Precise Measurement of the Σ^+ Magnetic Moment

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The Σ^+ magnetic moment is measured to be $(2.38\pm0.02)\mu_N$ with use of 44 457 polarized $\Sigma^+\to p\pi^0$ decays in a charged hyperon beam. The inclusively produced Σ^+ in this 210-GeV/c beam have a polarization of about 0.20 for production angles between 2.5 and 7.0 mrad.

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This paper reports a new precision measurement of the Σ^+ magnetic moment. The magnetic moments of the baryons have long been considered of fundamental importance and a powerful tool for studying the internal structure of the baryons.[1] High-energy polarized hyperon beams have recently become available, making possible precise measurements of the hyperon magnetic moments.[2] These more precise experiments show systematic discrepancies from the SU(6) quark model[3]; there is no convincing quantitative theory.[4] More recently, crude calculations of some baryon magnetic moments have been made with quantum chromodynamics (QCD) using lattice gauge theory techniques.[5]

In the experimental setup shown in Fig. 1, a 400-GeV/c proton beam was incident on a 1-interaction-length copper target at an angle with respect to the horizontal plane. This angle could be varied between -7 and 7 mrad. The target was placed at the upstream end of a 7-m-long, 14.4-T·m magnet. The 210-GeV/c secondary beam emerging from the magnet was limited by a tungsten channel to an emittance of ±16 GeV/c and 1 μsr. The beam typically contained 50 000 particles in a 1-sec pulse. The Σ^+ constituted 0.5% of the emerging beam; about half decayed in the region of the high-resolution proportional chambers (PWC) shown in Fig. 1.

The $\Sigma^+\to p\pi^0$ trigger consisted of the coincidence of a single incident track defined by beam scintillation counters in the PWC region, the detection by a downstream counter of the energetic decay proton, and a total energy deposition in the lead-glass of >1 GeV. The trigger rate was about 100/pulse. About $\frac{1}{3}$ of the triggers were genuine Σ^+ events; the remainder were background from interactions in the PWC's and drift chambers. Other triggers provided calibration data. These included a beam trigger which required the beam counters only, and a $\Sigma^+\to n\pi^+$ trigger which required, in addition, a neutral-particle signal from the neutron calorimeter.

The Σ^+ particles which decayed downstream of the PWC region were measured to an accuracy (σ) of 1.5 GeV/c in momentum, 50 μrad in dip. Protons from the decay $\Sigma^+\to p\pi^0$ emerging from

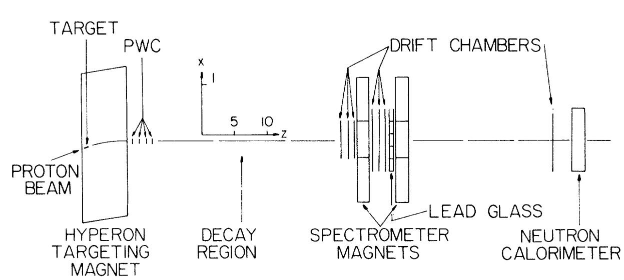

FIG. 1. Plan view of the apparatus; scale is in meters.

the 20-m decay region were measured with an accuracy of $\Delta p/p = 1\%$, 60 μrad in azimuth, and 40 μrad in dip.

The analysis was performed with events where a beam track was found in the PWC's and a decay track was found in the drift chambers. The beam track was required to extrapolate in the vertical view back to the center of the 2-mm-high target to within ±3 mm. The decay track was required to be properly reconstructed using the most downstream drift chamber in order to obtain the best resolution. The beam track and the decay track were constrained to meet at a vertex. For the successful fits, the position of the vertex was required to be in a fiducial volume extending from the beam-defining magnet to 5 m upstream of the drift chambers.

The largest backgrounds in this experiment were interactions and $\Sigma^+ \to p\pi^0$ decays in the PWC's. The PWC-track-fit confidence-level cut suppresses interactions and decays in the PWC's and the fiducial-volume cut eliminates most interactions in the drift chambers. The resolution on the vertex position in z was about 1 m and, therefore, not adequate to distinguish reliably between interactions in the PWC region and the bulk of the good events which occur just downstream of the PWC's.

After imposing the above requirements, there remained a large number of events where the decay track had small transverse momentum relative to the beam track. These events could be caused by Σ^+ decays in the PWC region or quasielastic interactions. These events were eliminated by requiring the decay track to have ≥ 30 MeV/c transverse to the beam track. Information from the lead-glass was not used except in the trigger. Figure 2 shows the Σ^+ mass calculated with the assumption of the decay mode $\Sigma^+ \to p\pi^0$. The background under the clear Σ^+ peak is less than 10%. We are able to see a signal from $K^+ \to \pi^+\pi^0$; this decay constitutes less than 1% of the events.

The y axis is defined to be vertical and the z axis to be in the direction of the secondary-Σ^+-beam momentum. With these definitions, the Σ^+ polarization at the target was parallel (or antiparallel) to the x axis. The polarization precessed about the vertical magnetic field through an angle ξ in the x-z plane proportional to the anomalous magnetic moment of the Σ^+, given by

$$\xi = \tfrac{1}{2}(g-2)\langle\eta\rangle\,\theta_B, \qquad (1)$$

where $\langle\eta\rangle = \langle P\rangle/m_{\Sigma^+}$, $\langle P\rangle$ is the momentum of

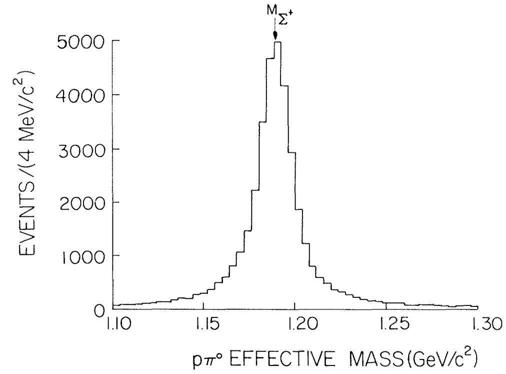

FIG. 2. The reconstructed Σ^+ mass distribution. The full width at half maximum is 20 MeV/c^2.

the central trajectory, and θ_B is the bend angle in the magnet. The magnetic moment, μ_Σ, of the Σ^+ is related to g by

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

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

To analyze the decay angular distributions, each event was kinematically fitted with the hypothesis $\Sigma^+ \to p\pi^0$ and the decay angles θ and φ were calculated, where

$$\theta = \cos^{-1}(p_z/p), \quad \varphi = \tan^{-1}(p_y/p_x), \qquad (3)$$

and $\vec{p} = (p_x, p_y, p_z)$ is the proton momentum in the Σ^+ rest frame. Instead of the 30-MeV/c transverse-momentum cut on the raw data, a somewhat more stringent cut, $|\cos\theta| < 0.94$, was imposed.

The polarization was obtained from the decay angular distribution for each targeting angle. Data from targeting angles ±2.5, ±3.2, ±5.0, and ±7.0 mrad were available. The data were binned in 100 bins (10 in $\cos\theta \times 10$ in φ) for each of the eight targeting angles. The distribution is assumed to be

$$\frac{dN}{d\cos\theta\, d\varphi} = \frac{N}{4\pi} A(\theta, \varphi)(1 + \alpha \vec{P} \cdot \hat{n}), \qquad (4)$$

where $A(\theta, \varphi)$ is the acceptance, $\hat{n}$ is a unit vector along the decay proton direction, and $\vec{P}$ is the polarization with components given by

$$P_x = P\sin\psi\,\cos\xi, \qquad (5a)$$

$$P_y = P\cos\psi, \qquad (5b)$$

$$P_z = P\sin\psi\,\sin\xi. \qquad (5c)$$

The analyzing power[6] ($\alpha = -0.979 \pm 0.016$) is very favorable for analysis of the polarization in the $\Sigma^+ \to p\pi^0$ decay mode. When the targeting angle is reversed, the parity-conserving polarization reverses. The x and z components of the polarization after precession change sign. If $\boldsymbol{P}_y$ is zero (as is expected from parity conservation) or changes sign when the targeting angle is reversed, then $A(\theta, \varphi)$ can be found from any symmetric pair of targeting angles. On the other hand, if $A(\theta, \varphi)$ is independent of φ, P_y can be found from the data. The former assumption yields a slightly better fit to the data, although both assumptions yield the same result for the magnetic moment. It is important to note that, while $\boldsymbol{A}(\theta, \varphi)$ is intended to describe the acceptance of the apparatus, it also corrects for backgrounds and biases to order $\alpha \boldsymbol{P}$. This is a crucial point, since the experiment effectively measures the asymmetry by comparing positive and negative targeting angles, thereby benefiting from the cancellation of biases that would be present if either targeting angle were taken alone.

The data were fitted by use of a maximum-likelihood method with 112 parameters. Of these, 100 gave the values $A(\theta, \varphi)$ for the 100 data bins, seven were for normalization, four gave the absolute value of the polarization at the four targeting angles, and one parameter (ξ) gave the rotation angle. The fit with a $\chi^2 = 740$ for 695 degrees of freedom gave $\xi = 1.01 \pm 0.05$ rad.

Several checks were made on this result. Different values of ξ were fitted for each targeting angle. Each was consistent (within 1σ) with the average value given above. A more stringent event selection requiring a 1% confidence level for the $\Sigma^+ \to p\pi^0$ hypothesis, which should substantially reject background events, changes ξ by 0.03 rad.

The magnetic field calibration was accomplished with beam track data and $\Sigma^+ \to n\pi^+$ triggers. Beam track triggers (which consist mostly of noninteracting protons) were used to adjust the relative normalizations of the upstream and downstream spectrometer magnets. The adjustments were made on each run and had an rms spread of 0.3%, which is a measure of the systematic error in the calibration (due, e.g., to small drifts in chamber positions). The overall normalization of the spectrometer was found by requiring the Σ^+ mass reconstructed from the $n\pi^+$ decay mode to be equal to the accepted value[6] of 1.1894 GeV. The mass normalization does not vary from run to run beyond ~0.2%, which is our ability to determine it. With this calibration the average momentum of particles exiting from the channel is known to 0.4%. From the construction of the channel, the bend angle of the central trajectory is 20.59 mrad. Since the beam particles do not uniformly populate the channel, the difference between the direction of the average beam particle and the center of the channel is only known to 80 μrad. This latter error is dominant. The $\langle \eta \rangle$ for a Σ^+ on the central trajectory of the channel is 175.8 ± 1.5. Other checks of possible systematic biases included verification that the final sample of Σ^+ had a lifetime consistent with the accepted value.[6] The data analysis codes were checked by generating $\Sigma^+ \to p\pi^0$ decays with use of Monte Carlo techniques and the measured experimental resolutions and requiring that the analyses reproduced the input Σ^+ polarization in direction and magnitude.

The same data sample was analyzed independently by using directly measured quantities and not subjecting them to the possible biases of geometrical and kinematical fitting procedures. In this analysis, the three polarization components were analyzed separately with $\hat{\boldsymbol{n}} = \hat{x}, \hat{y}, \hat{z}$ and integration over φ giving polarization and acceptance functions in terms of the three direction cosines, $\cos\theta_i$, with $i = 1, 2, 3$. Using the ratio $R_i(\cos\theta_i)$ of distributions from runs with equal and opposite targeting angles, both the acceptance functions, $A_i(\cos\theta_i)$, and the individual distributions in $\cos\theta_i$ are extracted. Figure 3 shows these distributions for the ± 5-mrad data. The plots of A_i illustrate the uniformity of our acceptance and the falloff at the edges of the $\cos\theta_i$

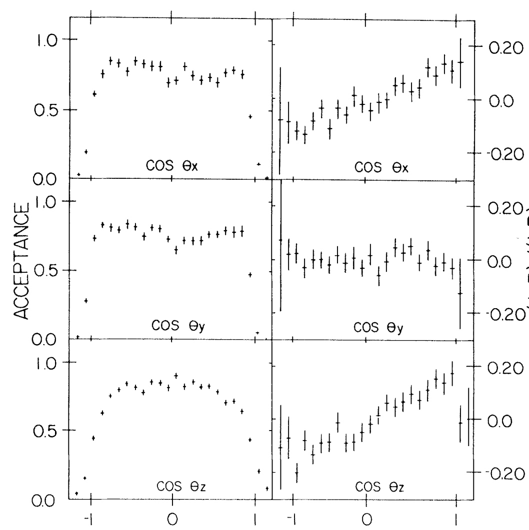

FIG. 3. Acceptance functions $A_i(\cos\theta_i)$ and $\alpha P_i \cos\theta_i = (1-R_i)/(1+R_i)$ for the directions $i = x, y$, and z.

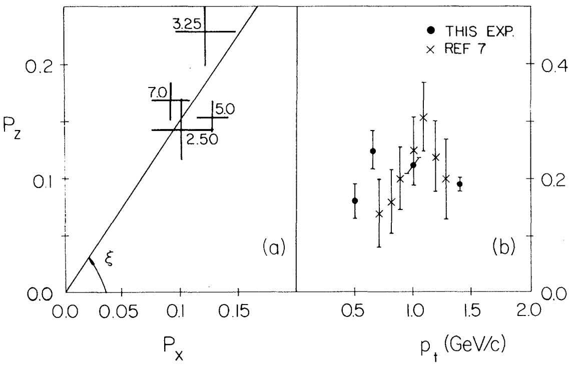

FIG. 4. (a) Σ^+ polarization components. The points are labeled by the corresponding vertical targeting angles in mrad. The angle ξ is the average precession angle modulo 2π. (b) The magnitude of the Σ^+ production polarization vs p_t, the Σ^+ transverse momentum. All data from this experiment are at a Feynman x of 0.53. The data of Ref. 7 have $x = p_t/(2.0\ \text{GeV}/c)$.

plots indicate the angular resolution in these center-of-mass quantities. The results obtained with this analysis are fully consistent with the earlier described analysis.

In Fig. 4(a) is shown the polarization vector of the Σ^+ at each of the four targeting angles. The polarization vs p_t is shown in Fig. 4(b), along with the data[7] of Wilkinson *et al.* There is qualitative agreement between the two data samples; however, only the data at $p_t = 1.0$ GeV/c were taken at the same value[8] of Feynman x. The polarization is in the direction of the vector product of the incident proton and produced Σ^+ momentum. This is opposite to the polarization direction of inclusively produced lambdas.[9]

To obtain agreement between the spin rotation angle and the world average value[6] of the magnetic moment $\mu_{\Sigma^+} = (2.33 \pm 0.13)\mu_N$, we must assume that the full rotation angle is $\xi + 2\pi$ or $\xi = 7.29 \pm 0.05$ rad. Applying (1) and (2) with the values of ξ, η, and θ_b given above we find $\mu_{\Sigma^+} = (2.38 \pm 0.02)\mu_N$, where the error includes the statistical (0.014) and the systematic (0.014) contributions.

The simple SU(6) static quark model[3] predicts a value for the Σ^+ magnetic moment of $2.67\mu_N$. The disagreement of $0.29\mu_N$ between this prediction and the measurement reported here is an order of magnitude larger than either the measurement uncertainty or the uncertainty due to experimental errors in the input parameters of the theory. Recent theoretical work[4] has attempted to improve the agreement of this type of model with the measured baryon magnetic moments. At present no model adequately fits all the measurements.

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[1]Of a sample of 72 articles published on this subject since 1978, six reported new experimental results.

[2]The first such experiment was reported by L. Schachinger *et al.*, Phys. Rev. Lett. 41, 1348 (1978).

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[7]C. Wilkinson *et al.*, Phys. Rev. Lett. 46, 803 (1981).

[8]Here Feynman x is approximated by the Σ^+ secondary momentum divided by the incident proton momentum: $x = (210\ \text{GeV}/c)/(400\ \text{GeV}/c) = 0.53$.

[9]G. Bunce *et al.*, Phys. Rev. Lett. 36, 1113 (1976).