Precise Measurement of the Ξ^- Magnetic Moment

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With 4.36×10^6 events, spin precession in a magnetic field has been used to measure the magnetic moment of the Ξ^- hyperon as -0.6505 ± 0.0025 nuclear magnetons.

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Since the discovery that polarized hyperons come from high-energy proton interactions [1], polarized hyperon beams have been used to measure the magnetic moments of the Λ, Σ^+, Σ^-, Ξ^0, Ξ^-, Ω^-, and $\bar{\Xi}^+$ hyperons [2–8]. The magnetic moments of three baryons, the proton, neutron, and Λ, are all measured to better than 1%. These measurements have been used together with models of the quark structure of baryons to determine the magnetic moments of three quarks (up, down, and strange) [9]. These models then predict the magnetic moments of the remaining hyperons. The result reported in this paper provides a fourth measurement, μ_{Ξ^-}, to a precision of better than 1% to guide and constrain models of baryon structure.

Measuring a magnetic moment by spin precession requires a polarized sample of particles. The magnetic moment is then determined from the precession of the spin as the particles pass through a magnetic field. For this measurement a sample of 4.36×10^6 Ξ^- hyperons was produced at an angle of 2.4 mrad by an 800-GeV proton beam interacting with a 9-cm-long beryllium target. The Ξ^-'s were produced with an average polarization of -0.120 ± 0.002 perpendicular to their production plane [10] and perpendicular to the magnetic field of a 7.3-m-long dipole magnet ($M1$) used to precess the spin. A curved collimator inside of $M1$ consisted of brass and tungsten sections centered between the pole pieces of the magnet with a radius of curvature of 497 m in the horizontal plane. The defining aperture of the collimator had a cross section of 5 mm$\times$5 mm and was located 225 cm downstream of the target. The field of $M1$ was vertical and, before data taking, was measured every 2.5 cm with a Hall probe calibrated using nuclear magnetic resonance in a reference magnet. The uncertainty of the field integral was 1%.

The Ξ^-'s were detected through the decay chain $\Xi^-\to\Lambda+\pi^-$, followed by $\Lambda\to p+\pi^-$, using a spectrometer which consisted of eight planes of silicon microstrip detectors (SSD's) with 100 μm pitch, nine multiwire proportional chambers (MWPC's) with 1- and 2-mm wire spacing, and an analyzing magnet consisting of two contiguous dipole magnets which gave a magnetic deflection of 1.54 GeV/c to the momenta of the daughter π^-'s and proton. For this experiment a coordinate system was defined with $\hat{\mathbf{z}}$ in the Ξ^- beam direction, $\hat{\mathbf{y}}$ directed up, and $\hat{\mathbf{x}}=\hat{\mathbf{y}}\times\hat{\mathbf{z}}$. The apparatus and details of the reconstruction and event selection are described in detail elsewhere [8,11]. Figure 1 is a histogram of the reconstructed Λ-π invariant mass from a subsample of the data to illustrate the quality of the Ξ^- events.

For a polarized Ξ^- beam one can measure the angle Φ between the polarization and the momentum direction; Φ is the sum of the effects due to the precession of the magnetic moment and the momentum in the magnetic field, as well as a Thomas precession due to the accelerating

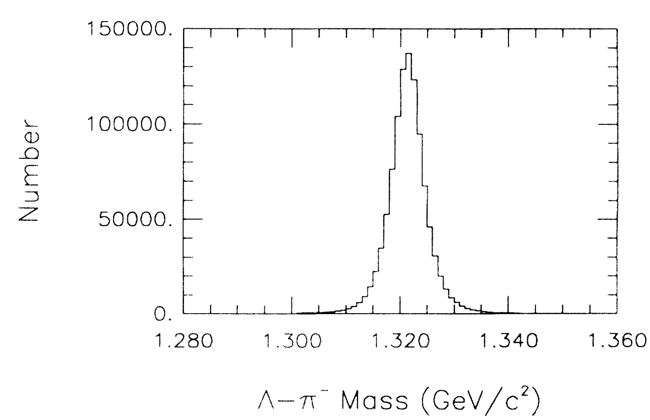

FIG. 1. The reconstructed Λ-π invariant mass from a subsample of the data.

TABLE I. The precession angle Φ and μ_Ξ for each of the five values of $\int B\,dl$ for $M1$.

$\int B\,dl$ (Tm)	Φ (deg)	μ_Ξ (nuclear magnetons)	Number of events
15.30 ± 0.15	-15.0 ± 2.7	-0.656 ± 0.010	745×10^3
19.43 ± 0.19	-20.9 ± 1.2	-0.651 ± 0.004	1971×10^3
22.18 ± 0.22	-26.0 ± 1.6	-0.646 ± 0.005	1034×10^3
24.11 ± 0.24	-28.1 ± 3.0	-0.647 ± 0.007	301×10^3
25.62 ± 0.26	-25.2 ± 3.1	-0.656 ± 0.007	314×10^3

rest frame of the Ξ^-. Φ is given by

$$\Phi = \frac{q}{\beta m_\Xi c^2}\left[-\frac{\mu_\Xi m_\Xi}{\mu_N m_p} - 1\right]\int B\,dl\,, \qquad (1)$$

where μ_{Ξ^-} is the Ξ^- magnetic moment, $q=-e$, m_p is the mass of the proton, $m_\Xi c^2 = 1.321$ GeV, μ_N is the nuclear magneton $(e\hbar/2m_pc)$, and $\int B\,dl$ is the total field integral along the path of the particle through $M1$. To the precision of this experiment $\beta=1$.

Since the initial polarization was perpendicular to the production plane (along $\hat{\mathbf{x}}$), as required by parity conservation, and the field of $M1$ was along $\hat{\mathbf{y}}$, the precession of the spin was in the x-z plane. The difference between the spin and the momentum precession could be determined from the ratio of the x and z components of the Ξ^- polarization, $\Phi = \arctan(P_z/P_x) \pm n(180°)$. A measurement at one field integral would be ambiguous up to an integral number of half revolutions, n. The use of five different values for $\int B\,dl$, 15.30, 19.43, 22.18, 24.11, and 25.62 Tm, resolved this ambiguity and determined that $n=0$. For example, the χ^2 per degree of freedom for the hypothesis that $n=1$ was found to be 192 as compared to 0.7 for $n=0$.

The components of the polarization of the Ξ^-'s (P_x,P_y,P_z) were found by measuring the components of the daughter Λ polarization [12]. The Λ polarization was measured from the distribution of the daughter proton in the Λ rest frame. This analysis is described in detail elsewhere [11]. In practice the technique that was used measures an asymmetry due to the real Λ polarization and any possible asymmetry (bias) which is a result of experimental effects not accounted for by the analysis. Because it is a result of the apparatus, the bias does not change sign as does the real polarization when the production angle is reversed. By combining the data with opposite signs of the production angle, the bias can be determined and eliminated to yield the true signal.

The magnetic moment was determined by minimizing a χ^2 defined by

$$\chi^2 = \sum_{ijk}\left[\frac{(P_{xijk} \mp P_{0i}\cos\Phi_j)^2}{\sigma^2_{xijk}} + \frac{(P_{zijk} \mp P_{0i}\sin\Phi_j)^2}{\sigma^2_{zijk}}\right], \qquad (2)$$

with Φ_j given by Eq. (1). P_{0i} is the polarization at the target which does not depend on the field of $M1$ and was determined by the fit together with μ_{Ξ^-}. P_{xijk} and P_{zijk} are the measured polarization signals, and σ^2_{xijk} and σ^2_{zijk} include the uncertainties of P_{xijk} and P_{zijk} from the polarization analysis as well as the uncertainties of $\int B\,dl$. The polarization is a function of momentum [10] and the subscript i runs over nine momentum bins. The five field integral values given in Table I are indicated by the subscript j. The two signs of the production angle are represented by k. Reversing the sign of the production angle changes the sign of the polarization at the target; the upper sign is used with the positive production angle. Minimizing this χ^2 gave $\mu_{\Xi^-} = (-0.6505 \pm 0.0025)\mu_N$ with a χ^2 per degree of freedom of 1.3 for 62 degrees of freedom. If the uncertainties of the polarization components were increased until the χ^2 per degree of freedom was 1.0, the uncertainty of μ_Ξ increased by 0.2σ.

Table I and Fig. 2 give the results of minimizing Eq. (2) if the precession angle is determined independently for each field integral. A straight-line fit for Φ vs $\int B\,dl$ constrained to pass through the origin yielded $\mu_{\Xi^-} = (-0.6499 \pm 0.0022)\mu_N$ with a χ^2 per degree of freedom of 0.7 for 4 degrees of freedom. The null hypothesis that there were no precession (i.e., P_z/P_x is constant) gave a χ^2 per degree of freedom of 4.5 for 4 degrees of freedom and was thus rejected.

The data were extensively studied to determine the stability of this result. The Ξ^- momentum is correlated to its position and angle as it enters the spectrometer. In ad-

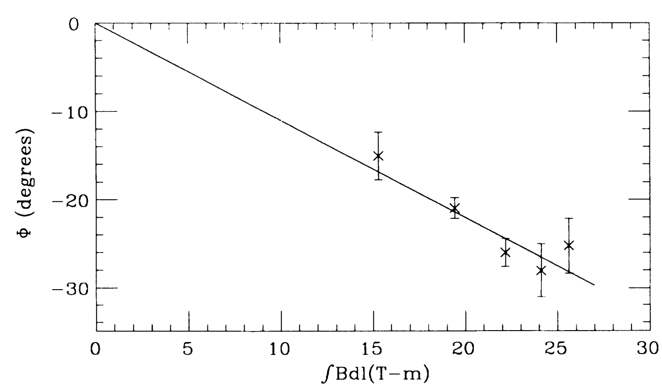

FIG. 2. The precession angle Φ for each of the five values of $\int B\,dl$ of $M1$.

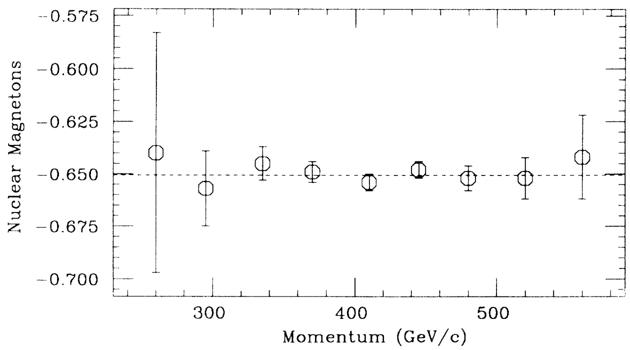

FIG. 3. μ_{Ξ^-} as a function of Ξ^- momentum.

dition, higher-momentum events tend to have daughter tracks that are closer together and are reconstructed less efficiently. If there were a systematic dependence of μ_{Ξ^-} on the Ξ^- position or the efficiency of the reconstruction it would most likely appear as a dependence of μ_{Ξ^-} on the Ξ^- momentum. Figure 3 shows, to the precision of this experiment, that no such problem exists.

Another study investigated the biases which were canceled in the polarization measurement using the difference of opposite-production-angle data. The overall biases in the x and y views were measured to be less than 1%, but the bias in the z direction varied approximately linearly as a function of Ξ^- momentum and ranged from -10% to $+10\%$. Although possible uncanceled remnants of the x and y biases were too small to affect the magnetic moment measurement, the z bias could be of some concern. Any small z component not completely canceled might systematically affect the magnetic moment measurement as a function of momentum. Figure 3 demonstrates that the magnetic moment measurement does not reflect the momentum dependence of the bias. As a further check, the data were systematically altered by adding 5 GeV/c to the reconstructed proton momentum which increased the magnitude of the z bias by about 0.05. The value of μ_{Ξ^-} for this altered sample was within 0.2σ of the measurement. We conclude there is no evidence that this bias affects the measurement.

Since the magnetic moment measurement is directly related to $\int B\,dl$, it is crucial that μ_{Ξ^-} show no dependence on this quantity. In Table I μ_{Ξ^-} was calculated independently for each of the five field integrals of $M1$ and showed no systematic dependence. Equation (1) shows that μ_Ξ is insensitive to small variations of $\int B\,dl$. For example, the value of the measured field integral could be systematically changed by 2%, well outside to its measurement uncertainty, before changing the value of μ_{Ξ^-} by 0.5σ.

As another test, data were taken with each sign of the magnetic field of the analyzing magnets in roughly equal proportions. Reversing the field changes the correlation of the downstream positions of the Ξ^- decay products with the Ξ^- momentum. The values of μ_{Ξ^-} from these two independent samples were $(-0.6516\pm0.0030)\mu_N$ and $(-0.6488\pm0.0037)\mu_N$, which agree to within 0.6σ. Finally, reasonable variations of the data selection criteria changed μ_{Ξ^-} by less than 0.5σ.

Most of the models that attempt to predict baryon magnetic moments use one or more of the well measured values as input [9]. For example, the naive quark model using $\mu_{\rm proton}$, $\mu_{\rm neutron}$, and μ_Λ as input yields $\mu_{\Xi^-} = -0.493\mu_N$, which differs from the result given here by $(0.157\pm0.003)\mu_N$ or 63σ. This model also gives $\mu_s=\mu_\Lambda=0.613\mu_N$ for the magnetic moment of the strange quark. If μ_{Ξ^-} is used in place of μ_Λ to determine the magnetic moment of the strange quark then $\mu_s=\mu_\Lambda=0.731\mu_N$, which differs from the measured value of μ_Λ by $(0.118\pm0.004)\mu_N$. All but one [13] of the more complex models known to us fails to predict all baryon magnet moments to within 10%. The one model which satisfies the 10% criteria uses an extra parameter to add an SU(3) (flavor) tensor term to the expression for the baryon magnetic moment.

In summary, we have measured the magnetic moment of the Ξ^- hyperon to be $(-0.6505\pm0.0025)\mu_N$, which is in agreement with the world average of $(-0.679\pm0.031)\mu_N$ [14] and is an order of magnitude more precise. We find no evidence for any systematic uncertainties which would make a significant contribution to the quoted statistical measurement uncertainty. The Ξ^- now has the most precisely measured magnetic moment of any hyperon, and this is the third most accurate baryon magnetic moment measurement.

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