Astronomy, The University of Minnesota, Minneapolis, Minnesota 55455

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The polarization and magnetic moment of the $\Sigma^+$ hyperon have been measured for $137,300 \Sigma^+ \to p\pi^0$ decays from $\Sigma^+$ produced at 5 mrad by 400-GeV/c protons on Be. The polarization averages 24% in the range 140 to 350 GeV/c and is opposite in sign to that of similarly produced $\Lambda$. The moment is $(2.479 \pm 0.012 \pm 0.022) \mu_N$, where the uncertainties are statistical and systematic, respectively.

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The discovery of hyperon polarization at high energy\(^1\) gives insight into the dynamics of baryon interactions\(^2\) and also furnishes a method for precise measurements of hyperon moments which, in turn, test composite models of baryon structure.\(^3,4\) This Letter reports a new measurement of the $\Sigma^+$ magnetic moment, and the polarization of inclusively produced $\Sigma^+$ hyperons. Our moment differs by more than three standard deviations from a recent measurement of comparable precision.\(^5\)

The polarization of $\Sigma^+$ hyperons was measured by the asymmetry of the angular distribution in $\Sigma^+ \to p\pi^0$. The magnetic moment of the $\Sigma^+$ was determined by precession of the spin in a magnetic field. The experiment was performed in the M2 beam line at Fermilab. The apparatus (Fig. 1) and data taking were described elsewhere.\(^6,7\) The 400-GeV/c proton beam was directed onto a Be target at angles of $\pm 5$ or $\mp 5$ mrad with respect to the $\Sigma^+$ direction. A 5.3-m-long collimator in a 1.24-T downward field defined a 10-mrad curved channel for the $\Sigma^+$ beam. The coordinate system at production has $+\hat{z}$ along the $\Sigma^+$ momentum, $+\hat{y}$ upwards, and $\hat{x} = \hat{y} \times \hat{z}$.

The decay chain $\Sigma^+ \to p\pi^0$, $\pi^0 \to 2\gamma$ was detected by a wire-chamber spectrometer and a lead-glass array (PbG). The trigger required a charged particle in the spectrometer ($S_1 - C_4 - PC$), and at least one $\gamma$ in the lead glass ($T$-PbG). Two radiation lengths of lead were placed before $C_5$ above and below the M3 aperture to shower wide-angle $\gamma$'s for position determination in $C_5$.

Event categories were based on the amount of information present. Gamma categories were events with only one $\gamma$ in PbG and the other undetected, one $\gamma$ in PbG and position data on the other in $C_5$, or both $\gamma$'s in PbG. Charged-track data fell in two categories: 60% were "kink" events where a decay vertex to constrain the reconstruction was found between $C_1$ and $C_3$ by tracking data, and 40% were "nonkink" events where it was determined only by kinematic reconstruction. Reconstructable events were of five types: kink events with any of the three $\gamma$ categories, and nonkink events with two $\gamma$'s detected. Typical $\Sigma^+$ momentum and vertex position resolutions for all event types were $\Delta p/p = 7\%$ and $\Delta z = 1$ m. The typical laboratory decay angle was $\sim 1$ mrad, with a resolution of 0.25 mrad. The $p\pi^0$ invariant-mass plot from charged-track data alone ($\Sigma^+$ and $p$ momenta) gave a $\Sigma^+$ mass with 60 MeV/c\(^2\) FWHM.\(^6,7\) The actual event reconstruction was done by

![FIG. 1. Plan view of the detector in the bend plane of precession magnet M2. Magnet M1 brought the incident proton beam to the target at angles of $\pm 5$ mrad in the $y$ direction. The spectrometer consisted of drift chambers DC1–DC3, multiwire proportional chambers $C_1$–$C_5$, and scintillator counters $S_1$–$S_2$, $T$, and PC. $\gamma$ rays were detected by a lead-glass array and lead-scintillator sandwiches on $C_5$ and $C_5$. A 10 $\times$ 30 cm\(^2\) hole in the glass array, offset from the spectrometer center line, allowed the protons to pass through the array. (Not to scale.)](image-url)
a fit to the charged-track and PbG data, constrained by target and collimator positions and the \( \Sigma^+ \) and \( \pi^0 \) masses. Monte Carlo (MC) estimates of background were 0.3% from beam tracks with accidents in PbG, 0.2% from \( K^+ \to \pi^+ \pi \), and 0.1% from \( \Sigma^+ \to n \pi^+ \). The contribution to the \( \Sigma^+ \) polarization and moment from these sources was negligible.

Momentum vectors from the fit gave the following direction cosines of the daughter proton in the \( \Sigma^+ \) rest frame: \( \hat{z} \) along the laboratory \( \Sigma^+ \) momentum, \( \hat{y} \) upward in the vertical plane, and \( \hat{x} = \hat{y} \times \hat{z} \) horizontal. The cosine distribution along each coordinate axis \( j = x, y, z \) is given by

\[
\alpha_j = \frac{R_j^{(p, \cos \theta_{ij})} - R_j^{(p, \cos \theta_{ij})}}{R_j^{(p, \cos \theta_{ij})} + R_j^{(p, \cos \theta_{ij})}}
\]

on the assumption that \( A_j^+ = A_j^- \).

The polarization \( \alpha_j \) was calculated for each momentum and direction \( (j) \) by fitting of a straight line to the twenty \( \cos \theta_{ij} \) data points. Fitted values are given in Table I, and plots of the ratios in Eq. (2) for all momenta combined are shown in Fig. 2. The momentum averages of the three components are \( P_x = -0.219 \pm 0.004 \), \( P_y = 0.002 \pm 0.004 \), and \( P_z = 0.090 \pm 0.006 \).

Differences between \( A_j^+ \) and \( A_j^- \) were caused by the offset hole in the lead-glass array. Because the polarization asymmetry was large and mostly in the \( x \) direction, on average \( \gamma \)'s from \( \pm 5 \mathrm{mrad} \) data were directed toward the hole, while those \( \gamma \)'s from \( \pm 5 \mathrm{mrad} \) data were directed away from the hole, producing an overall 2% difference in acceptance. A slight left-to-right shift in the \( \Sigma^+ \) beam direction from \( \pm 5 \) to \( \pm 5 \mathrm{mrad} \) contribut-

| \( \Sigma^+ \) Momentum (GeV/c) | \( \alpha_x P_x \) | \( \alpha_y P_y \) | \( \alpha_z P_z \) | \( |P| \) | \( \mu_{\Sigma^+}/\mu_N \) |
|---|---|---|---|---|---|
| 140–160 | 0.131 ± 0.021 | 0.042 ± 0.025 | 0.001 ± 0.022 | 0.133 ± 0.023 | 2.285 ± 0.081 |
| 160–180 | 0.160 ± 0.011 | 0.011 ± 0.013 | 0.006 ± 0.013 | 0.176 ± 0.012 | 2.471 ± 0.035 |
| 180–200 | 0.171 ± 0.091 | 0.013 ± 0.010 | 0.005 ± 0.011 | 0.183 ± 0.010 | 2.431 ± 0.029 |
| 200–220 | 0.216 ± 0.009 | 0.010 ± 0.009 | 0.005 ± 0.010 | 0.232 ± 0.010 | 2.437 ± 0.024 |
| 220–240 | 0.253 ± 0.011 | 0.012 ± 0.011 | 0.010 ± 0.014 | 0.279 ± 0.012 | 2.475 ± 0.023 |
| 240–260 | 0.279 ± 0.013 | 0.039 ± 0.013 | 0.129 ± 0.018 | 0.316 ± 0.015 | 2.496 ± 0.027 |
| 260–280 | 0.309 ± 0.018 | 0.052 ± 0.025 | 0.150 ± 0.025 | 0.354 ± 0.020 | 2.514 ± 0.033 |
| 280–300 | 0.337 ± 0.028 | 0.043 ± 0.026 | 0.153 ± 0.036 | 0.288 ± 0.030 | 2.563 ± 0.058 |
| 300–350 | 0.373 ± 0.037 | 0.071 ± 0.035 | 0.143 ± 0.047 | 0.315 ± 0.039 | 2.519 ± 0.069 |

All event types

140–350 Kink tracks, \( \gamma \) in PbG 0.230 ± 0.009 2.472 ± 0.023
140–350 Kink tracks, 2 \( \gamma \)'s in PbG 0.232 ± 0.011 2.486 ± 0.038
140–350 Kink tracks, 1 \( \gamma \) in PbG, 1 \( \gamma \) in C 0.217 ± 0.016 2.450 ± 0.055
140–350 No observed kink, 2 \( \gamma \)'s in PbG 0.245 ± 0.009 2.426 ± 0.027
140–350 No observed kink, 1 \( \gamma \) in PbG, 1 \( \gamma \) in C 0.239 ± 0.012 2.464 ± 0.034
140–350 All events 0.237 ± 0.005 2.479 ± 0.012
The fitted precession angle was \((201.5 \pm 1.3)\)° with \(\chi^2/\text{dof} = 13/8\). Values of \(P_k\) are given in Table I and Fig. 3. Also in Table I are the momenta from analyses of single momentum bins. While the lowest momentum bin deviates from the combined result, dropping of it makes no significant change.

The uncorrected magnetic moment calculated from the precession angle by Eq. (3) for the full data sample is \((2.469 \pm 0.011)\mu_N\). It was also calculated for the five individual event types, and these uncorrected results deviated from that of the combined sample significantly (worst case \(0.083 \pm 0.035\)) with \(\chi^2/\text{dof} = 22/4\). The same analysis of a MC sample seven times larger showed deviations by event type nearly identical to the data. MC analysis established that these effects arose from the differences in the acceptance between \(+5\) and \(-5\) mrad mentioned above. Deviations of MC results from the input value \((2.469\mu_N)\) were used to correct the data. Corrected values for the five event types agreed with the corrected value for the full analysis, \(\chi^2/\text{dof} = 4.4/4\). The correction raised the result by \((0.010 \pm 0.004)\mu_N\) to \(\mu_{x+} = (2.479 \pm 0.012)\mu_N\).

To study systematic effects, the analysis procedure was varied. The three subsets with kinked events (60\% of the total) yielded \((2.482 \pm 0.017)\mu_N\), whereas the same events, reconstructed without the \(\gamma\)-ray data (a one-constraint fit) yielded a value \((0.022)\mu_N\) higher. All other studies of systematic uncertainties, e.g., variation of cuts, yielded smaller changes. Therefore, we assign a systematic uncertainty to our result of \((0.022)\mu_N\). The final result is \(\mu_{x+} = (2.479 \pm 0.012 \pm 0.022)\mu_N\), where the quoted uncertainties are statistical and systematic, respectively.

The measurement reported in Ref. 5, \(\mu_{x+} = (2.38 \pm 0.014 \pm 0.014)\mu_N\) differs by \((0.10 \pm 0.03)\mu_N\) from the result given here. The larger magnetic field of Ref. 5 and the larger number of events in the present result account for the similar uncertainties. The background quoted for Ref. 5 (<10\%) is higher than in our sample. Reference 5 used only charged-track information (a one-constraint fit for \(\Sigma^+\) reconstruction). A similar analysis of a subsample of our data (see above) actually enhances the discrepancy slightly. We feel that our result is strengthened by the good agreement among five different event topologies, but we find no significant defects in either experiment and believe that only new measurements with several values of the precession field in a single setup will resolve the difference.

Our result differs by \(0.19\mu_N\) from the simple quark-model prediction of \(2.67\mu_N\). Similar disagreements are seen for \(\Xi^-\) and \(\Xi^0\). Several attempts have been made to improve the agreement through refinements to
the simple models, but there is as yet no satisfactory model which predicts all the baryon magnetic moments within measurement errors.  

The polarization versus momentum is shown in Fig. 3, along with the results for \( \Lambda \), \( \Xi^0 \), \( \Xi^- \), and \( \Sigma^- \) at \( 5 \text{ mrad} \) and for \( \Sigma^- \) at \( 7.5 \text{ mrad} \). The magnitudes and signs of the hyperon polarizations follow the approximate relationship \( P_\Lambda \approx P_{\Xi^0} \approx P_{\Xi^-} \approx -P_{\Sigma^+} \approx -P_{\Sigma^-} \). The mean value of the \( \Sigma^+ \) polarization over the momentum range is \( 0.234 \pm 0.005 \). The transverse momentum is \( 0.7 < p_t < 1.75 \text{ GeV/c} \) and Feynman \( x \) is \( 0.35 < x_F < 0.88 \). The sign difference between \( \Lambda \) and \( \Sigma^+ \) polarization is predicted by the simple quark model and was first reported for a subset of these data. Our polarization data and those of Ref. 5 are consistent.

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\( ^{(a)} \)Present address: MP-4, MS-H846, Los Alamos National Laboratory, Box 1663, Los Alamos, NM 87545.

\( ^{(b)} \)Present address: Physics Department, Ohio State University, Columbus, OH 43210.

\( ^{(c)} \)Present address: Physics Department, Rockefeller University, New York, NY 10021; mailing address: CERN, CH-1211, Geneva 23, Switzerland.

\( ^{(d)} \)Present address: CERN, CH-1211, Geneva 23, Switzerland.

\( ^{(e)} \)Present address: Fonar Corp., Melville, NY 11747.

\( ^{(f)} \)Present address: Honeywell Corp., MN38-1500, 10400 Yellow Circle Dr., Minnetonka, MN 55343.

\( ^{(g)} \)Present address: Fermilab, P.O. Box 500, Batavia, IL 60510.

\( ^{(h)} \)Present address: W. W. Gaertner Research, Inc., 30 Buxton Farm Rd., Stamford, CT 06905.


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\( ^{(q)} \)This supersedes a preliminary result quoted by R. Handler et al., in High Energy Spin Physics—1982, edited by G. Bunce, AIP Conference Proceedings No. 95 (American Institute of Physics, New York, 1983), p. 58. The earlier result was uncorrected for background and biases.


