Measurement of the Magnetic Moments of the Σ^+ and $\bar{\Sigma}^-$ Hyperons

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We have measured the magnetic moments of the Σ^+ and $\bar{\Sigma}^-$ hyperons produced by 800-GeV protons incident on a Cu target. We determine the Σ^+ magnetic moment to be $(2.4613 \pm 0.0034 \pm 0.0040)\mu_N$ where the uncertainties are statistical and systematic, respectively. In this first measurement we determine the magnetic moment of the $\bar{\Sigma}^-$ to be $-(2.428 \pm 0.036 \pm 0.007)\mu_N$. The magnetic moments of the Σ^+ and $\bar{\Sigma}^-$ are consistent with each other in magnitude but opposite in sign as required by *CPT* invariance.

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High energy proton nucleus interactions have provided us with flexible and copious sources of polarized hyperons and antihyperons [1,2]. These polarized beams have made possible precise measurements of hyperon magnetic moments which offer insights into the quark structure of the baryons.

In a previous publication [3] we have shown that both the Σ^+ and $\bar{\Sigma}^-$ are produced with significant polarizations. Here we present measurements of the Σ^+ and $\bar{\Sigma}^-$ magnetic moments. These measurements [4] were performed as part of Fermilab experiment E761 whose primary goal was the measurement of the asymmetry parameter [5] in the weak radiative decay $\Sigma^+ \to p\gamma$.

The configuration and experimental resolutions are the same as in the polarization [3] and asymmetry parameter measurements [5]. The full experimental configuration is shown in those publications. We show an expanded view of part of the E761 apparatus (Fig. 1) emphasizing those aspects of particular relevance to these magnetic moment measurements.

Protons of 800 GeV/c were steered and focused onto the hyperon production target. The charged hyperon beam originated from a one interaction length Cu target in the upstream end of a 7.3-m-long hyperon magnet (HM1 in Fig. 1) which deflected and collimated the 375-GeV/c hyperon beam. Dipole magnets upstream of

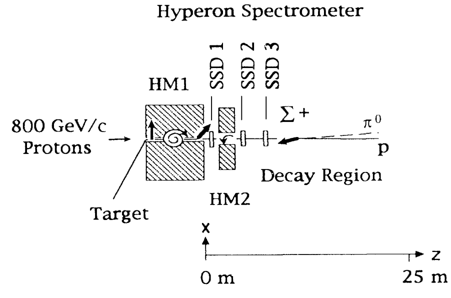

FIG. 1. Plan view of the apparatus showing the incident proton beam and hyperon spectrometer. Depicted are the precession angles in HM1 and HM2. The bold arrows indicate the spin directions of the Σ^+.

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TABLE I. Measured Σ^+ and $\bar{\Sigma}^-$ decay asymmetries.

Particle	⟨Angle⟩ (mrad)	Events	Asymmetries A_x	A_y	A_z	ξ (rad)
$\bar{\Sigma}^-$	± 2.9	11 806	-0.0191 ± 0.0166	-0.0227 ± 0.0167	-0.0678 ± 0.0171	-10.72 ± 0.24
Σ^+	± 2.9	249 863	0.0094 ± 0.0036	-0.0055 ± 0.0036	0.1598 ± 0.0037	-10.937 ± 0.022

the target (not shown in Fig. 1) could vary the targeting angle over the range $\approx \pm 5$ mrad in either the horizontal (xz) or vertical (yz) plane. This allowed the hyperons to be produced, in a controlled manner, with polarization directions either parallel or perpendicular to the vertical (y) magnetic field of the hyperon magnet. These two conditions correspond to no hyperon spin precession or maximal spin precession, respectively, in the magnets. The currents in all of the magnets shown in Fig. 1 could be reversed thus allowing selection of a positive or negative beam containing Σ^+ or $\bar{\Sigma}^-$, respectively.

The data collected for these magnetic moment measurements were produced with the targeting angle in the vertical plane. Parity conservation in the hyperon production process requires that any produced polarization be perpendicular to the production plane. Thus the hyperon polarization was perpendicular to the vertical magnetic field of the hyperon magnet (HM1) allowing for maximum spin precession in the hyperon magnet. The beam traversed a second magnet (HM2) where the magnetic field was also in the vertical direction but opposite in sign to HM1. Thus the spin precession caused by HM1 is partially canceled by HM2. This experimental configuration of magnets was dictated by the requirements of another measurement [5] and is not optimized for these magnetic moment measurements.

This study used the $\Sigma^+ \to p\pi^0$ ($\bar{\Sigma}^- \to \bar{p}\pi^0$) decay mode (52% branching fraction [6]) for analysis of the Σ^+ ($\bar{\Sigma}^-$) magnetic moment. The detection apparatus consisted of a hyperon spectrometer to measure the hyperon momentum, a baryon spectrometer to measure the p ($\bar{p}$) momentum, and a photon spectrometer to detect the photon decay products of the π^0. There was a 76×76 mm^2 hole in the photon spectrometer to allow passage of the baryon and undecayed beam. This angular region was covered by a downstream lead glass array. These spectrometers, trigger, and the data selection process have been described in previous publications [3,5]. Since the data sample presented here is part of the same sample [3] used to measure the Σ^+ ($\bar{\Sigma}^-$) polarization, we will only discuss those additional aspects relevant to the magnetic moment measurements.

Data were collected at pairs of targeting angles as shown in Table I. The targeting angles were of equal magnitudes but opposite signs, thus allowing the polarization direction to be reversed periodically to separate the asymmetry from instrumental biases [5]. The asymmetry (**A**) and polarization (**P**) are related by $\mathbf{A} = \alpha \mathbf{P}$ where α for the Σ^+ decay [6] is -0.98. Note that the measured A_y components are small, consistent with initial polarization only in the x direction.

The reconstructed neutral particle (X^0) missing mass squared for the decays $\Sigma^+ \to pX^0$ ($\bar{\Sigma}^- \to \bar{p}X^0$) are shown in Fig. 2(a) [2(b)], respectively. Events have been rejected where the p ($\bar{p}$) trajectory was near the edges of the hole in the photon spectrometer as well as events whose reconstructed neutral mass, assuming a decay $K^+ \to \pi^+ X^0$ ($K^- \to \pi^- X^0$), was near the π^0 mass. Figure 2 of Ref. [3] shows similar event samples before these restrictions were imposed. We assume [7] the masses of the hyperons are the same as the antihyperons. We can write the spin precession angle ξ of the Σ^+ ($\bar{\Sigma}^-$) after it traverses the magnets as

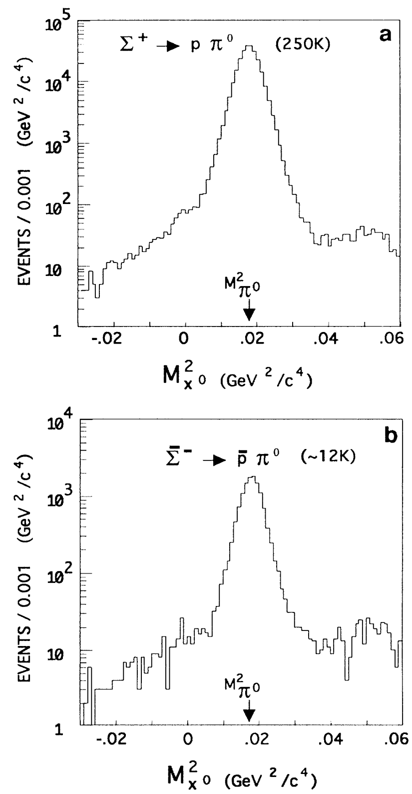

FIG. 2. (a) Event distributions of the mass squared of the missing neutral particle (X^0) for the hypothesis $\Sigma^+ \to pX^0$ for positive beam candidates. (b) Event distributions of the mass squared of the missing neutral particle (X^0) for the hypothesis $\bar{\Sigma}^- \to \bar{p}X^0$ for negative beam candidates.

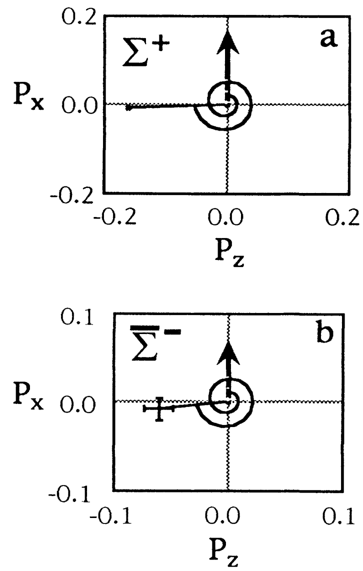

FIG. 3. (a),(b) Rotation of the polarization vectors of the Σ^+ and $\bar{\Sigma}^-$. The initial polarization is produced in the $+x$ direction and precesses into $\approx -z$ direction for each of the two hyperons.

$$\xi = \frac{q}{2\beta m_\Sigma c^2}(g-2)\int \mathbf{B}\cdot d\mathbf{L}\,, \qquad (1)$$

where q is the hyperon charge, β (is equal to 1 to a very good approximation) is the relativistic velocity divided by the speed of light, and $\int \mathbf{B}\cdot d\mathbf{L}$ is the field integral of HM1 and HM2. The magnetic moment μ_Σ is related to g, the gyromagnetic ratio, by

$$\mu_\Sigma = (g m_p / 2 m_\Sigma)\mu_N\,, \qquad (2)$$

where m_p (m_Σ) is the proton (Σ^+) mass and $\mu_N = e\hbar/2m_p c$ is the nuclear magneton.

Shown in Table I are the three components of the Σ^+ and $\bar{\Sigma}^-$ decay asymmetry **A** measured using the same techniques as in an earlier publication [5]. An earlier measurement [8] demonstrated that 2π rad must be added to the measured angles to bring them into agreement with previous measurements. This implies that $\xi = \tan^{-1}(|A_x/A_z|) - 3.5\pi$. Shown graphically in Fig. 3 are the polarization vectors, initially in the positive x direction, then rotated in the xz plane due to the HM1 and HM2 magnetic fields. We measure ξ for the Σ^+ and $\bar{\Sigma}^-$ decays to be -10.937 ± 0.022 and -10.72 ± 0.24 rad, respectively, where the uncertainties are statistical only.

Table II. Summary of systematic and statistical uncertainties in nuclear magnetons.

Systematic uncertainties	Σ^+	$\bar{\Sigma}^-$
Variation of ξ to cuts	0.0026	0.003
Asymmetry procedure	0.0013	0.001
Finite target length	0.0010	0.001
HM1 field integral	0.0025	0.003
HM2 field integral	0.0005	0.001
$\bar{\Sigma}^-, \Sigma^+$ HM1 field difference		0.006
Total systematic uncertainties	0.0040	0.007
Statistical uncertainty	0.0034	0.036
Total uncertainty	0.0052	0.037

The hyperon trajectories in HM1 were constrained by a precision tungsten collimator inserted between its steel pole tips. A measurement of the magnetic field in HM1 presented a particular challenge since a precision of $\approx 10^{-3}$ is needed and at its narrowest point the collimator [9] has a width of only 1.4 mm. The measurement of the field integral of HM1 was done by mapping the field with a special miniature Hall probe which was calibrated with a NMR probe. Although the magnetic field of HM2 was also measured with a Hall probe, its final field integral was more precisely fixed [4] by using the known masses [6] and the angular distribution of the protons in the $\Sigma^+ \to p\pi^0$ decay. The produced hyperons experienced a field integral of -25.215 ± 0.031 Tm in HM1 and $+4.750 \pm 0.007$ Tm in HM2.

We measure the Σ^+ and $\bar{\Sigma}^-$ magnetic moments to be $(2.4613 \pm 0.0034 \pm 0.0040)\mu_N$ and $(-2.428 \pm 0.036 \pm 0.007)\mu_N$, respectively. The stated uncertainties are statistical and systematic, respectively. Table II shows the contributions to the systematic uncertainty. The displayed total error is the combination of the individual uncertainties in quadrature. The combined errors for each of these measurements give an uncertainty ($\Delta\mu_\Sigma/\mu_\Sigma$) in the Σ^+ and $\bar{\Sigma}^-$ magnetic moments of 0.21% and 1.52%, respectively. We note that the Σ^+ and $\bar{\Sigma}^-$ moments are consistent in magnitude but opposite in sign as required by *CPT* invariance.

Table III shows the previous measurements. Two of these measurements [8,10] of the Σ^+ magnetic moment were performed using Fermilab hyperon beams. Each claimed an uncertainty ($\Delta\mu_\Sigma/\mu_\Sigma$) of $\approx 1\%$ yet their results differ by $\approx 3\sigma$ from each other. One of them [8], Fermilab E497, used the same hyperon magnet and channel as this experiment, but utilized a 210-GeV/c Σ^+ beam produced by 400 GeV protons. That experiment determined the HM1 magnetic field from the target posi-

TABLE III. Compilation of Σ^+ magnetic moment measurements (nuclear magnetons).

Experiment	Magnetic moment	Uncertainty
Settles *et al.* [11]	2.3000	0.1400
Ankenbrandt *et al.* [8], revised	2.4040	0.0198
Wilkinson *et al.* [10]	2.4790	0.0251
This experiment	2.4613	0.0052
Weighted mean and scaled error	2.4583	0.0101

tion, measured beam momentum, and angles.

We have directly measured the field integral of the same hyperon magnet at the same current used [8] by E497 to measure the Σ^+ magnetic moment. Using this new measurement of the field integral changes the E497 result [8] from $(2.38 \pm 0.02)\mu_N$ to $(2.40 \pm 0.02)\mu_N$, a shift of 1σ.

The current Paticle Data Group compilation [6] includes three experiments [8,10,11] in their world average of the Σ^+ magnetic moment. Including results from this experiment, the corrected magnetic field result [8] from E497, and using the same Particle Data Group procedures [6] we have determined a new world average and error (Table III). These experiments give a value of the Σ^+ magnetic moment of $(2.458 \pm 0.010)\mu_N$ with a confidence level of 0.02 and scale factor of 2.1. The major contribution to this rather poor confidence level comes from the corrected E497 result.

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