Measurement of the Ω^- Magnetic Moment

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A sample of 24700 Ω^- hyperons was produced by a polarized neutral beam in a spin-transfer reaction. The Ω^- polarizations are found to be -0.054 ± 0.019 and -0.149 ± 0.055 at mean Ω^- momenta of 322 and 398 GeV/c, respectively. The directions of these polarizations give an Ω^- magnetic moment of $-1.94 \pm 0.17 \pm 0.14$ nuclear magnetons.

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Nearly thirty years ago, when the first predictions for the static magnetic moments of the baryon octet were made by Coleman and Glashow [1], experimental verification for baryons other than the proton and neutron was not imminent. In the subsequent three decades, as experimental techniques to produce, detect, and measure the properties of hyperons have evolved, so has our understanding of hadronic structure. Indeed the measurements of baryon magnetic moments have confirmed our understanding of symmetry breaking and constituent quark masses obtained from the hadron mass spectra. The proton, neutron, and Λ magnetic moments have been used as inputs to predict the moments of other members of the baryon octet, as well as that of the long-lived decuplet member, the Ω^-. At the present time, however, even theoretical calculations which embellish the simple quark model disagree with the experimental results at the level of about 0.2 nuclear magneton (μ_N) for some of the baryons [2]. The Ω^- magnetic moment μ_{Ω^-} holds particular interest because the Ω^- is the simplest of the experimentally accessible baryons, three strange valence quarks with parallel spins. A measurement of μ_{Ω^-} determines the strange-quark magnetic moment in an environment free of the effects of the light up and down quarks that are present in the Λ. Whereas the P-wave mixing in the spin-$\frac{1}{2}$ octet members can cause sizable corrections to their magnetic moments, the D-wave ($L=2$) components in the Ω^- have negligible effects on its magnetic moment [3,4]. For the Ω^- the theoretical predictions [3-12] range from $-1.3\mu_N$ to $-2.7\mu_N$.

A standard technique for measuring hyperon magnetic moments is to produce a beam of polarized hyperons, precess the polarization vector in a magnetic field, and then determine the final spin direction by observing the asymmetry in the decay distributions of the hyperons. The discovery that hyperons produced by protons were polarized normal to the production plane made possible precision measurements of the Λ [13], Ξ^0 [14,15], Ξ^- [16,17], Σ^- [18,19], and Σ^+ [20,21] magnetic moments. Recently, the $\bar{\Xi}^+$ magnetic moment was also measured using this method [22]. The present experiment employed the same precession technique to make the first determination of μ_{Ω^-}, but a different approach was used to produce a sample of polarized Ω^-'s.

The Ω^-'s were produced in a spin-transfer process. First a neutral beam containing polarized Λ's and Ξ^0's was produced by a Fermilab 800-GeV/c proton beam in the inclusive reaction $p+\mathrm{Cu} \rightarrow (\Lambda,\Xi^0)+X$ at ± 2.0 mrad. The polarized neutral beam was then targeted at 0 mrad to produce Ω^-'s by the reaction $(\Lambda,\Xi^0)+\mathrm{Cu} \rightarrow \Omega^- + X$. Although hyperons constituted less than 10% of the neutral beam, based on the measured strange-particle-production cross sections, Ξ^0's and Λ's were estimated to produce at least 20 times and 5 times more Ω^-'s than neutrons, respectively [23]. The polarization of 24700 Ω^-'s produced in this manner was measured and used to determine μ_{Ω^-}.

The Ω^- production target (Cu, $5 \times 5 \times 152$ mm^3) was located just upstream of a 7.3-m-long magnet $M1$, which was fitted with a brass and tungsten momentum-selecting channel with a defining aperture of 5×5 mm^2. Using a right-handed coordinate system in which $\hat{y}$ is up and $\hat{z}$ is along the neutral beam axis, the field in $M1$ was in the $-y$ direction. The channel curvature gave the central ray an effective bend of 14.7 mrad in the x-z plane and selected negative particles in a momentum range of 240-500 GeV/c when the magnet was operated at a field of 1.98 T.

For Ω^- hyperons which exited $M1$, a multiwire proportional chamber spectrometer [22,23] recorded the charged decay products of the $\Omega^- \rightarrow \Lambda K^-$, $\Lambda \rightarrow p\pi^-$ decay chain. Signals from scintillation counters and wire chambers were used to form a data-acquisition trigger for selecting three track events with at least one positively charged and one negatively charged track.

All three-track triggers were passed to an off-line reconstruction program which searched for the three-track, two-vertex topology. Event selection was based on both geometric and kinematic criteria. Selected events were required to have a geometric χ^2 for the topological fit not larger than 70 for typically 30 degrees of freedom. The tracks belonging to the downstream vertex were assigned to be the proton and pion, and the p-π^- invariant mass was required to be from 1108 to 1124 MeV/c^2. The momentum vector of the reconstructed hyperon was required to trace back to within 6.3 mm of the center of the Ω^- production target. The resolution of this process was better than 1.4 mm. The reconstructed events were primarily $\Xi^- \rightarrow \Lambda\pi^-$, which were recorded along with $\Omega^- \rightarrow \Lambda K^-$ typically in the ratio of 70 to 1 after reconstruction. All events were reconstructed under both the $\Xi^- \rightarrow \Lambda\pi^-$ and $\Omega^- \rightarrow \Lambda K^-$ hypotheses. Most of the Ξ^-'s were rejected by requiring that the Λ-π^- invariant mass not fall between 1297 and 1350 MeV/c^2. Further elimination of Ξ^-'s was achieved by cutting on the angle of the Λ in the Λ-π^- center-of-mass system and on the angles of K^- in the Λ-K^- rest frame [24]. These requirements were identical to the cuts described in detail in Ref. [24]. Finally, the invariant mass under the Λ-K^- hypothesis was required to be between 1657 and 1687 MeV/c^2. The resulting events were predominately $\Omega^- \rightarrow \Lambda K^-$ but contained a 3% background mainly due to $\Omega^- \rightarrow \Xi^0\pi^-$ decays. The invariant-mass distribution of the Ω^- sample without the final mass selection is shown in Fig. 1.

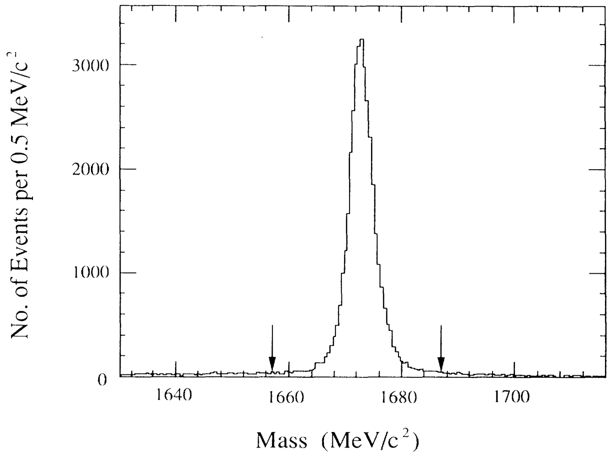

FIG. 1. Λ-K^- invariant mass of the final data sample. The mass selection criterion is shown by the arrows.

The vector polarization of the Ω^-, $\mathbf{P}_\Omega$, is related to the polarization of the daughter Λ, $\mathbf{P}_\Lambda$, by [24]

$$\mathbf{P}_\Omega = \frac{2(J+1)}{1+\gamma_\Omega(2J+1)}\mathbf{P}_\Lambda , \tag{1}$$

where $J=\frac{3}{2}$ is taken as the spin of the Ω^-. The decay parameter γ_Ω has not been directly measured, but the value of the decay parameter α_Ω - (-0.026 ± 0.026) [25] implies $\gamma_\Omega{}^2 \simeq 1$. The sign of γ_Ω is predicted to be positive [26-28]. The Λ polarization was determined by measuring the asymmetry in the distribution of the decay proton in the Λ rest frame, which is given by

$$\frac{1}{N_{\text{tot}}}\frac{dN_p}{d(\cos\theta_p)} = \frac{1}{2}(1+\alpha_\Lambda \mathbf{P}_\Lambda \cdot \hat{\mathbf{n}}\cos\theta_p) , \tag{2}$$

where N_{tot} is the total number of events, $\hat{\mathbf{n}}$ are unit vectors parallel to the laboratory axes, $\cos\theta_p$ is $\hat{\mathbf{n}}\cdot\hat{\mathbf{p}}$, and $\hat{\mathbf{p}}$ is a unit vector in the direction of the proton momentum in the Λ rest frame.

The measured distribution of protons is affected by the acceptance and resolution of both the apparatus and the reconstruction software. To correct for these effects, we used a modification [29] of the hybrid Monte Carlo technique [30]. For each real event, Monte Carlo events were generated with the same decay vertex and momentum for the Λ as the real event but with zero Λ polarization. Each simulated event passed the same reconstruction and event selection as the data. The accepted Monte Carlo events were then weighted by a polarization so that the cosine distributions of the proton in the Λ rest frame

TABLE I. The average momentum and the components of the polarization and bias are shown as a function of targeting angle for the two values of the $M1$ field integral.

$M1$ field (Tm)	Production angle (mrad) at $M1$	$\langle p\rangle$ (GeV/c)	Component	$\alpha_\Lambda P_\Lambda$	Bias
−14.77	2.0	322	x	-0.033 ± 0.012	-0.001 ± 0.012
			y	$+0.003\pm0.013$	$+0.003\pm0.013$
			z	-0.012 ± 0.017	-0.029 ± 0.017
	0.0	332	x		-0.012 ± 0.028
			y		$+0.007\pm0.021$
			z		-0.006 ± 0.023
−19.53	2.0	398	x	-0.077 ± 0.032	$+0.031\pm0.032$
			y	-0.059 ± 0.033	$+0.017\pm0.033$
			z	-0.050 ± 0.041	$+0.005\pm0.041$

agreed with those of the data. But any difference between the behavior of the real apparatus and the simulation program can give rise to a false asymmetry or bias. Since such a bias arises from some unaccounted for property of the real apparatus, it does not reverse its sign, as does a polarization, when the sign of the polarization of the neutral beam changes. Thus the polarization can be determined from the difference of the measured asymmetries of the Λ for opposite production angles, and the bias can be determined from the sum. Table I shows the components of the Ω^- polarization and bias measured for the two different $M1$ fields. The polarizations were primarily in the $-x$ direction. The biases were small. The χ^2 values of the Λ asymmetry determination were less than 35 for 19 degrees of freedom. The bias was also measured with Ω^-'s produced by an unpolarized neutral beam with $M1$ at the -14.77-Tm field integral. The results were also small, in agreement with the 2-mrad data, as shown in Table II. An additional test of the validity of the asymmetry is provided by the y components of the polarization for the two fields, which were consistent with zero as required by conservation of parity in strong interactions.

The polarization of a negatively charged hyperon Y with spin J moving in a magnetic field perpendicular to both the momentum and the spin will precess through an angle, relative to its momentum,

$$\theta = \frac{e}{\beta m_Y c^2}\left[\frac{m_Y}{m_p}\frac{\mu_Y}{2J}+1\right]\int B\,dl\,, \tag{3}$$

where e is the magnitude of the electron charge, $\beta = v/c$, m_p is the mass of the proton, m_Y is the mass of the hyperon, $\int B\,dl$ is the field integral of the precession magnet $M1$, given in Tm, and μ_Y is the magnetic moment given in μ_N. The expected x and z components of the polarization downstream of $M1$ are given by $P_x = P_{\text{tgt}}\cos\theta$ and $P_z = P_{\text{tgt}}\sin\theta$, where P_{tgt} is the polarization at the second target. The measured asymmetries at each $M1$ field value gave μ_{Ω^-} results of $(-1.90 \pm 0.29)\mu_N$ and $(-1.96 \pm 0.20)\mu_N$ for the -14.77- and -19.53-Tm field integrals, respectively. Although the -19.53-Tm sample was about 8 times smaller, its polarization and field integral were larger, leading to a smaller statistical uncertainty in μ_{Ω^-}. Constraining both data samples to have the same magnetic moment determined the polarizations of the Ω^- at the second target, the x and z biases, and the magnetic moment [13]. The polarizations at the target were -0.054 ± 0.019 and -0.149 ± 0.055 for the -14.77- and -19.53-Tm field integrals, respectively [31]. Figure 2 shows P_x and P_z for the two fields. Since the direction of the polarization at the target and the sense of the precession were not known *a priori,* the spin precession angle for a given field would have a fourfold ambiguity when only angles less than 2π were considered. The four lowest-order solutions are shown in Table II. The preferred solution gave μ_{Ω^-} as $(-1.94 \pm 0.17)\mu_N$. Because this result depends on the ratio of P_z to P_x, it is independent of the sign of γ_Ω. Alternative solutions for the magnetic moment due to the addition of integral multiples of π to the precession angles were also eliminated.

TABLE II. μ_{Ω^-} for the four lowest-order solutions to Eq. (3). In the first column, the top sign is for the case $\gamma_\Omega = 1$ and the bottom sign is for $\gamma_\Omega = -1$. For the precession angles, a positive sign indicates clockwise rotation.

Initial direction of $\mathbf{P}_\Omega$	Precession angle (deg) at -14.77 Tm	-19.53 Tm	μ_Ω (μ_N)	χ^2/N_{DF}
$\mp x$	$+23 \pm 15$	$+31 \pm 20$	-1.94 ± 0.17	0.03
$\mp x$	-373 ± 16	-493 ± 18	$+2.44 \pm 0.15$	1.63
$\pm x$	$+171 \pm 14$	-226 ± 19	-3.58 ± 0.16	1.31
$\pm x$	-134 ± 16	-177 ± 21	-0.20 ± 0.18	2.50

The systematic uncertainties were investigated by varying the event-selection criteria and by measuring the asymmetries without relying on Monte Carlo simulation [32]. The most sizable change to the polarization components, which occurred in the -19.53-Tm sample, was comparable to the statistical uncertainty. The systematic uncertainty in μ_{Ω^-} was estimated to be $0.14\mu_N$. As an additional check for systematic errors, a sample of 64000 Ξ^- events taken under the same conditions was analyzed. The polarizations were -0.108 ± 0.013 and -0.137 ± 0.025 for the samples recorded with average momenta of 318 and 394 GeV/c, and field integrals of -14.77 and -19.53 Tm, respectively. The magnetic moment was found to be $(-0.688 \pm 0.024)\mu_N$, consistent with previously reported measurements [16,17].

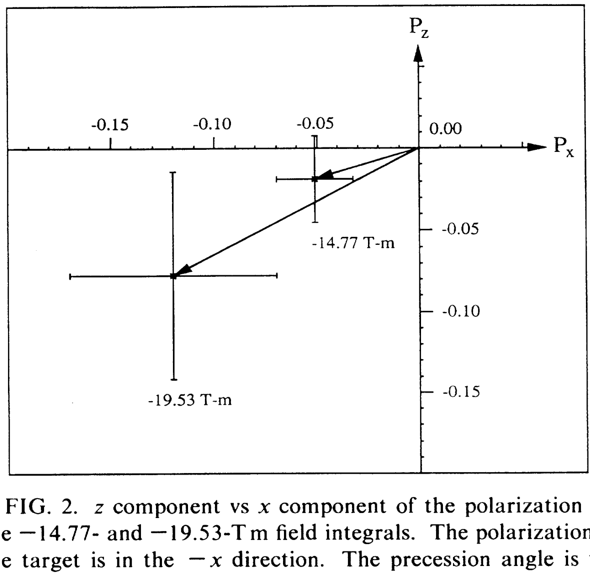

FIG. 2. z component vs x component of the polarization for the -14.77- and -19.53-Tm field integrals. The polarization at the target is in the $-x$ direction. The precession angle is the angle between the $-x$ axis and the final polarization vector for a particular field integral.

We have measured the polarization of Ω^- hyperons produced by a polarized neutral beam in a spin-transfer reaction. The average Ω^- polarizations are -0.054 ± 0.019 and -0.149 ± 0.055 at mean momenta of 322 and 398 GeV/c, respectively. Based on these polarizations, the Ω^- magnetic moment is determined to be $(-1.94 \pm 0.17 \pm 0.14)\mu_N$, in good agreement with the naive-quark-model prediction of $-1.84\mu_N$.

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