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A MEASUREMENT OF THE Σ^- MAGNETIC MOMENT USING THE $\Sigma^- \to ne^-\bar{\nu}$ AND $\Sigma^- \to n\pi^-$ DECAY MODES*

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Abstract

We have used the spin precession technique to measure the Σ^- magnetic moment (μ_{Σ^-}). A Σ^- beam with a polarization of 22% was produced by a 400 GeV proton beam striking a Cu target at nominal production angles of ±3 mrad. We simultaneously recorded 21,000 $\Sigma^- \to n e^- \overline{\nu}$ decays and 650,000 $\Sigma^- \to n\pi^-$ decays at Σ^- beam momenta of 253 and 308 GeV/c. We find $\mu_\Sigma = -1.166 \pm 0.014 \pm 0.010\ \mu_N$, where the quoted errors are statistical and systematic, repectively.

The magnetic moments of the spin 1/2 baryon octet provide a probe of the baryons' internal structure.[1-12] Quark wavefunctions have been modeled by corrections to the nonrelativistic SU(6) quark model.[3,4,6-11] They have also been modeled within the framework of the relativistic bag model.[2,5,12] The weak decay of the hyperons in the octet (save the Σ^0) makes their magnetic moments accessible to the spin precession method.[13] This method requires a hyperon beam polarized normal to a magnetic field. The polarization vector then precesses through an angle determined by the magnetic moment and the field integral. The polarization vector is analyzed downstream of the magnet with the hyperon decay asymmetry.

The previous measurements of Deck et al. ($\mu_\Sigma = -0.89 \pm 0.14\ \mu_N$, where μ_N is the nuclear magneton)[14] and Wah et al. ($\mu_\Sigma = -1.23 \pm 0.04\ \mu_N$)[15] were performed with the spin precession method using the hadronic $\Sigma^- \to n\pi^-$ decay mode. The measurement of μ_Σ from the $\Sigma^- \to n\pi^-$ decay is difficult because of the small asymmetry parameter ($\alpha_\pi = 0.068 \pm 0.008$).[16] We report a new measurement of μ_Σ from a sample of 21,000 beta decays: $\Sigma^- \to n e^- \overline{\nu}$. The electron asymmetry parameter is much larger ($\alpha_e = -0.53 \pm 0.14$)[17] compensating for the small branching ratio (1.02×10^{-3}).[16] We also obtain a value from 650,000 hadronic decays.

The apparatus[17,18] is pictured in Figure 1. A 400 GeV proton beam from the Fermilab Tevatron was directed onto a Cu target placed in the upstream portion of the hyperon magnet. A curved channel through the hyperon magnet momentum selected a negative beam composed at the channel exit of approximately 87% π^-, 10% Σ^-, and the rest K^-, Ξ^-, $\overline{p}$, and e^-. The selected momenta were 253 GeV/c (17.6 Tm) and 308 GeV/c (21.4 Tm) at nominal production angles of +3 or -3 mrad. The beam emerging from the hyperon magnet was limited to 1 μsr with a momentum spread of $\Delta p/p$ = 7%. The allowed (parity conserving) component of the polarization is normal to the production plane defined by the proton and Σ^- momenta. We have previously reported[17] a Σ^- polarization of 22 ± 4% in the direction given by $p_{proton} \times p_{\Sigma^-}$. This polarization is along the positive x axis for +3 mrad, where our coordinate system is defined with y in the vertical direction (opposite to the field in the hyperon magnet), z along the beam axis, and x oriented to yield a right-handed system. Note that the polarization vector changes sign when the production angle is reversed.

We recorded beta decays and hadronic decays simultaneously. The $\Sigma^- \to n\pi^-$ trigger required an incident particle defined by beam scintillation counters in the proportional wire chamber (PWC) region and the detection of a neutral particle in the neutron calorimeter located at the downstream end of the apparatus. The $\Sigma^- \to ne^-\overline{\nu}$ trigger required in addition the detection of an electron in the transition radiation detector (TRD)[19] and a selection on the pulse heights of four scintillators (multiplicity counters) to reject hadronic showers initiated in the TRD.

The field integrals in the hyperon magnet and in the magnet spectrometer are determined by the requirement that the Σ^- mass reconstructed from the $\Sigma^- \to n\pi^-$ decay be independent of the angle between the z axis and the π^- momentum in the Σ^- rest frame. We determine the field integral of the hyperon magnet to within ±1%; our error reflects the uncertainty of the Σ^- production point in the target.

Σ^- decay candidates were required to have a single track in the

PWCs and in the drift chambers. The position of the decay vertex was restricted to an evacuated 12 m fiducial region immediately downstream of the PWCs.

Hadronic decays were identified by requiring the π^- momentum in the Σ^- rest frame to be near its expected value of 193 MeV/c (Figure 2a). This suppressed $\Xi^- \rightarrow \Lambda\pi^-$ background, estimated to be 2% in the final event sample. Expanding the cut to double the background produced no significant change in the μ_Σ result.

The TRD and a lead glass calorimeter (LGC) separated the $\Sigma^- \rightarrow ne^-\bar{\nu}$ from the $\Sigma^- \rightarrow n\pi^-$ background. Σ^- decay electrons were restricted to the fiducial area of the LGC by requiring the electron momentum to be between 12.5 and 50 GeV/c. The overall beta decay efficiency was 93%; hadronic decays were suppressed by 50,000. We included selection criteria based upon the shower development in the LGC and the requirement that the energy E measured by the LGC agree with the momentum P determined by the magnet spectrometer. The distribution of the ratio E/P is shown in Figure 2b for the final beta decay sample. Examination of the tails of the distribution indicates a 4% background from Σ^- and Ξ^- hadronic decays in the final event sample. Expanding the E/P cut to triple this background did not produce a significant change in the μ_Σ result.

The observed angular distribution of any daughter particle in the Σ^- rest frame may be written as

$$\frac{dN}{d(\cos\theta_\zeta)} = A(\cos\theta_\zeta)[1+\alpha P_\zeta \cos\theta_\zeta]\,, \tag{1}$$

where $A(\cos\theta_\zeta)$ is the experimental acceptance, P_ζ is the component of polarization along the ζ axis, and θ_ζ is the angle between the daughter particle momentum and the ζ axis.

To extract the precession angle θ_p, we determine the orientation of the polarization vector in the horizontal plane after the beam has exited the hyperon magnet. We calculate the fraction of events for each $\cos\theta_\zeta$ bin for ζ = x, y, or z. We then form the quantity $(F_\zeta^+ - F_\zeta^-)/(F_\zeta^+ + F_\zeta^-) = \alpha P_\zeta \cos\theta_\zeta$, where $F_\zeta^{+(-)}$ is the fraction of events in the $\cos\theta_\zeta$ bin with an initial polarization vector parallel (+) or antiparallel (-) to the x axis. This procedure cancels false asymmetries due to our instrumental acceptance. The precession angle depends upon the anomalous magnetic moment of the Σ^-

$$(2) \qquad \theta_p = \gamma \Phi_B \left(\frac{g}{2} - 1 \right),$$

where γ is the Lorentz factor of the Σ^- corresponding to the momentum of the central trajectory in the hyperon magnet, and Φ_B is the bend angle of the magnet. The Σ^- magnetic moment is related to g by

$$(3) \qquad \mu_\Sigma = (g m_p / 2 m_\Sigma) \mu_N .$$

Quantities which characterize the Σ^- trajectory in the x-z plane (momentum and azimuth angle) have well matched distributions for both production angles. The distributions for the dip angle are less well matched because of the dependence of Σ^- production on transverse momentum. We have weighted the data by the dip angle to improve the agreement. The result is insensitive to the weighting procedure.

The decay angular distribution has been analyzed for four independent data sets: 253 GeV/c $\Sigma^- \to n e^- \bar{\nu}$ (15,000 events), 308 GeV/c $\Sigma^- \to n e^- \bar{\nu}$ (6000 events), 253 GeV/c $\Sigma^- \to n \pi^-$ (310,000 events), and 308 GeV/c $\Sigma^- \to n \pi^-$ (340,000 events). Figure 3 shows the projected distributions for the 253 GeV/c data. The asymmetries and μ_Σ values from all four data sets are given in Table 1. These asymmetries are in agreement with our earlier results for Σ^- particles polarized in the y direction.[17] The 12 χ^2 values associated with the fits to the four data sets have an average value of 19.3 for 18 degrees of freedom. We expect and find no component of polarization along the y axis.

The μ_Σ values in Table 1 are calculated with the assumption that $0<\theta_p<2\pi$. The $2n\pi$ ambiguity and the ambiguity in the sense of precession may be eliminated by using the information at both beam energies (see Figure 4) and by demanding modest agreement (within 10 σ) with the measurement of Hertzog et al.[20] using the hyperfine x-ray splitting in Σ^- atoms. Hertzog's measurement ($\mu_\Sigma = -1.111 \pm 0.033\ \mu_N$) involves ambiguities which are different from those in the spin precession technique.

We have considered systematic errors from the following sources: chamber alignment, uncertainty in the field integrals of the hyperon and spectrometer magnets, polarized background from $\Xi^-\rightarrow\Lambda\pi^-$ and $\Xi^-\rightarrow\Lambda e^-\overline{\nu}$ decay, bremsstrahlung of the electron from $\Sigma^-\rightarrow n e^-\overline{\nu}$ decay, stability of the result as the selection criteria are varied, and sensitivity of the result to the phase space available to the beam. The systematic error from each of these sources is significantly less than the statistical error for each of the four measurements.

Our combined result for all four data sets is $-1.166 \pm .014 \pm .010\ \mu_N$, where the quoted errors are statistical and systematic, respectively. An important feature of this experiment is that the magnetic moments obtained from the beta decays and the hadronic decays agree. The beta decays are subject to potential biases in the electron identification while the hadronic decays are sensitive to small geometric biases. The agreement between the two decay modes gives a valuable check on the systematic errors.

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Table 1. Components of asymmetry, Σ^- magnetic moment in nuclear magnetons, and sample size for each data set.

	$\Sigma^- \to n e^- \bar{\nu}$		$\Sigma^- \to n \pi^-$	
	253 GeV/c	308 GeV/c	253 GeV/c	308 GeV/c
αP_x	0.077±0.015	0.117±0.023	-0.0084±0.0034	-0.0166±0.0034
αP_y	0.018±0.014	0.019±0.023	0.0057±0.0034	0.0027±0.0034
αP_z	-0.103±0.022	-0.099±0.034	0.0137±0.0034	0.0077±0.0034
μ_Σ	-1.178±0.024	-1.140±0.028	-1.161±0.038	-1.179±0.027
Events	15,000	6000	310,000	350,000

Figure Captions

1. Plan view of the apparatus. Note that the horizontal scale is compressed. Typical particle trajectories are shown.

2. (a) The π^- momentum (P_π) distribution in the Σ^- rest frame for the 253 GeV/c $\Sigma^- \to n\pi^-$. We accept events between the arrows in the region $0.164 < P_\pi < 0.225$ GeV/c. (b) The E/P distribution for the 253 GeV/c $\Sigma^- \to ne^-\overline{\nu}$. We accept events between the arrows in the region $0.84 < E/P < 1.14$.

3. Graph of $(F_\zeta^+ - F_\zeta^-)/(F_\zeta^+ + F_\zeta^-)$ vs. $\cos\theta_\zeta$ for ζ = x, y, and z for (a) 253 GeV/c $\Sigma^- \to ne^-\overline{\nu}$ and (b) 253 GeV/c $\Sigma^- \to n\pi^-$. Note that the slopes have opposite signs for the two decay modes because the asymmetry parameters α_e and α_π have opposite signs. Note also the different vertical scales.

4. The precession angle (θ_p) vs. the field integral ($\int Bdl$) in the hyperon magnet for the two Σ^- decay modes. The line shows the expected dependence for $\mu_\Sigma = -1.166\ \mu_N$. Note the suppressed zero.

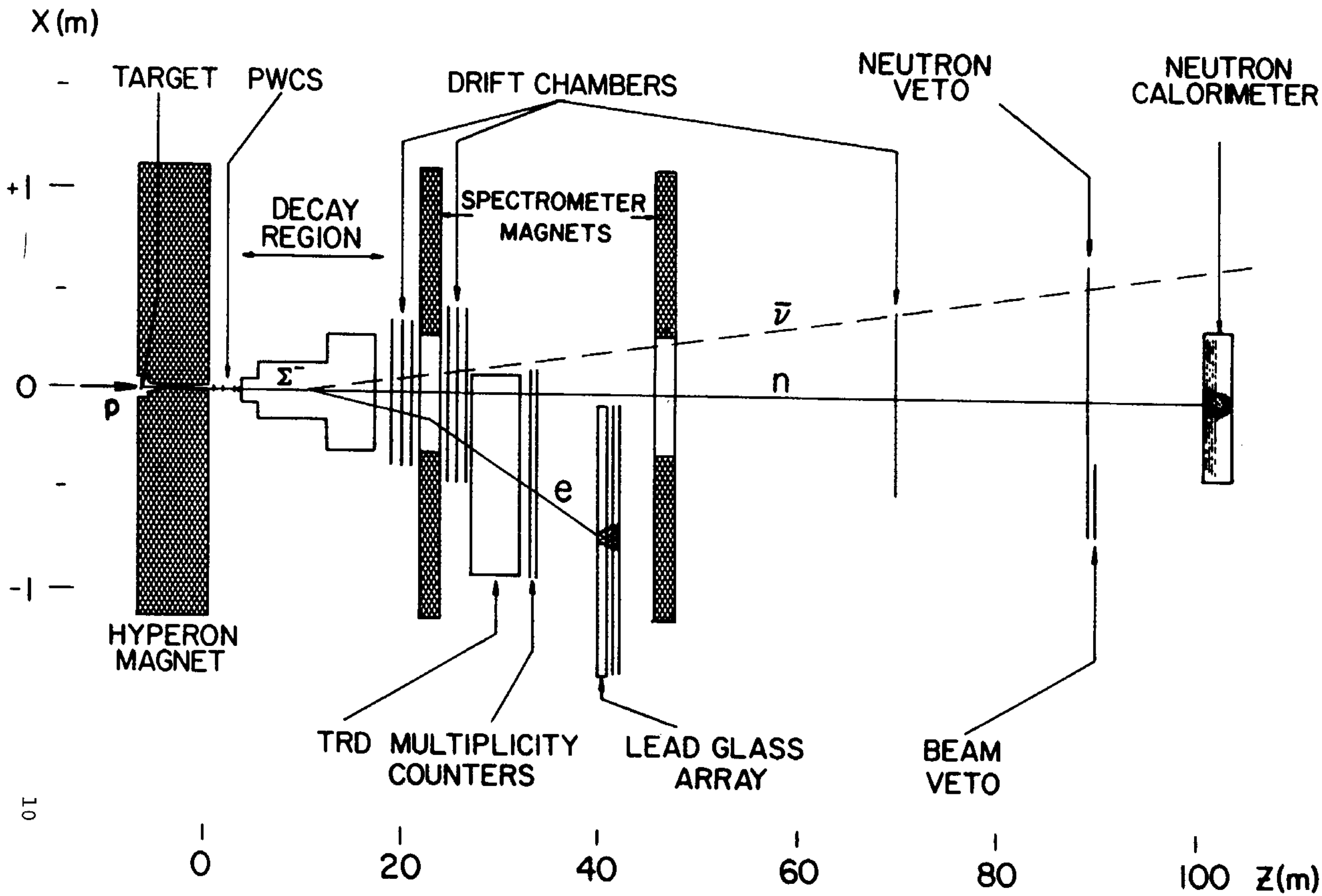
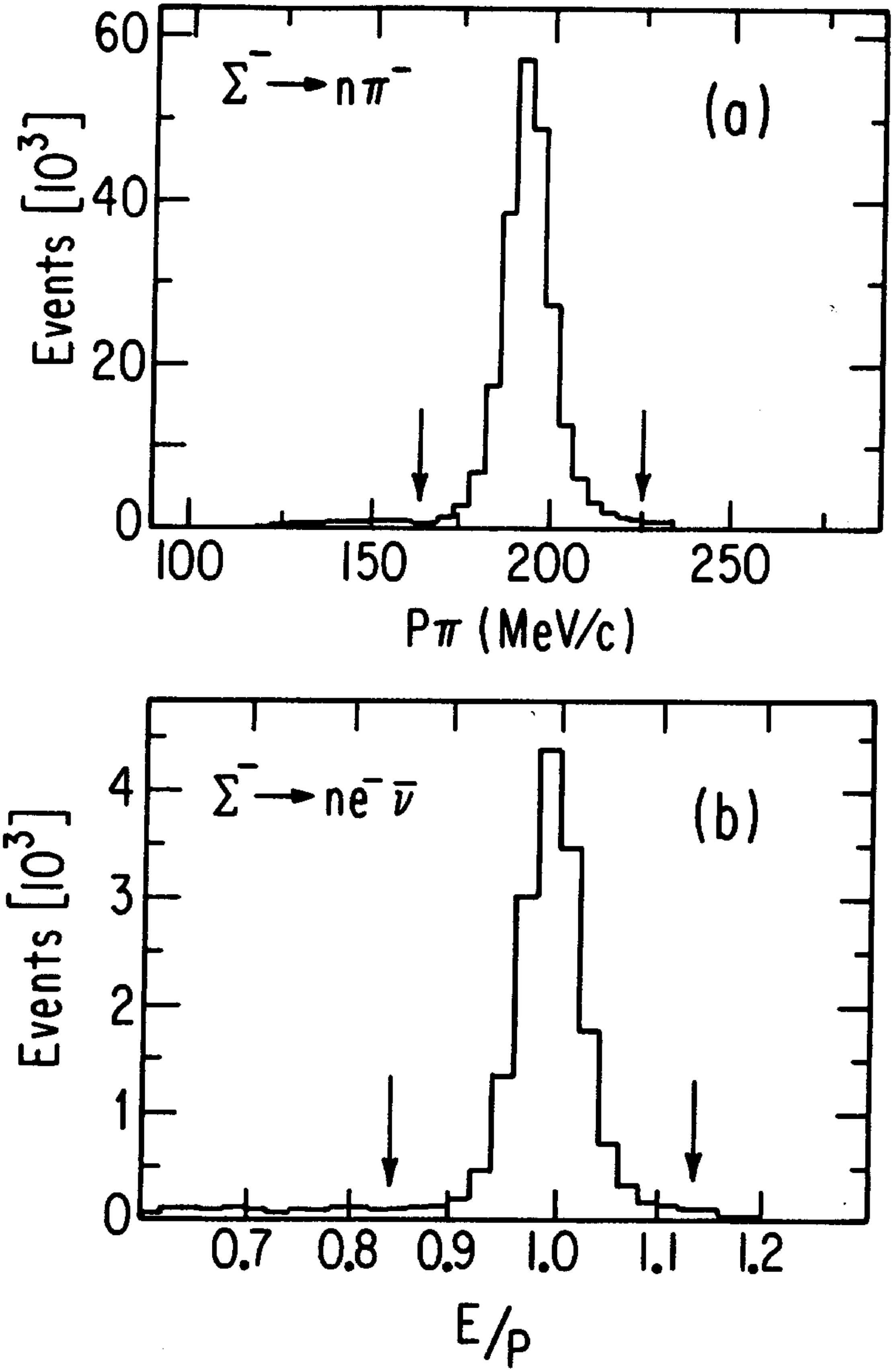

X (m)
TARGET
PWCS
DRIFT CHAMBERS
NEUTRON VETO
NEUTRON CALORIMETER
+1
DECAY REGION
SPECTROMETER MAGNETS
$\bar{\nu}$
Σ^-
n
0
p
e
-1
HYPERON MAGNET
TRD
MULTIPLICITY COUNTERS
LEAD GLASS ARRAY
BEAM VETO
0
20
40
60
80
100
Z(m)

Figure 1



60
40
20
0
Events [10^3]
$\Sigma^- \rightarrow n\pi^-$
(a)
100
150
200
250
$P\pi$ (MeV/c)
4
3
2
1
0
Events [10^3]
$\Sigma^- \rightarrow ne^-\bar{\nu}$
(b)
0.7
0.8
0.9
1.0
1.1
1.2
E/p

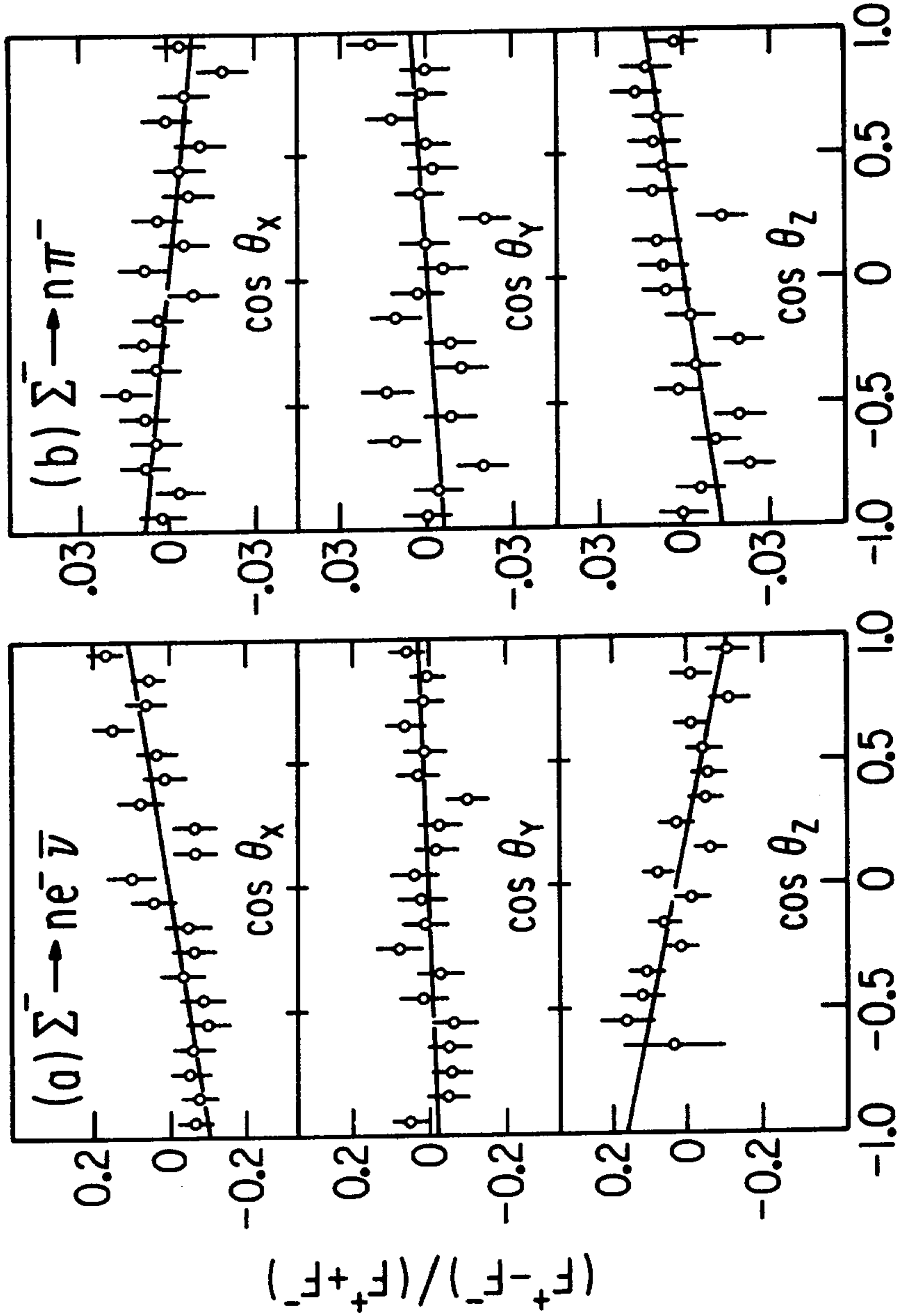
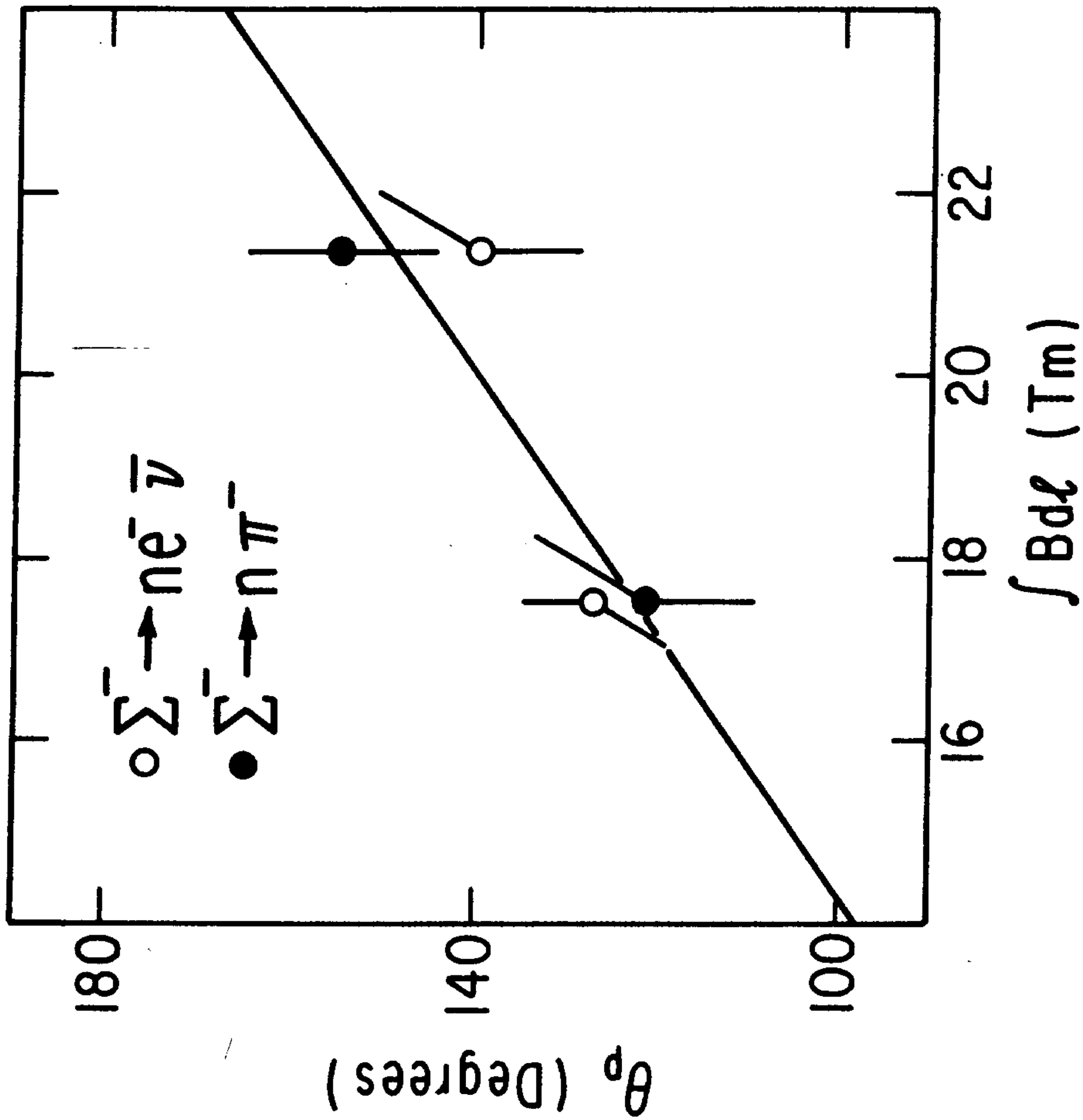

(a) Σ⁻ → ne⁻ν̄
(b) Σ⁻ → nπ⁻
cos θX
cos θY
cos θZ
(F⁺−F⁻)/(F⁺+F⁻)
0.2
0
−0.2
.03
−.03
−1.0
−0.5
0.5
1.0

Figure 4



$\Sigma^- \to n e^- \bar{\nu}$
$\Sigma^- \to n \pi^-$
180
140
100
θ_p (Degrees)
16
18
20
22
$\int B d\ell$ (Tm)