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A Precise Measurement of the Λ^o Magnetic Moment

by

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ABSTRACT

The magnetic moment of the Λ^o hyperon has been measured to be $\mu_\Lambda = -0.6138 \pm 0.0047$ nuclear magneton.

Magnetic moments have played a major role in the development of our current understanding of the structure of matter. The Zeeman effect and the Stern-Gerlach experiments were crucial to modern ideas of angular momentum, spin, quantum mechanics and atomic structure. Extraordinarily precise measurements of the magnetic moments of the electron and muon have supported the validity of quantum electrodynamics and established that these charged leptons behave as pointlike Dirac particles. The magnetic moments of the deuteron and other nuclei shed light on the structure of these composite systems. If the lessons of the past are any guide, precise measurements of baryon magnetic moments will provide us with strong constraints on models of hadronic structure, and important information about the nature of the constituents of hadrons.

The large anomalous moments for the neutron and proton have shown that these particles are not elementary. Their structures can be related by unitary symmetry schemes which predict the ratio of their moments with an accuracy of 3%. Unitary symmetry also predicts the moments of the strange baryons. Previous measurements of the Λ^0 moment indicate that the symmetry is not exact, and that an additional, symmetry-breaking parameter must be introduced into the theory.

In a simple s-wave quark model of the baryons, the nucleons contain only u and d quarks, and their moments can be used to calculate these quark moments. The magnetic moments of the other members of the baryon octet involve the strange quark. The lambda hyperon consists of u, d and s quarks with the u and d quarks in a state with spin J = 0. The spin and magnetic moment of the Λ^o are identical to those of its s-quark. Among the stable baryons, this property is unique. Thus a precise measurement of the Λ^o moment gives the s quark moment directly. This, in turn, can be compared with the moment of the u quark to give the symmetry breaking. Further assumptions regarding the relationship between mass and magnetic moment allow calculations of quark masses which can be compared to those determined directly from hadron masses.

The observation that Λ^o's inclusively produced by 300 GeV protons are polarized has been reported.[1] This polarization offered an opportunity to measure the Λ^o magnetic moment with unprecedented precision because of several advantages over earlier experiments. The large inclusive cross section and rapid data-acquisition techniques make it possible to obtain a large sample of polarized Λ^o's in a relatively short time. The high energy results in a average decay length of order 10 meters. Conventional DC magnets over such distances give large precession angles. Finally, the Fermilab neutral hyperon spectrometer has high acceptance (greater than 70% averaged over momentum) in the Λ^o center of mass which reduces systematic errors in measurements of the polarization vector. A measurement of the Λ^o magnetic moment (to 9% uncertainty) was an intrinsic part of the original discovery of polarization. It was clear that a number of improvements could be made in a new experiment specifically designed to measure the moment.

The basic apparatus common to both measurements is illustrated in Fig. 1a.[2] The coordinate system (Fig. 1b) has $\hat{Z}$ along the neutral beam direction. $\hat{Y}$ is vertical upwards, and $\hat{X} = \hat{Y}\times\hat{Z}$ is horizontal. The incident proton beam was steered in the Y-Z plane onto the Be production target at each of several positive and negative angles relative to the Z-axis. At the production target the polarization was in the parity-allowed direction, $-(\hat{k}_p \times \hat{k}_\Lambda)$ where $\hat{k}_p(\hat{k}_\Lambda)$ is the proton (Λ^o) momentum direction. The hyperon beam was defined by a brass collimator which constrained $\hat{k}_\Lambda$ to lie within a cone of 0.5 mrad half angle, centered on the Z-axis.

A vertical magnetic field, applied along the entire 5.3 m length of the collimator, served to sweep charged particles from the neutral beam, as well as to precess the Λ^o spin in the horizontal plane through an angle $\phi = (\mu_\Lambda c/\hbar\beta)\int BdL$ where $\int BdL$ is the integral of the field over the Λ^o path, and μ_Λ is the Λ^o magnetic moment. Above 60 GeV/c, $\beta = 1$ to an accuracy of 0.02% or better. Only Λ^o's which passed through the full length of the field and decayed within a well-defined volume were accepted. The proton and π^- from the charged decay mode were detected in a multi-wire proportional chamber spectrometer of conventional design. Each of the three components of the polarization vector was obtained from the asymmetry of the decay proton angular distribution in the Λ^o rest frame.[3] The direction of this vector, measured for various known values of the magnetic field integral, yielded the magnetic moment.

Three major improvements increased the precision of the present measurement over the previous one. First, the sample of Λ^0's was increased by a factor of ten to 3×10^6 with an average polarization of 8%. The Λ^0 sample and its polarization are described in more detail in Ref. 4.

Second, the sweeping magnet field was measured precisely in two ways. The brass collimator was removed, a proton-resonance probe inserted into the magnet, and the field was recorded every 2.5 cm along the collimator axis. The fringe field, which comprised 7% of the integral, was measured with a Hall probe. The precision of this method was 0.07% of the integral. A stretched-wire flip coil, which measured the field integral directly was used to provide independent measurements, and to extend them outside the limited frequency range of the resonance probe. The coil, which consisted of two turns of 0.1 mm tungsten wire, was 7.5 m long and 1.27 cm wide. It was flipped 180° in the field, and the emf induced in the wire was integrated. The reproducibility was 0.2% and the absolute calibration of this method alone was known to 1%. The coil was used to obtain a full excitation curve for the magnet. Where the two types of measurements overlapped, they agreed within errors. The proton-resonance results were used to calibrate the stretched wire results so that the overall precision for all field integral values was 0.2%. A resonance probe was left in a fixed position in the magnet to define and monitor the field during the magnetic measurements and during the data collection. Run-to-run fluctuations were 0.1%, and variations during a run were negligible.

The third improvement involved bias-cancelling techniques. The earlier measurements[1] included periodic reversals of the sweeper magnetic field, which reversed the sign of the precession angle, and of the spectrometer magnetic field, which interchanged left and right in the downstream chambers. In the present experiment, the production angle, θ, was also reversed, thus reversing the Λ^o spin direction in space. Data were taken at $\theta = 0$, $+7.2$ and -7.2 mrad.

The acceptance of the apparatus was well-simulated by Monte Carlo calculations. However small biases remained in the asymmetry measurements. These biases were independent of production angle and precession field integral, but they did depend on hyperon momentum. The biases were measured and eliminated by production angle and magnetic field reversals.

As a check on systematic errors, seven values of the field integral were used: 0, ± 9.05, ± 10.55, and ± 13.64 Tesla-meters. Thus, one can determine the change in the direction of polarization without any assumptions about its direction at the production target.

Fig. 2 displays the precession quite clearly in terms of the measured asymmetries, αP_x and αP_z, where $\alpha = 0.647 \pm 0.013$ is the Λ^o decay asymmetry parameter.[5] P_x and P_z with precessing field off show that the polarization is entirely along $-\hat{X}$. For +13.64 T-m the X-component has changed sign, and strong

Z-components have developed. The results can be understood in terms of the precession diagram inset into the figure.

The calculation of the magnetic moment was done by a least-squares technique, minimizing

$$\chi^2 = \sum_{ijk} [\pm \alpha P_i \cos(\phi_j) \pm A_{xi} + B_{xi} - \alpha P_{xijk}]^2 / \sigma^2_{xijk} + [\pm \alpha P_i \sin(\phi_j) \pm A_{zi} + B_{zi} - \alpha P_{zijk}]^2 / \sigma^2_{zijk}$$

where P_{xijk} and P_{zijk} are the measured components of the polarization for the seven momentum bins between 60 and 270 GeV/c ($i = 1,7$), sweeper field settings ($j = 1,7$), and the four conditions of production angle sign and spectrometer polarity ($k = 1,4$). The parameters, P_i, represent the X-components of the polarization vectors at the production target in the various momentum bins. An independent calculation established that the Z-components were zero. The values of P_i reverse sign with production angle. The precession angles, ϕ_j, measured relative to the initial polarization vector, were computed from the measured field integrals and the magnetic moment parameter through the relation

$$\phi_j = (\mu_\Lambda / \mu_N)(18.30 \text{ degrees/Tesla-m}) \int B_j dL,$$

where μ_N = nuclear magneton = $e\hbar/2M_p c$ = 3.15252×10^{-14} MeV/Tesla.[6] The fit allowed for biases both symmetric and antisymmetric with respect to the spectrometer magnetic field. The bias parameters, A_{xi} and A_{zi}, reverse sign with spectrometer polarity. The bias parameters, B_{xi} and B_{zi}, do not. The results of the fit are presented in Table I. A single value of μ_Λ fits the data, with good χ^2, over a variety of precession angles, momentum bins and bias conditions.

The overall consistency of the data can be illustrated in other ways. In Fig. 3a, the precession angle has been calculated for each of the field integrals. They are well-represented by a straight line passing through the origin. In Fig. 3b, the fit described above was performed separately for each momentum bin. The magnetic moment shows no dependence on momentum despite the strong momentum dependence of the biases given in Table I.

The selection criteria required to ensure a clean sample of Λ^o's involved relatively loose cuts. The magnetic moment was stable against wide variation of cuts to better than 0.5 std. dev. Backgrounds in the final sample were 0.5% K_S^o, 5% Λ^o's produced by neutrons in the collimator, and 0.1% Λ^o's from Ξ^o decay. These effects changed the moment by less than 0.1 std. dev.

Our result for the magnetic moment of the Λ^o is

$$\mu_\Lambda = (-0.6138 \pm 0.0047)\, \mu_N.$$

This is to be compared with the average of all previous measurements[1,7-13] $(-0.606 \pm 0.034)\, \mu_N$.

This number, together with the nucleon magnetic moments, can be used to calculate the magnetic moments of the quarks, provided that some assumptions are made regarding the addition of quark moments to form the baryons. In the simplest S-wave broken SU(6) model, with $\mu_d = -\mu_u/2$, the value of μ_u can be calculated from either the proton or neutron moment. Taking a simple average of the two results for μ_u, and $\mu_s = \mu_\Lambda$ gives the quark moments shown in Table II. From these the other baryon magnetic moments were calculated.

It has been noted[14] that, assuming a g-factor of 2.0, the quark magnetic moments can be used to determine the quark masses through the relation $M_q = (e_q \hbar)/(2\mu_q c)$. The masses thus obtained are $M_u = M_d = 0.331$ GeV/c^2, $M_s = 0.510$ GeV/c^2. It has been suggested[15] that, because of strong spin-spin effects among constituents of hadrons, the quark mass splitting should be $M_s - M_u = M_\Lambda - M_p = 0.177$ GeV/c^2. The quark mass difference of 0.179 GeV/^{2}, obtained from the magnetic moments, agrees well with this relation.

In general, the magnitudes of quark masses obtained from magnetic moments agree fairly well with the "realistic"[16] masses determined from splittings of hadron multiplets. This implies that quarks have no large anomalous moments and may be pointlike Dirac particles.

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FOOTNOTES AND REFERENCES

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2. A complete description of the apparatus is given in P. Skubic et al., to be published in Phys. Rev. D. A more detailed account of all aspects of the present experiment can be found in L. Schachinger, Ph. D. Thesis, Rutgers University, 1978 (unpublished).

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FIGURE CAPTIONS

Fig. 1 (a) An elevation view of the apparatus. M1 was a vertical bending magnet used to vary the proton beam direction as it struck the Be target, T. S, IC, and BCI were proton beam detectors. M2 was the sweeper/precession magnet. The VETO scintillation counter defined the upstream boundary of the decay region. C_i were multi-wire proportional chambers before and after the spectrometer magnet, M3. TS was a scintillation counter used for precise timing. (b) A schematic view of the coordinate system, production angle, polarization vector and precession angle.

Fig. 2 X- and Z-components of the Λ^0 polarization vector with precessing field off (solid squares), positive precession angle (solid circles), and negative precession angle (open circles). Note that the polarization is along $-\hat{X}$ with field off; rotates so that it has a large component along $+\hat{X}$ with the field on, independent of polarity; and acquires a Z component which reverses as the polarity, or precession sense, is reversed.

Fig. 3 (a) A plot of the measured precession angle versus the measured field integral. (b) A plot of the measured Λ^0 magnetic moment for each of seven momentum bins.

Table I. Results of Fit to Λ° Precession Data

Momentum (GeV/c)	αP_i	A_{xi}	A_{zi}	B_{xi}	B_{zi}
77	-0.022±0.002	0.024±0.002	-0.003±0.003	0.005±0.002	-0.141±0.003
105	-0.045 0.002	0.019 0.002	-0.009 0.002	-0.001 0.002	-0.043 0.002
133	-0.067 0.002	0.010 0.002	-0.014 0.002	-0.002 0.002	-0.025 0.002
163	-0.090 0.003	0.014 0.003	-0.020 0.003	0.003 0.003	-0.011 0.003
192	-0.117 0.005	0.007 0.005	-0.024 0.005	+0.003 0.005	-0.020 0.005
222	-0.135 0.009	-0.008 0.009	-0.026 0.009	-0.002 0.009	0.004 0.009
252	-0.144 0.017	-0.015 0.017	-0.028 0.017	-0.049 0.017	0.011 0.017

$\mu_\Lambda = (-0.6138 \pm 0.0047)\ \mu_N$

392 Data Points 36 parameters

$\chi^2 = 380.4$, Degrees of Freedom = 356

$P(\chi^2) = 0.18$

Table II. Quark Model Magnetic Moments

Moment	Predicted	Observed
$\mu(p)$	2.8313	2.7928 (a,c)
$\mu(n)$	-1.8875	-1.9130 (a,d)
$\mu(\Lambda^o)$	-0.6138	-0.6138 (a)
$\mu(\Sigma^+)$	2.7213	2.95 ± 0.31 (e)
$\mu(\Sigma^o)$	0.8338	--
$\mu(\Sigma^-)$	-1.0537	-1.48 ± 0.37 (f)
$\mu(\Xi^o)$	-1.4476	--
$\mu(\Xi^-)$	-0.5038	-1.85 ± 0.75 (g)
$\mu(\Omega^-)$	-1.8414	--
$\mu(\Sigma^o \rightarrow \Lambda^o \gamma)$	-1.6346	$\lvert\mu\rvert = 1.82^{+0.25}_{-0.18}$ (h)
$\mu(u)$	1.8875 (b)	--
$\mu(d)$	-0.9438 (b)	--
$\mu(s)$	-0.6138 (b)	--

NOTES:

(a) Data used as input.

(b) Parameters

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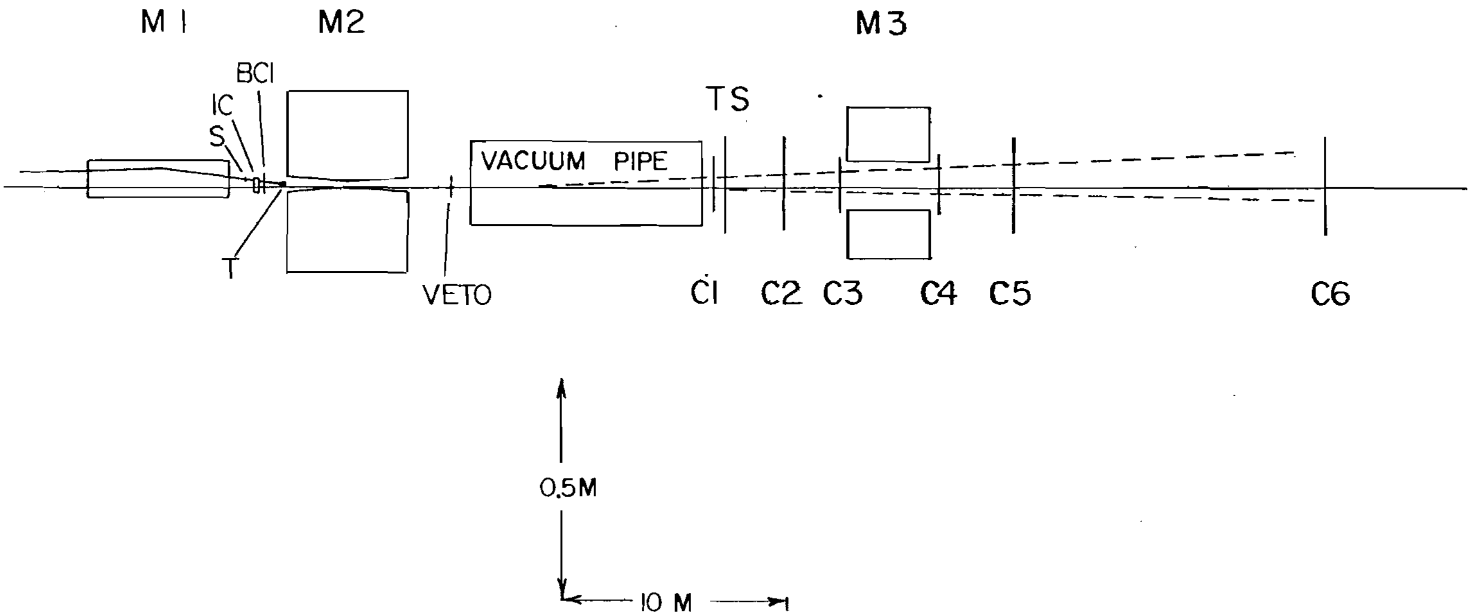
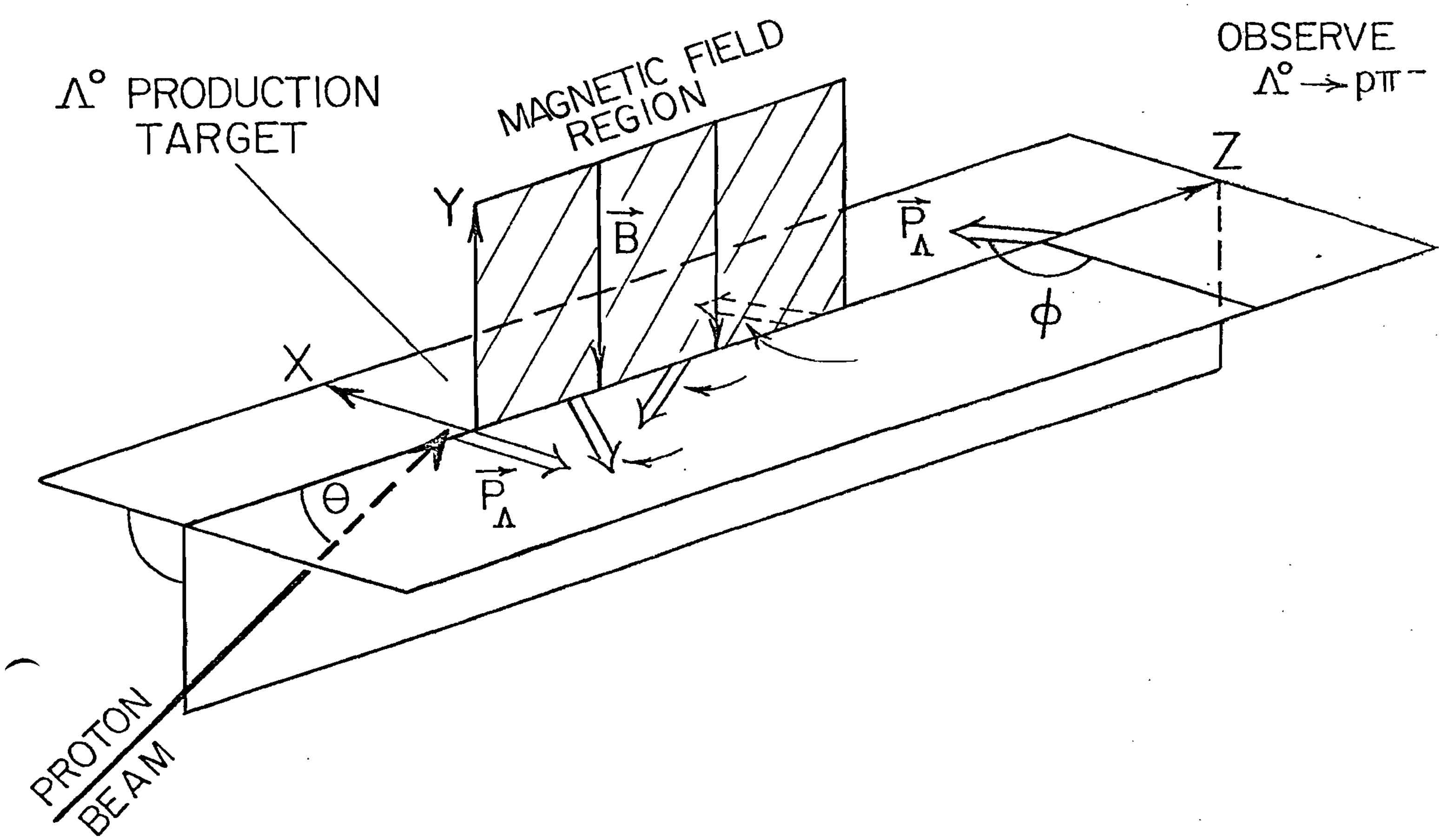
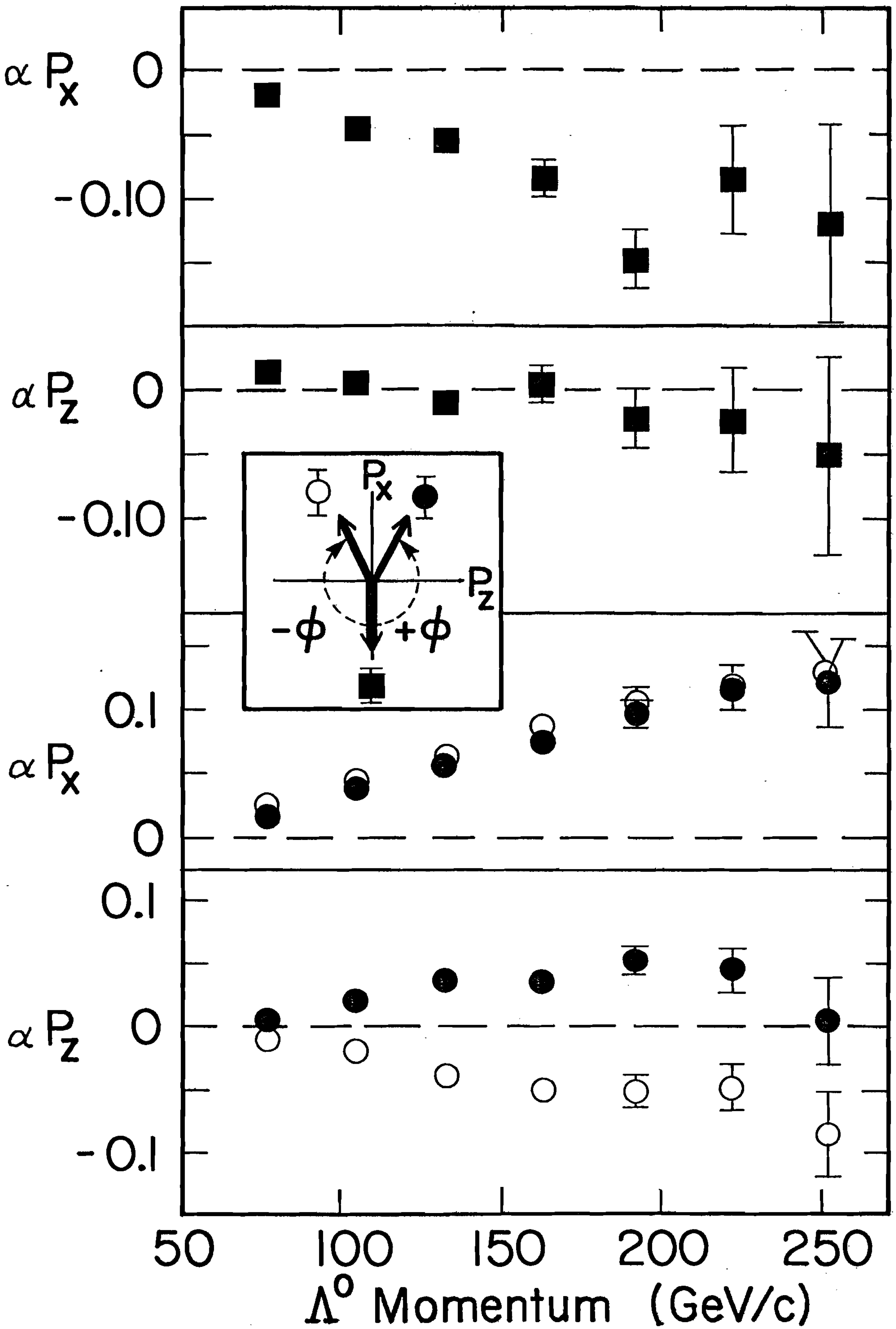
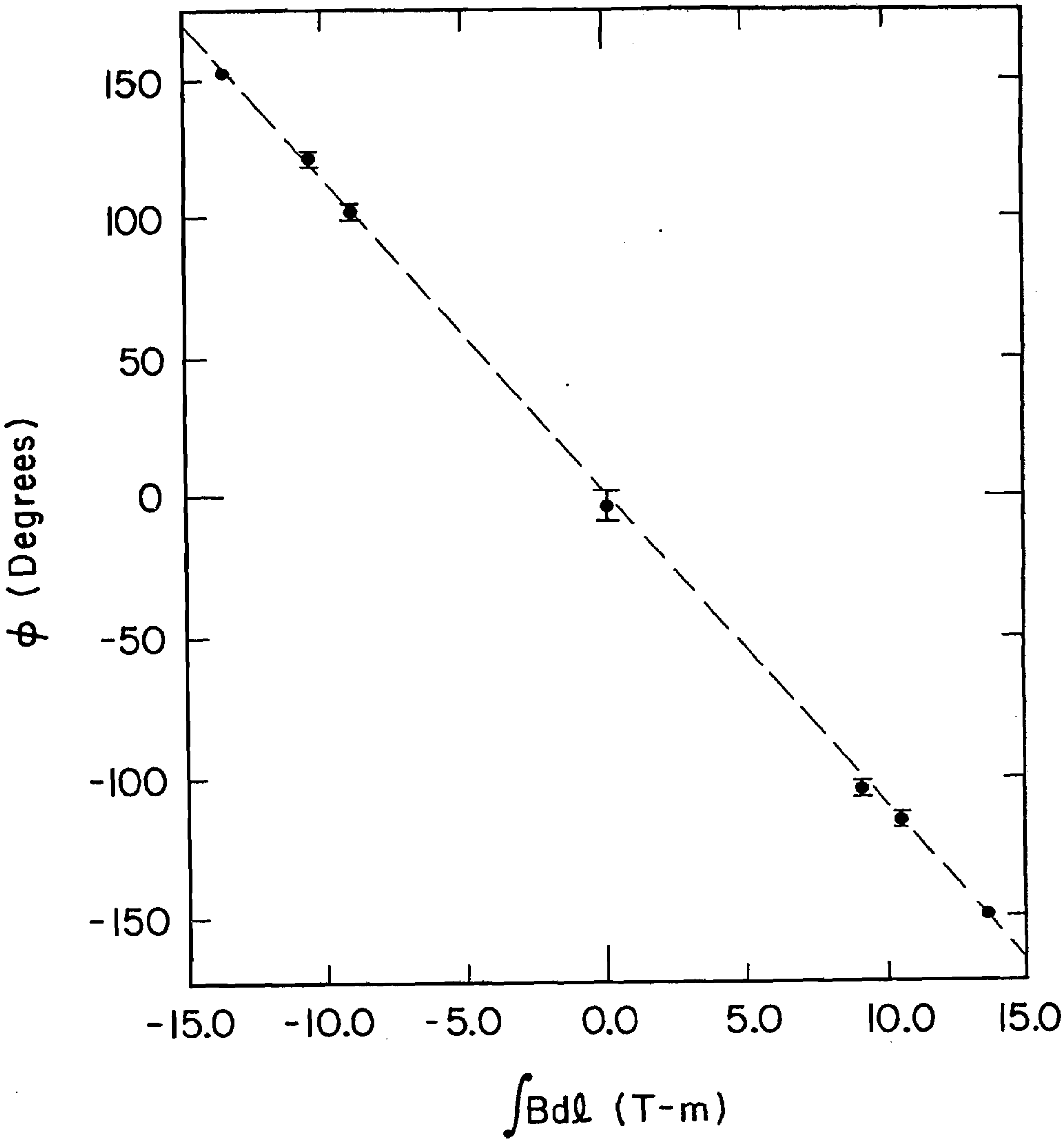
ELEVATION VIEW



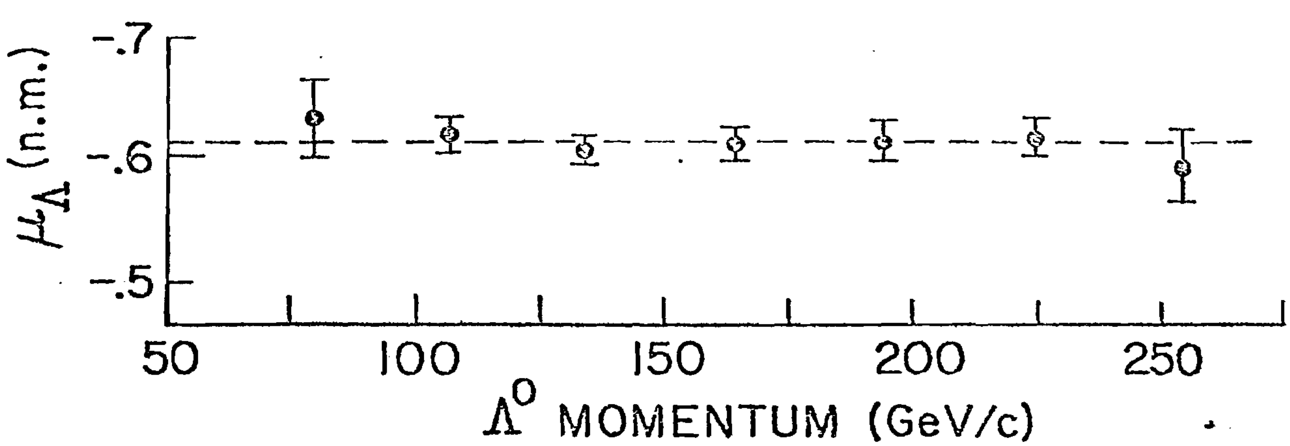




α Px
0
-0.10
α Pz
0
-0.10
Px
Pz
-φ
+φ
0.1
α Px
0
0.1
α Pz
0
-0.1
50
100
150
200
250
Λ0 Momentum (GeV/c)



150
100
50
0
-50
-100
-150
φ (Degrees)
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
∫Bdℓ (T-m)



-.7
-.6
-.5
μ_Λ (n.m.)
50
100
150
200
250
Λ^0 MOMENTUM (GeV/c)