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495

Precise Measurement of the Ξ^{0} Magnetic Moment

P.T.Cox[(a)], J.Dworkin, and O.E.Overseth,

Department of Physics, University of Michigan,
Ann Arbor, Michigan 48109,

R.Handler, R.Grobel[(b)], L.Pondrom, M.Sheaff,
and C.Wilkinson,

Physics Department, University of Wisconsin,
Madison, Wisconsin 53706,

L.Deck, T.Devlin, K.B.Luk, R.Rameika, and P.Skubic,

Physics Department, Rutgers - The State University,
Piscataway, New Jersey 08854,

K. Heller

Department of Physics, University of Michigan,
Ann Arbor, Michigan 48109
and Department of Physics, University of Minnesota
Minneapolis, Minnesota 55455,

and

G.Bunce,

Accelerator Department, Brookhaven National Laboratory,
Upton, New York 11973.

ABSTRACT

The magnetic moment of the Ξ^{0} hyperon has been measured to be $\mu_{\Xi^{0}} = (-1.253 \pm 0.014)$ nuclear magnetons. This differs from the prediction of the simple quark model by fourteen standard deviations.

The magnetic moments of the members of the baryon octet were first calculated assuming perfect SU_3 symmetry by Coleman and Glashow,[1] who obtained values for the static moments, μ_Λ, μ_{Σ^+}, μ_{Σ^o}, μ_{Σ^-}, μ_{Ξ^o}, μ_{Ξ^-}, and the transition moment, $\mu_{\Sigma\Lambda}$ in terms of the magnetic moments of the proton and neutron. SU_6 symmetry subsequently predicted $\mu_n/\mu_p = -2/3$,[2] in good agreement with the experimental value, $\mu_n/\mu_p = -0.685$. The color-symmetric quark model[3] specifies the spin configuration of the three quarks (u, d, s) which combine to form the baryon octet, and gives simple formulae for the baryon magnetic moments in terms of the quark moments.[4] If the quark moments are assumed to be proportional to their charges ($\mu_d = \mu_s = -\mu_u/2$) then the Coleman-Glashow relations and the μ_n/μ_p prediction follow. If μ_s is assumed to violate this constraint, then its value can be obtained from μ_Λ.[5] The result, $\mu_s = -0.614$ nuclear magnetons (1 n.m. = $e\hbar/2m_pc$, m_p = proton mass), is in good agreement with the value calculated using the s-quark mass obtained from a gauge theory treatment of baryon mass splittings[6] if g=2 is assumed. Given μ_u, μ_d and μ_s, precise measurements of other baryon magnetic moments test the validity of the color-symmetric three-quark model.

Two published results differ from the predictions of this model by three to four standard deviations. For Σ^+, $\mu_{\Sigma^+} = (2.33 \pm 0.13)$ n.m.,[7,8] compared with the model prediction of 2.67 n.m.[8] For Ξ^o, $\mu_{\Xi^o} = (-1.20 \pm 0.06)$ n.m., whereas the prediction is -1.45 n.m.[9]

The Ξ^o result was based on a sample of 40,000 Λ's from decays $\Xi^o \rightarrow \Lambda\, \pi^o$. The daughter Λ's were selected on the basis of their spatial distribution, since the γ-rays from π^o decay were not detected.

In the present experiment, 270,000 fully - reconstructed $\Xi^o \rightarrow \Lambda\, \pi^o$ events with an average Ξ^o momentum of 134 GeV/c were obtained by detecting the subsequent $\pi^o \rightarrow 2\gamma$ and $\Xi^o \rightarrow p\, \pi^-$ decays. These data were used to measure the inclusive polarization of Ξ^o's from $p+N \rightarrow \Xi^o + X$ and to obtain a precise measurement of μ_{Ξ^o}.

The apparatus and coordinate system are shown in Fig.1. The multiwire proportional chamber (MWPC) spectrometer has been described previously.[10,11] A 400 GeV proton beam produced Ξ^o hyperons in a 6 mm diameter target. The angle of incidence of the protons was varied from -10 to +10 mrad in the vertical (Y-Z) plane by the magnets, M1. The hyperon beam was defined by a brass collimator with a 0.5 mrad half - angle centered on the Z-axis. The collimator was embedded in a 5.3 m long magnet, M2, with a vertical (Y) field which swept charged particles out of the neutral beam, and precessed the hyperon spins in the X-Z plane. A veto scintillation counter, S1, defined the beginning of the decay region.

The charged products of the $\Lambda \rightarrow P\pi^-$ decay were detected in a spectrometer (C1-C6, M3, S6). Fast "OR" signals from the chambers were used in coincidence to trigger the data acquisition electronics. Separate signals from left and right halves of C5 and C6 were used to detect positive (P) and negative (N) particles downstream of M3. The coincidence $\Lambda = \overline{S1}*C1*C5N*C6P*S6$ yielded a high concentration (~50%) of Λ, both direct and from Ξ^o decay.

The γ-rays from $\pi^o \rightarrow 2\gamma$ were detected in an array of 69 lead glass blocks at the end of the spectrometer. An array of fast comparators was used to determine the number of showers striking the glass. A scintillator - lead - MWPC detector formed from chamber C7 increased the spatial resolution for γ-rays detected in the glass. To avoid false triggers from the proton from Λ decay, a 10 x 40 cm^2 hole was left in the lead glass array. Some of the π^- struck the glass, and these were detected in the hodoscope, H_π, which suppressed corresponding signals in the comparator logic. To increase the γ-ray acceptance two scintillator-lead shower detectors, S2-S5, were placed in front of C3 above and below the aperture of M3.

Two samples of Ξ^o triggers were accepted: one with the Λ trigger and both γ's detected in the lead glass (the "G2" sample), and the other with the Λ trigger, one γ detected in the glass and the second in one of the C3 shower detectors (the "G1" sample). Simultaneously, a pre-scaled fraction (1/128) of Λ coincidences was collected for normalization and calibration. The Ξ^o/Λ ratio was about 2%.

Data were taken at production angles of 0, ±4, ±7.6, and ±10 mrad, and with M2 field integral values of ±8.93, ±10.41, and ±13.46 T m. The field integral was known to within 0.1% and its setting was monitored continuously with a nuclear magnetic resonance probe. Only Ξ^o's which passed through the full length of the field before decay were accepted. Further details about the data and the Ξ^o reconstruction are given by Cox.[12]

If parity is conserved in the Ξ^o production process the polarization vector, $\vec{P}_\Xi$, is either parallel or antiparallel to the direction $\vec{k}_{in} \times \vec{k}_{out}$ at production, where $\vec{k}_{in}$ and $\vec{k}_{out}$ are the momenta of the incident proton and produced hyperon. The magnetic field in the beam channel causes $\vec{P}_\Xi$ at production to precess in the X-Z plane through an angle

$$\phi = \frac{2\mu_{\Xi^o}}{\hbar \beta c}\int Bdl,$$

where βc is the Ξ^o velocity, which equals c to 0.01%, and $\int Bdl$ is the field integral over the Ξ^o path. Through this relationship, a measurement of ϕ from the direction of $\vec{P}_\Xi$ after precession gives the magnetic moment.

The Ξ^o polarization was measured by relating it to the daughter Λ polarization. The Λ polarization is approximately given by the expression

$$\vec{P}_\Lambda \approx \alpha_\Xi \hat{k} + \gamma_\Xi \vec{P}_\Xi$$

where $\vec{P}_\Lambda$ is the Λ polarization, $\alpha_\Xi = (-0.412 \pm 0.011)$,[12] $\gamma_\Xi = (0.91 \pm 0.01)$, and $\hat{k}$ is the Λ momentum direction in the Ξ^o rest frame. This relation assumes time reversal invariance and ignores small terms which were found to be negligible in the analysis. One can form the scalar product $\vec{P}_\Lambda \cdot \hat{n}$ where $\hat{n}$ is $\hat{X}$, $\hat{Y}$ or $\hat{Z}$, center-of-mass coordinates parallel to the fixed lab axes. The α_Ξ term is explicitly calculable for each event. Its contribution, averaged over the acceptance of the apparatus is small, and completely cancels in the bias elimination procedure described below. Thus, $\vec{P}_\Xi$ can be determined from $\vec{P}_\Lambda$.

The Λ polarization was measured by the angular distribution of its decay proton. A hybrid Monte Carlo technique[13] was used to simulate the experimental acceptance and to extract the proton asymmetry with respect to $\hat{X}$, $\hat{Y}$ and $\hat{Z}$. From these, $\vec{P}_\Lambda$ and $\vec{P}_\Xi$ were computed. The Y components were consistent with zero as expected.

Systematic biases in the polarization measurements were eliminated by several methods. Data were taken at both positive and negative values of the precession field (reversing the precession angle), at both signs of the incident production angle (reversing the initial polarization), and at zero production angle (zero initial polarization). Biases, measured and eliminated by these methods, depended on Ξ^o momentum, but were independent of production angle and precession field.

In each of six momentum bins there were 24 data points: twelve combinations of magnetic field integral and initial polarization for the X and Z polarization components. The G1 and G2 samples were analyzed separately and found to be consistent. The results from the two samples were combined. A least - squares technique was used to fit each set of 24 data points with four free parameters: two bias terms (in X and Z), $\vec{P}_\Xi$, and μ_{Ξ^o}. The fitted values of μ_{Ξ^o} are shown in Fig. 2. The weighted average is shown, $\mu_{\Xi^o}= -1.253\pm0.014$ n.m., with $\chi^2=2.1$ for 5 d.f. The average polarization was -0.108 ± 0.006.[12]

For each field integral, Fig. 3 shows the precession angle calculated from the measured X and Z polarization components of the ± 7.6 mrad data. The least - squares fit straight line is shown; it was unconstrained at the origin, and the slope gave the value $\mu_{\Xi^o} = -1.252 \pm 0.022$ n.m. ($\chi^2 =$ 11 for 4 d.f.).

The value for the moment was stable against a wide variation of event selection cuts to better than 0.5σ . Backgrounds in the final sample were estimated to be less than 1%.[12] Unpolarized background would affect $\vec{P}_{\Xi}$ but not μ_{Ξ^o}. Several hypothetical polarized backgrounds, including beam Λ's, were introduced into the fit without improving χ^2 or changing μ_{Ξ^o}.

The final result for the magnetic moment of the Ξ^o is $\mu_{\Xi^o} = -1.253 \pm 0.014$ n.m., where the error is purely statistical. Systematic errors are estimated to be less than the statistical error. The second most precise measurement of the Λ magnetic moment was also obtained from an analogous procedure applied to the beam Λ events. This gave $\mu_{\Lambda} =$ -0.606 ± 0.015 n.m. The new world averages are: $\mu_{\Xi^o} = (-1.250 \pm 0.014)$ n.m., and $\mu_{\Lambda} = (-0.6129 \pm 0.0045)$ n.m.

The measured value of μ_{Ξ^o} differs from the simple quark model prediction by (0.20 ± 0.014) n.m., or fourteen standard deviations. Differences between precise measurements and the predictions of the simple model could arise from relativistic effects, mass corrections, configuration mixing and contributions from non-valence constituents.[6,8,14,15] Some of these corrections improve the agreement between theory and experiment, but none is completely satisfactory.

Coleman and Glashow[1] predicted $\mu_\Lambda = \mu_n/2$ and $\mu_{\Xi^o} = \mu_n$. Neither relation agrees well with experiment, but the ratio, $\mu_{\Xi^o}/\mu_\Lambda = 2$ is in remarkably good agreement with the present result, $\mu_{\Xi^o}/\mu_\Lambda = (2.039 \pm 0.027)$.

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FOOTNOTES

(a) Present address: EP Division, CERN, CH1211 Geneva 23, Switzerland.

(b) Present address: Physics Department, New York University, New York, New York 10003.

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FERMILAB-PUB-81-102-E

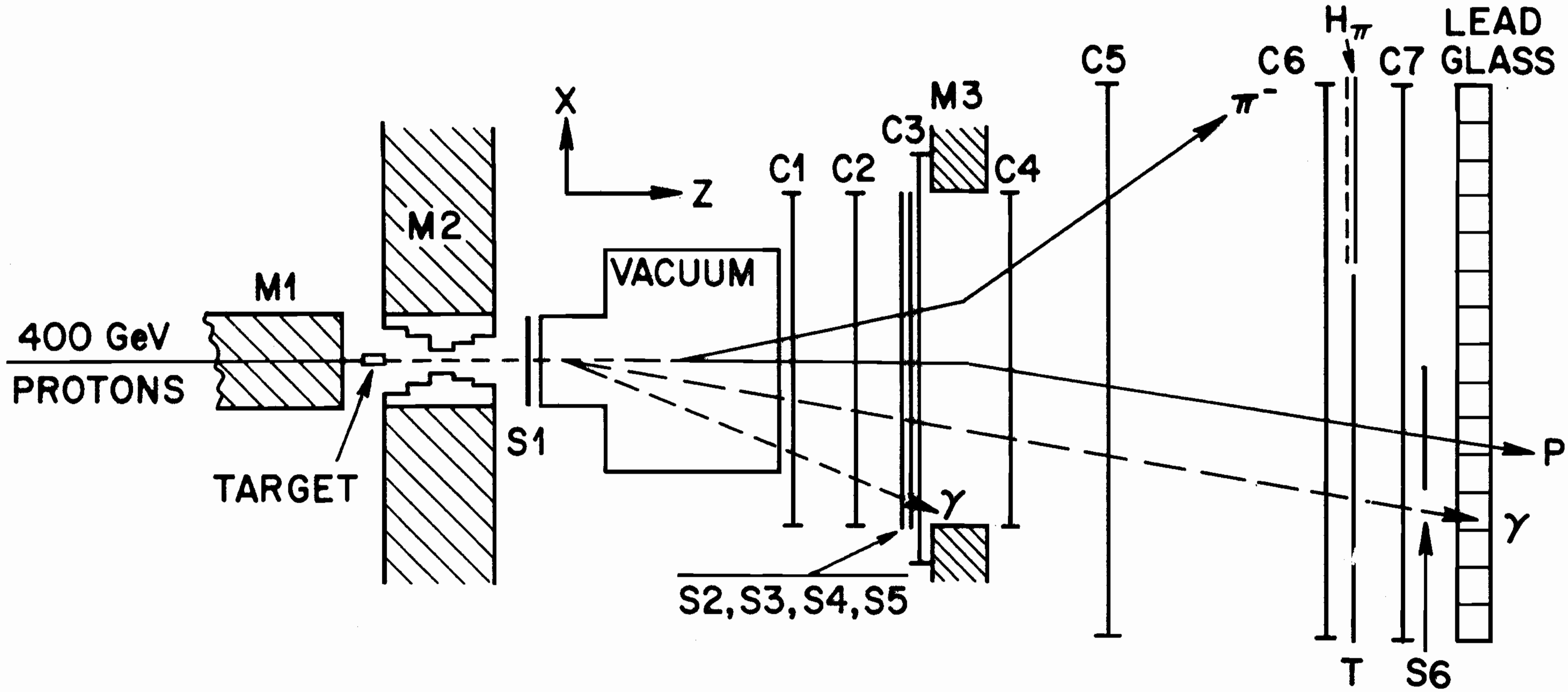
FIGURE CAPTIONS

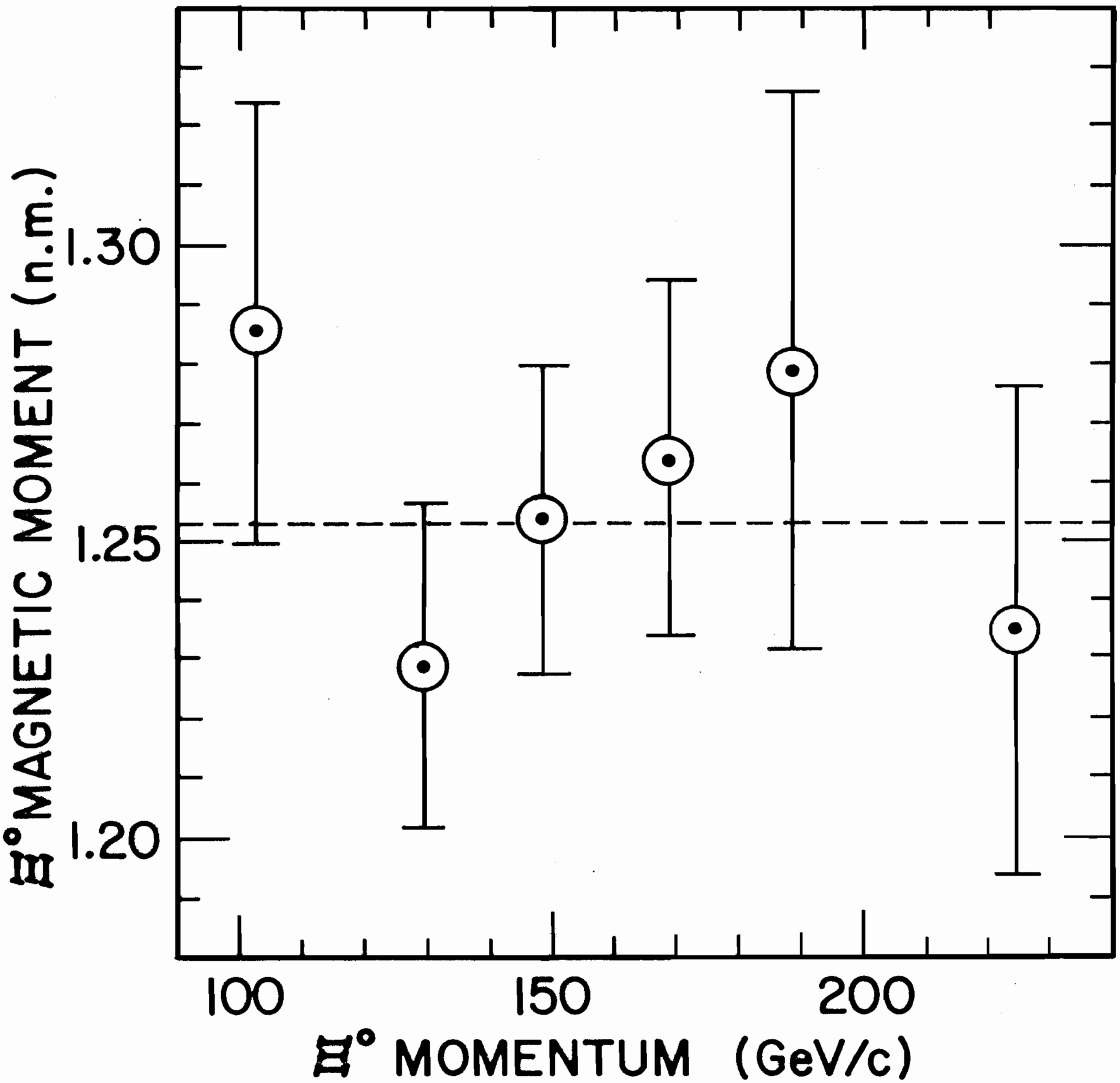
Fig.1 A plan view of the apparatus and coordinate system described in the text. For clarity, some features are not drawn to scale. An event with a type G1 trigger is shown. The coordinate system is right-handed with Y vertical.

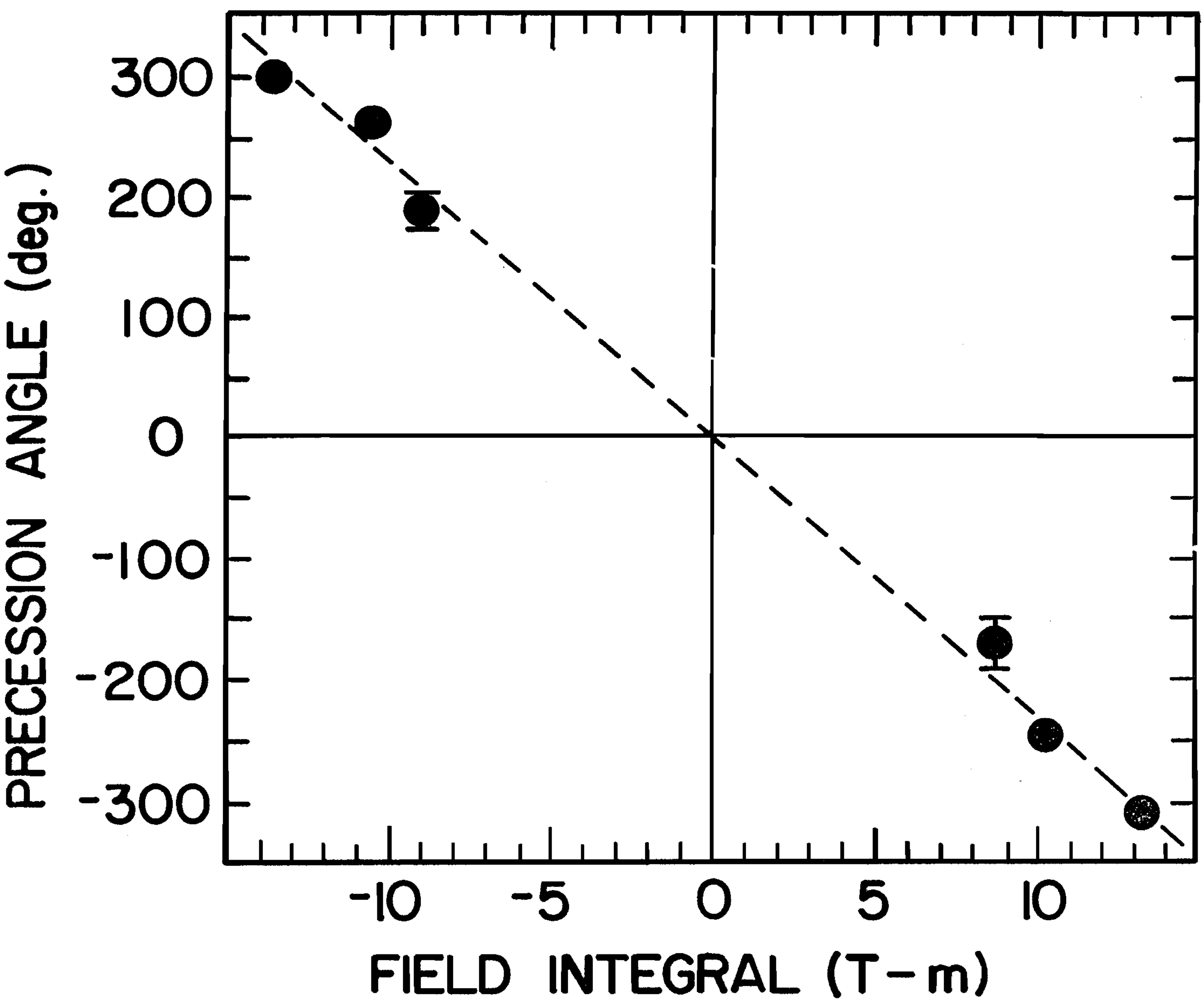
Fig.2 The magnetic moment of the Ξ^{o} hyperon measured for each of six momentum bins. Note suppressed zero.

Fig.3 Precession angle vs. field integral ($\pm$7.6 mrad data) The magnetic moment is proportional to the slope of the fitted line.

FERMILAB-PUB-81-102-E




1.30
1.25
1.20
Ξ° MAGNETIC MOMENT (n.m.)
100
150
200
Ξ° MOMENTUM (GeV/c)


PRECESSION ANGLE (deg.)
300
200
100
0
-100
-200
-300
-10
-5
0
5
10
FIELD INTEGRAL (T-m)