Measurement of the Σ^- Magnetic Moment Using the $\Sigma^- \to ne^-\bar{\nu}$ and $\Sigma^- \to n\pi^-$ Decay Modes

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(Received 23 June 1986)

We have used the spin-precession technique to measure the Σ^- magnetic moment (μ_Σ). A Σ^- beam with a polarization of 22% was produced by a 400-GeV proton beam striking a Cu target at nominal production angles of ±3 mrad. We simultaneously recorded 21 000 $\Sigma^- \to ne^-\bar{\nu}$ decays and 650 000 $\Sigma^- \to n\pi^-$ decays at Σ^- beam momenta of 253 and 308 GeV/*c*. We find $\mu_\Sigma = -1.166 \pm 0.014 \pm 0.010$ nuclear magnetons, where the quoted errors are statistical and systematic, respectively.

PACS numbers: 13.40.Fn, 13.30.–a, 14.20.Jn

The magnetic moments of the spin-$\frac{1}{2}$ baryon octet provide a probe of the baryons' internal structure.[1-12] Quark wave functions have been modeled by corrections to the nonrelativistic SU(6) quark model[3,4,6-11] and within the framework of the relativistic bag model.[2,5,12] The weak decay of the hyperons in the octet (save the Σ^0) makes their magnetic moments accessible to the spin-precession method.[13] The polarization vector of a hyperon beam polarized normal to a magnetic field is precessed through an angle determined by the magnetic moment and the field integral. The polarization vector is analyzed with the hyperon-decay asymmetry.

The previous measurements by Deck *et al.* [$\mu_\Sigma = (-0.89 \pm 0.14)\mu_N$, where μ_N is the nuclear magneton][14] and Wah *et al.* [$\mu_\Sigma = (-1.23 \pm 0.04)\mu_N$][15] were performed with the spin-precession method by use of the hadronic $\Sigma^- \to n\pi^-$ decay mode. The measurement of μ_Σ from the decay $\Sigma^- \to n\pi^-$ is difficult because of the small asymmetry parameter ($\alpha_\pi = 0.068 \pm 0.008$).[16] We report a new measurement from a sample of 21 000 beta decays: $\Sigma^- \to ne^-\bar{\nu}$. The electron asymmetry parameter is much larger ($\alpha_e = -0.53 \pm 0.14$),[17] compensating for the small branching ratio (1.02×10^{-3}).[16] We also obtain a value from 650 000 hadronic decays.

The apparatus[17,18] is shown in Fig. 1. A 400-GeV proton beam from the Fermilab Tevatron was directed onto a Cu target placed in the upstream portion of the hyperon magnet. A curved channel through the hyperon magnet selected by momentum a negative beam composed at the channel exit of approximately 87% π^-, 10% Σ^-, and the rest K^-, Ξ^-, $\bar{p}$, and e^-. The selected momenta were 253 GeV/*c* (17.6 T m) and 308 GeV/*c* (21.4 T m) at nominal production angles of +3 or −3 mrad. The beam emerging from the hyperon magnet was limited to 1 μsr with a momentum spread of $\Delta p/p = 7\%$. The allowed (parity-conserving)

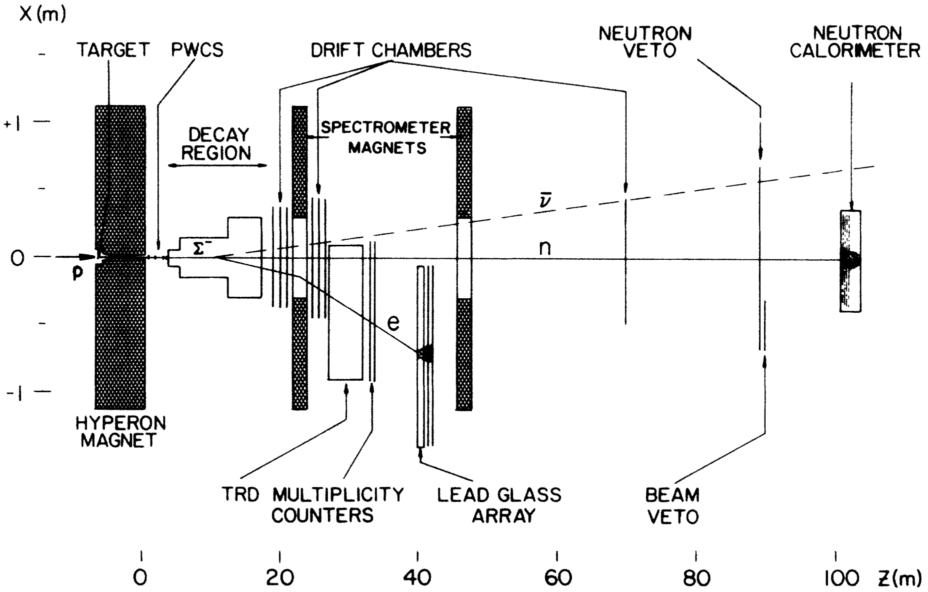

FIG. 1. Plan view of the apparatus. Note that the horizontal scale is compressed. Typical particle trajectories are shown.

polarization component is normal to the production plane defined by the proton and Σ^- momenta. We have previously reported[17] a Σ^- polarization of $(22 \pm 4)\%$ in the direction given by $\mathbf{p}_{\text{proton}} \times \mathbf{p}_{\Sigma^-}$. This polarization is along the positive x axis for $+3$ mrad, where our coordinate system is defined with y in the vertical direction (opposite to the field in the hyperon magnet), z along the beam axis, and x oriented to yield a right-handed system. Note that the polarization changes sign when the production angle is reversed.

The $\Sigma \rightarrow n\pi^-$ trigger required an incident particle defined by beam scintillation counters in the proportional-wire-chamber (PWC) region and the detection of a neutral particle in the neutron calorimeter. The $\Sigma^- \rightarrow ne^-\bar{\nu}$ trigger required in addition the detection of an electron in the transition-radiation detector (TRD)[19] and a selection on the pulse heights of four scintillators (multiplicity counters) to reject hadronic showers initiated in the TRD.

The field integrals in the hyperon magnet and in the magnet spectrometer are determined by the requirement that the Σ^- mass reconstructed from the $\Sigma^- \rightarrow n\pi^-$ decay be independent of the angle between the z axis and the π^- momentum in the Σ^- rest frame. We determine the field integral of the hyperon magnet to within $\pm 1\%$; our error reflects the uncertainty of the Σ^- production point in the target.

Σ^--decay candidates were required to have a single track in the PWC's and drift chambers. The decay vertex was restricted to an evacuated 12-m fiducial region immediately downstream of the PWC's.

Hadronic decays were identified by the requirement that the π^- momentum in the Σ^- rest frame be near its expected value of 193 MeV/c [Fig. 2(a)]. This suppressed the $\Xi^- \rightarrow \Lambda\pi^-$ background, estimated to be 2% in the final event sample. Expanding the cut to double the background produced no significant change in the μ_Σ result.

The TRD and a lead-glass calorimeter (LGC) separated the $\Sigma^- \rightarrow ne^-\bar{\nu}$ from the $\Sigma^- n\pi^-$ background. Σ^--decay electrons were restricted to the fiducial area

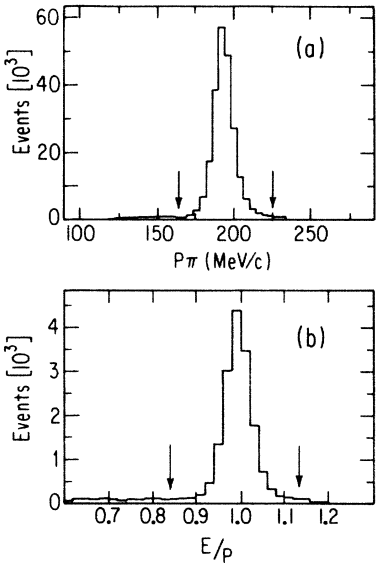

FIG. 2. (a) The π^- momentum (P_π) distribution in the Σ^- rest frame for the 253-GeV/c $\Sigma^- \rightarrow n\pi^-$. We accept events between the arrows in the region $0.164 < P_\pi < 0.225$ GeV/c. (b) The E/P distribution for the 253-GeV/c $\Sigma^- \rightarrow ne^-\bar{\nu}$. We accept events between the arrows in the region $0.84 < E/P < 1.14$.

of the LGC by the requirement that the electron momentum be between 12.5 and 50 GeV/c. The overall beta-decay efficiency was 93%; hadronic decays were suppressed by 50 000. We included selection criteria based upon the shower development in the LGC and the requirement that the energy E measured by the LGC agree with the momentum P determined by the magnet spectrometer. The distribution in E/P is shown in Fig. 2(b) for the final beta decay sample. Examination of the tails of the distribution indicates a 4% background from Σ^- and Ξ^- hadronic decays. Expanding the E/P cut to triple this background did not produce a significant change in the μ_Σ result.

The angular distribution of any daughter particle in the Σ^- rest frame is

$$dN/d(\cos\theta_\zeta) = A(\cos\theta_\zeta)[1+\alpha P_\zeta \cos\theta_\zeta], \qquad (1)$$

where $A(\cos\theta_\zeta)$ is the acceptance, P_ζ is the ζ component of polarization, and θ_ζ is the angle between the daughter particle momentum and the ζ axis.

To extract the precession angle θ_p, we determine the orientation of the polarization vector in the horizontal plane after the beam has exited from the hyperon magnet. We calculate the fraction of events for each $\cos\theta_\zeta$ bin for $\zeta = x$, y, or z. We then form the quantity $(F_\zeta^+ - F_\zeta^-)/(F_\zeta^+ + F_\zeta^-) = \alpha P_\zeta \cos\theta_\zeta$, where $F_\zeta^{+(-)}$ is the fraction of events in the $\cos\theta_\zeta$ bin with an initial polarization vector parallel (+) or antiparallel (−) to the x axis. This procedure cancels false asymmetries due to our instrumental acceptance. The precession angle depends upon the anomalous magnetic moment of the Σ^-:

$$\theta_p = \gamma\Phi_B(g/2-1), \qquad (2)$$

where γ is the Lorentz factor of the Σ^- corresponding to the momentum of the central trajectory in the hyperon magnet, and Φ_B is the bend angle of the magnet. The Σ^- magnetic moment is

$$\mu_\Sigma = (gm_p/2m_\Sigma)\mu_N. \qquad (3)$$

Quantities which characterize the Σ^- trajectory in the x-z plane (momentum and azimuth angle) have well-matched distributions for both production angles. The distributions for the dip angle are less well matched because of the dependence of Σ^- production on transverse momentum. We have weighted the data by the dip angle to improve the agreement. The result is insensitive to the weighting procedure.

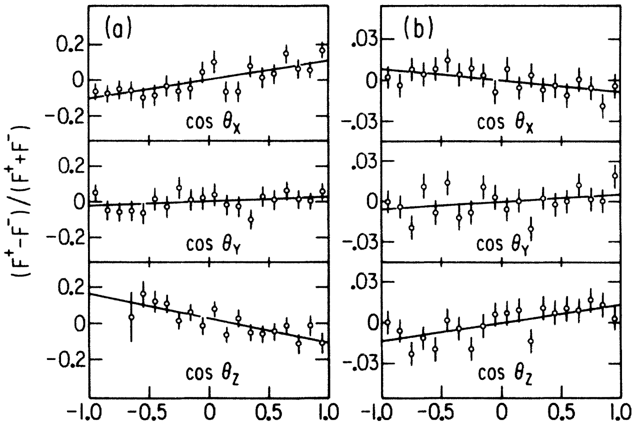

FIG. 3. Graph of $(F_\zeta^+ - F_\zeta^-)/(F_\zeta^+ + F_\zeta^-)$ vs $\cos\theta_\zeta$ for $\zeta = x$, y, and z for (a) 253-GeV/c $\Sigma^- \to ne^-\bar{\nu}$ and (b) 253-GeV/c $\Sigma^- \to n\pi^-$. Note that the slopes have opposite signs for the two decay modes because the asymmetry parameters α_e and α_π have opposite signs. Note also the different vertical scales.

The decay angular distribution has been analyzed for four independent data sets: 253-GeV/c $\Sigma^- \to ne^-\bar{\nu}$ (15 000 events), 308-GeV/c $\Sigma^- \to ne^-\bar{\nu}$ (6000 events), 253-GeV/c $\Sigma^- \to n\pi^-$ (310 000 events), and 308-GeV/c $\Sigma^- \to n\pi^-$ (340 000 events). Figure 3 shows the projected distributions for the 253-GeV/c data. The asymmetries and μ_Σ values from all four data sets are given in Table I. These asymmetries are in agreement with our earlier results for Σ^- particles polarized in the y direction.[17] The twelve χ^2 values associated with the fits to the four data sets have an average value of 19.3 for 18 degrees of freedom. We expect and find no component of polarization along the y axis.

The μ_Σ values in Table I are calculated with the assumption that $0 < \theta_p < 2\pi$. The $2n\pi$ ambiguity and the ambiguity in the sense of precession may be eliminated by use of the information at both beam energies (see Fig. 4) and by the demand of modest agreement (within 10σ) with the measurement of Hertzog *et al.*[20]

TABLE I. Components of asymmetry, Σ^- magnetic moment in nuclear magnetons, and sample size for each data set.

	αP_x	αP_y	αP_z	μ_Σ	Events
		$\Sigma^- \to ne^-\bar{\nu}$			
253 GeV/c	0.077 ±0.015	0.018 ±0.014	−0.103 ±0.022	−1.178 ±0.024	15 000
308 GeV/c	0.177 ±0.023	0.019 ±0.023	−0.099 ±0.034	−1.140 ±0.028	6000
		$\Sigma^- \to n\pi^-$			
253 GeV/c	−0.0084 ±0.0034	0.0057 ±0.0034	0.0137 ±0.0034	−1.161 ±0.038	310 000
308 GeV/c	−0.0166 ±0.0034	0.0027 ±0.0034	0.0077 ±0.0034	−1.179 ±0.027	350 000

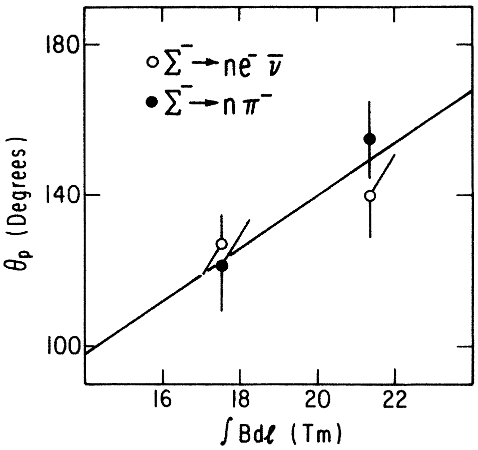

FIG. 4. The precession angle (θ_p) vs the field integral ($\int Bdl$) in the hyperon magnet for the two Σ^- decay modes. The line shows the expected dependence for $\mu_\Sigma = -1.166\mu_N$. Note the suppressed zero.

using the hyperfine x-ray splitting in Σ^- atoms. Hertzog *et al.*'s measurement $[\mu_\Sigma = (-1.111 \pm 0.033)\mu_N]$ involves ambiguities which differ from those in the spin precession technique.

We have considered systematic errors from the following sources: chamber alignment, uncertainty in the field integrals of the hyperon and spectrometer magnets, polarized background from $\Xi^- \to \Lambda\pi^-$ and $\Xi^- \to \Lambda e^-\bar{\nu}$ decays, bremsstrahlung of the electron from $\Sigma^- \to ne^-\bar{\nu}$ decay, stability of the result as the selection criteria are varied, and sensitivity of the result to the beam phase space. The systematic error from each of these sources is significantly less than the statistical error for each of the four measurements.

Our combined result for all four data sets is $(-1.166 \pm 0.014 \pm 0.010)\mu_N$, where the quoted errors are statistical and systematic, respectively. An important feature of this experiment is that the magnetic moments obtained from the beta decays and the hadronic decays agree. The beta decays are subject to potential biases in the electron identification while the hadronic decays are sensitive to small geometric biases. The agreement between the two decay modes gives a valuable check on the systematic errors.

We thank the staff of Fermilab for their assistance. This work was supported in part by the U. S. Department of Energy under Contracts No. DE-AC02-80ER10587, No. DE-AC02-76CH0300, and No. DE-AC02-76ER03075, and by the U.S.S.R. Academy of Sciences. This report is submitted in partial fulfillment of the requirements for a Ph.D. degree in physics at the University of Chicago for one of us (G.Z.).

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