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LOCKYER, NIGEL STUART

PARITY VIOLATION IN PROTON-NUCLEUS SCATTERING AT 6 GEV/C

The Ohio State University

PH.D.

1980

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PARITY VIOLATION IN PROTON-NUCLEUS
SCATTERING AT 6 GeV/c

DISSERTATION

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Nigel Stuart Lockyer, B.Sc., M.Sc.

* * * * *

The Ohio State University

1980

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INTRODUCTION

This thesis describes an experiment, which was the culmination of a series of attempts, to search for parity violation in proton-nucleon scattering at 6 GeV/c using the polarized proton beam at the Argonne National Laboratory Zero Gradient Synchrotron. With the advent of a high flux, high energy polarized proton beam, the possibility of observing a parity-violating signal became experimentally feasible and was attractive because it would complement the low energy scattering experiments. We used two independent detector systems, scintillation counters and ionization chambers, to make a transmission measurement of protons through a water target. The signals were integrated in order to accept higher beam intensities. The experiment was specifically designed to measure the helicity dependence of the total cross section while being insensitive to variations in explicitly polarization independent beam characteristics such as position and intensity. This dependence, which arose from an interference between the weak and strong scattering amplitudes, was parametrized by the parity nonconserving asymmetry $A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, where $\sigma_+(\sigma_-)$ was the total cross section for positive (negative) helicity protons. A dimensional estimate yields 10^{-6} for the magnitude of A_L .

CHAPTER I

THEORY AND BACKGROUND

Weak interaction theory began to take form in the 1930's when the neutron was discovered and Pauli postulated the existence of the neutrino.¹ The rate of nuclear beta decay, a semi-leptonic process, was known to be proportional to G^2 , the square of the weak coupling constant.² (See Figure 1) This suggested that a weak internucleon force was present and proportional to G^2 -- much too small to be observed. The current x current³ formulation of the weak interaction predicted weak hadronic forces of order G . (See Figure 2) An estimate for the weak internucleon force can be obtained from the ratio

$$\sqrt{\frac{\sigma_{vp}}{\sigma_{pp}}} \sim 10^{-6} \quad (1)$$

where σ_{vp} (σ_{pp}) is the total neutrino-proton (proton-proton) cross section. The measurement of a parity-violating signal is the only direct method of detecting the weak force in the presence of the strong interaction. T. D. Lee and C. N. Yang proposed parity nonconservation in the weak interaction as a solution to the tau theta puzzle.⁴ Here two particles, tau and theta, exhibited identical properties except for their intrinsic parity, and since parity conservation was a

dogma, the paradox was why had nature created such similar particles? C. S. Wu, et al., conclusively showed that parity⁵ was not conserved in the beta decay of polarized ^{60}Co nuclei.

Shortly afterwards, the V-A theory of Feynman and Gell-Mann described the main features of leptonic weak interactions including noninvariance under parity transformations.³ Predictions of the V-A theory for hypercharge changing $|\Delta Y| = 1$ transitions were roughly 20 times larger than the observed rates. Cabibbo modified the weak current of hadrons to correct for this disagreement of theory with experiment.⁶ This phenomenological Hamiltonian described weak interaction processes, but at sufficiently high energy (~ 300 GeV) unitarity was violated and divergences in perturbative calculations could not be removed by redefining masses, coupling constants, and wave functions. This process of redefining constants called renormalization solved similar divergence problems in the successful abelian gauge theory of electromagnetic processes, quantum electrodynamics.

The introduction of massive intermediate vector bosons instead of the four Fermi point interaction helped suppress divergences in some processes, such as $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$, but not in $e^+e^- \rightarrow W^+W^-$ for example. A renormalizable theory of weak interactions was needed, and a prime candidate was a Yang-Mills type⁷ or non-abelian gauge theory. (See Figures 3 and 4)

Figure 1. Weak Internucleon Force of Order G^2 When Only Semi-leptonic Processes Were Known.

Figure 2. Weak Internucleon Force of Order G .

Figure 3. Neutron Beta Decay in Four Fermi Theory.

Figure 4. Introduction of Intermediate Vector Boson W^- to Figure 3.

The Weinberg-Salam model⁸ unified the weak and electromagnetic interactions and was based on the gauge group $SU(2) \times U(1)$ and local gauge invariance. There were four intermediate vector bosons, three of which (W^+ , W^- , Z^0) were identified with the weak force and the fourth was the photon, γ , carrier of the electromagnetic force. The W^+ , W^- and Z^0 acquired a non-zero mass by the spontaneous breakdown of the symmetry. In nature most symmetries are not perfect; for example, the mass difference between the proton and neutron indicates that isospin symmetry is broken. A simple way to introduce symmetry breaking into a theory is to add a noninvariant term to the Lagrangian. An alternative method, "spontaneous symmetry breaking," produces a ground state which is noninvariant under group transformations even though the Lagrangian is symmetric. The ground state of a quantized field theory is the vacuum, and a non-zero vacuum expectation value removes the mass degeneracy. In general the spontaneous breaking of a global symmetry predicts massless scalar particles (Goldstone theorem)⁹ which are not observed in nature. However, in the Weinberg-Salam model there are no unobserved massless particles because the Goldstone bosons provide the three extra degrees of freedom needed when the gauge vector mesons $W^\pm$ and Z^0 become massive. This is a property of spontaneous broken gauge theories and is called the Higgs mechanism.¹⁰

Glashow, Iliopoulos and Maiani (GIM)¹¹ introduced a new hadronic quantum number (charm) to explain the observed suppression of the $|\Delta Y| = 1$ neutral current process $K_L \rightarrow \mu^+ \mu^-$. This four quark model when combined with the Weinberg-Salam model is referred to as the standard model. It was shown by t'Hooft¹² that any gauge theory spontaneously broken by the Higgs mechanism was renormalizable. The standard model was theoretically tractable and consistent with experimental data. It motivated the successful search for weak neutral current processes in neutrino scattering and correctly predicted the presence and magnitude of the new parity-violating interaction measured in polarized electron-nucleon scattering. Weak interaction phenomena below center of mass energy $\sqrt{s} = 30$ GeV are described well by the standard model.

Parity nonconservation was observed in the inelastic scattering of longitudinally polarized electrons from a deuterium target. The experiment was performed at the Stanford Linear Accelerator Center (SLAC) and the measured parity-violating asymmetry is

$$\frac{A_L}{Q^2} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = (-9.5 \pm 1.6) \times 10^{-5} \quad (2)$$

where Q^2 is the four-momentum-transfer-squared and is about $1.4(\frac{\text{GeV}}{c})^2$ and $\sigma_+(\sigma_-)$ is the cross section for positive (negative) helicity electrons.¹³ The parity violation arises

from the interference between the electromagnetic and weak neutral current or simply a γ - Z^0 interference. In many respects the SLAC experiment is similar to the experiment described in this thesis. (See Figure 5)

Leptons and quarks, believed to be the fundamental constituents of matter, form at least two families and in the standard model are assigned to left-handed weak isospin doublets of fermions.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L + \dots, e_R^- \quad (3)$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L + \dots, u_R$$

where following Cabibbo-like mixing $d' = d \cos\theta + s \sin\theta$ and $s' = s \cos\theta + d \sin\theta$. Right-handed fields are put in weak isospin singlets.

The weak interactions of these fermions can be described by an effective Lagrangian operator

$$L_{\text{eff}} = \frac{G}{\sqrt{2}} (J_\lambda^+ J_\lambda^- + J_\lambda^0 J_\lambda^0) + \text{hermitian conjugate} \quad (4)$$

formed by the products of charged and neutral currents; J_λ^+ and J_λ^- are the isospin raising and lowering operators of the weak isospin current. Each current is given by

$$\vec{J}_\lambda = \sum_i \bar{\Psi}_i \gamma_\lambda (1 - \gamma_5) \vec{T} \Psi_i \quad (5)$$

Figure 5. The top two graphs illustrate the weak-electromagnetic interference observed in the SLAC experiment. The lower graphs depict the weak-strong interference that this thesis will describe.

where Ψ_i represents a sum over the weak isospin doublets of fermions, both quarks and leptons, and the $\vec{T}$ are combinations of the Pauli matrices. The neutral current is

$$J^0 = J_\lambda^3 - \sin^2 \theta_w J_\lambda^{\text{em}} \quad (6)$$

where J_λ^3 is the third component of the weak isospin current, J_λ^{em} is the electromagnetic current, and $\theta_w = e/g$ where e is the electron charge, g is the coupling of the SU(2) vectors to the fermion doublet, and θ_w is the weak mixing angle.

The success of the standard model in describing weak leptonic interactions has been established experimentally within the energy range accessible to present particle accelerators. Hadronic weak effects are difficult to calculate from the effective Lagrangian due to poor understanding of the strong interaction. Recent experimental results provide the necessary data for better calculations.

Five experimental methods are used to measure the magnitude of the parity-violating weak hadronic interaction:

1. Search for Parity Forbidden Decays

The parity forbidden alpha decay of $^{16}\text{O}(2^-, 8.88 \text{ Mev}) \rightarrow ^{12}\text{C}(0^+, \text{g.s.}) + \alpha(0^+)$ yields a width of $\Gamma_\alpha = (1.02 \pm 0.26) \times 10^{-10} \text{ ev}$ and is the evidence for existence of a $\Delta Y=0$ nonleptonic weak interaction.¹⁴ H. Robertson, et al., are studying $\alpha(0^+) + d(0^+) \rightarrow ^6\text{Li}(1^+)$, have measured the width of the alpha state and found $\Gamma_\alpha = (0.9 \pm 0.7) \times 10^{-6} \text{ ev}$.¹⁵

2. Measurement of Circular Polarization of Gamma Rays

The mixing of opposite parity states allows for the presence of E1 and M1 transitions, which are 90 degrees out of phase, and this leads to a net circular polarization of the emitted gamma ray. Lobashov and his group studied thermal neutron capture in $n + p + d + \gamma$ and found the net circular polarization of the gamma ray to be $P_\gamma = (-1.3 \pm 0.45) \times 10^{-6}$ which is roughly 50 times larger than present calculations indicate.¹⁶ Lobashov is repeating this experiment and the study of the inverse reaction will soon be attempted at Chalk River by A. McDonald, et al. The net circular polarization of gamma rays emitted from unpolarized heavy nuclei¹⁷ has been measured in transitions of $^{175}\text{Lu}(\frac{9}{2}^- \rightarrow \frac{7}{2}^+, 396 \text{ KeV})$, where $P_\gamma = (5.5 \pm 0.7) \times 10^{-5}$, and $^{181}\text{Ta}(\frac{5}{2}^+ \rightarrow \frac{7}{2}^+, 482 \text{ keV})$ where $P_\gamma = -(5.2 \pm 0.5) \times 10^{-6}$.

3. Measurement of Gamma Ray Asymmetry

The gamma ray asymmetry in the capture of polarized neutrons by protons $\vec{n} + p + d + \gamma$ has been measured at Grenoble¹⁸ and gave $A_\gamma = (0.6 \pm 2.1) \times 10^{-7}$. Adelburger, et al.,¹⁹ studied $^{19}\text{F}(\frac{1}{2}^-, 110 \text{ keV}) \rightarrow ^{19}\text{F}(\frac{1}{2}^+, \text{g.s.}) + \gamma$ and found $A_\gamma = -(8.5 \pm 2.6) \times 10^{-5}$.

4. Measurement of Counting Rate

In the experiment $^6\text{Li}(1^+) + \alpha(0^+) \rightarrow ^{10}\text{B}(2^\pm, 5.166 \text{ MeV})$ polarized ^6Li nuclei are captured on a tungsten surface. A beam of alpha particles forms an excited state of ^{10}B and

the rate of gamma ray emission is compared to the ${}^6\text{Li}$ polarization. This experiment was designed at Argonne National Laboratory by R. McKeown, et al., and will soon yield results.

5. Measurement of Polarized Proton-Proton and Proton-Nucleon Scattering

The parity-violating asymmetry $A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$ where σ_+ (σ_-) is the total cross section for positive (negative) helicity protons has been measured at low energy. The asymmetry A_L is $(-1.2 \pm 0.6) \times 10^{-7}$ and $(-3.2 \pm 1.1) \times 10^{-7}$ at 15 MeV²⁰ and 45 MeV²¹ respectively. Calculations by Brown, et al.,²² and by Simonius,²³ modified by Holstein,²⁴ reproduce these results. An experiment performed with polarized protons at the ZGS extended these measurements to 6 GeV/c. Due to the closure of the ZGS, this measurement cannot be repeated until a new high energy polarized proton beam facility is available. There are plans to accelerate polarized protons in the 28 GeV/c Alternating Gradient Synchrotron at Brookhaven National Laboratory within the next few years. At this time the measurements at 6 GeV/c have produced the highest energy results. Henley and Krejs calculate A_L to be $\sim -1.0 \times 10^{-7}$ at 6 GeV/c.²⁵ The weak interaction is a short range force and the observed effects are naively expected to increase at smaller distances, i.e., at higher energies. This calculation did not predict a larger asymmetry at

6 GeV/c because hadronic absorptive effects, which scale upward with energy, reduced the amplitude of the incident wave. More precise strong interaction amplitude data now exist from recent measurements at 6 GeV/c which will permit a more accurate attempt to calculate this parity-violating asymmetry.²⁶

The longitudinal asymmetry A_L is dimensionless and its magnitude can be estimated from the ratio

$$A_L \sim \left(\frac{\sigma_{\text{weak}}}{\sigma_{\text{strong}}} \right)^{1/2} \quad (7)$$

where σ_{weak} (σ_{strong}) is the weak (strong) total cross section. The weak total cross section is proportional to G , which has units of $1/M^2$, and this suggests

$$A_L \sim \frac{GM_N^2}{g^2/4\pi} \sim 10^{-6} \quad (8)$$

where M_N is the nucleon mass. An asymmetry scaling with energy gives

$$A_L \approx \frac{G \sqrt{s}}{(40\text{mb})^{1/2}} \approx 10^{-5} \left(\frac{s(\text{GeV})^2}{40} \right)^{1/2} \quad (9)$$

where $\sqrt{s}$ is the center of mass energy. Since the asymmetry $A_L \sim \frac{\text{Re}(A^S A^{W*})}{|A^S|^2}$, where A^S and A^W are the strong and weak scattering amplitudes respectively, is caused by an interference, more detailed calculations may reduce the magnitude of

dimensional estimates, so at present $A_L \sim 10^{-6}$ is an upper limit for calculations.

The first attempt to measure parity violation at the ZGS was carried out in 1974.²⁷ In that experiment 6 GeV/c polarized protons were scattered by a beryllium target and the measured asymmetry was $A_L = (5.0 \pm 9.0) \times 10^{-6}$. (The best previous limit was $A_L < 5 \times 10^{-3}$, which resulted from a double scattering experiment performed at 660 MeV/c.)²⁸

A subsequent run at the ZGS using an H_2O target found $A_L = -(15.0 \pm 2.4) \times 10^{-6}$.²⁹ In this measurement decay products from polarized hyperons may have contributed to the measured longitudinal asymmetry. A collimator and magnetic spectrometer were inserted downstream of the target to prevent off-beam momentum particles from striking the transmission detectors.

The measurement was repeated with this spectrometer and found $A_L = -(26.3 \pm 7.0) \times 10^{-6}$.³⁰ Towards the end of this experiment another source of systematic uncertainty caused by an asymmetric incident beam halo was detected, but there was insufficient time to study its effects. Random fluctuations in the measured transmission signal were 10 times larger than in the previous experiment and were not understood. The results from this experiment were inconclusive and this measurement needed to be repeated. The remainder of this thesis

will discuss the final version of these experiments and the results. The main features of this transmission experiment are shown in Figure 7, a parity transformation is illustrated in Figure 6 and the previous high energy results are summarized in Table 1.

Figure 6. PARITY TRANSFORMATION. Illustrated is a scattering system and its mirror image. Invariance under PARITY TRANSFORMATION or MIRROR REFLECTION implies the laws of physics are identical for the system and its mirror image. The top (bottom) drawing represents σ_+ (σ_-) the total cross section for positive (negative) helicity protons on a nuclear target.

Figure 7. Main features of this transmission experiment. The incident beam intensity was measured by the I detector. The T detector measured the intensity of the beam which passed through the H₂O target and was not stopped by the collimator C.

TABLE 1

PARITY VIOLATION RESULTS AT "HIGH ENERGY"

Asymmetry Value	Beam Momentum	Target Material	Year	Comments
$<5 \times 10^{-3}$	660 MeV/c	C	1971	Double scat- tering ex- periment <u>ZGS Experiments</u>
$(5.0 \pm 9.0) \times 10^{-6}$	6 GeV/c	Be	1974-1975	First ver- sion exper- iment
$-(15.0 \pm 2.4) \times 10^{-6}$	6 GeV/c	H ₂ O	1975-1976	Hyperon signal
$-(26.3 \pm 7.0) \times 10^{-6}$	6 GeV/c	H ₂ O	1976-1978	Spectrometer removes hyperons

CHAPTER II

EXPERIMENTAL CONSIDERATIONS

The purpose of this experiment was to perform a transmission measurement of polarized protons through a water target with a helicity dependent sensitivity of 5×10^{-7} at 6 GeV/c.

The magnitude of this parity-violating longitudinal asymmetry A_L is parametrized by

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad (1)$$

where $\sigma_+(\sigma_-)$ is the total cross section for positive (negative) helicity protons incident on a water target. The transmission is related to the total cross section by

$$Z_{\pm}^{\dagger} = \exp(-\rho\sigma_{\pm}\ell) \quad (2)$$

where ρ is the target density, ℓ is the length of the target, and $Z^{\dagger}$ is the fraction of unscattered beam. The transmission asymmetry is given by

$$\frac{\delta Z}{2\langle Z \rangle} = \frac{Z_+ - Z_-}{Z_+ + Z_-} \quad (3)$$

This is related to the asymmetry A_L by

$$A_L = \frac{1}{P\langle \ln Z \rangle} \frac{\delta Z}{2\langle Z \rangle} \quad (4)$$

where P is the beam polarization. The dagger indicates that

this experiment measured the effective total cross section since small angle scatterers were detected by the transmission detectors and will be omitted in subsequent expressions. P is shortened notation for $|\bar{P}|$.

Absorption of the proton beam in the target is a binomial process and it can be shown that this leads to fluctuations of the asymmetry A_L given by

$$\delta A_L = - \frac{1}{P \ln \tau} \left(\frac{1-\tau}{N\tau} \right)^{1/2} \quad (5)$$

where N was the total number of protons incident on target $\sim 1 \times 10^{14}$, τ was the fraction of beam transmitted $\sim 20\%$, and P was the beam polarization, typically 71%. The measured fluctuations in the asymmetry during the experiment were roughly five times greater than expected from equation 5. These extra sources of noise came from beam motion, the non-linear conversion of the varying beam intensity to a current signal by the detectors, and several spurious contributions to the longitudinal asymmetry. The latter led to a false parity-violating asymmetry which must be measured and the result corrected in the data analysis. These corrections would increase the error on the final result if not measured with sufficient precision. The fastest available electronics limits the counting of individual particles to $\sim 10^8/\text{sec}$. Because high proton statistics were required, the detector currents were

integrated in order to accept higher beam intensities and reach the desired sensitivity of 5×10^{-7} in about a month.

BEAM CHARACTERISTICS

Beam properties can change coherently and incoherently with polarization reversal, and therefore could mask or mimic the small helicity dependence of the total cross section.

The following list of beam properties contributed to fluctuations in the measured transmission:

(a) Intensity

Beam intensity fluctuations pulse-to-pulse were about 10%. This was caused by an unstable beam position at the primary septum magnet where the beam intensity was divided in half. Intensity fluctuations pulse-to-pulse under stable conditions from the ZGS were 4%. Random and systematic noise dominated the fluctuations in the measured longitudinal asymmetry above 5×10^8 protons/pulse; therefore, the calculated error did not improve with increased beam intensity in accordance with equation 5, setting a practical upper limit to the amount of beam received per spill. The average beam intensity on target was 3.2×10^8 protons/pulse.

(b) Time Structure

Both detector systems were sensitive to instantaneous beam intensity variations during the spill. In an attempt to reduce this time structure, two methods were

tested to extract the proton beam from the ZGS: Energy Loss Extraction and Resonant Extraction. "Energy Loss Extraction" required a thin fixed target to be placed inside a main ring magnet aperture after the beam had been accelerated to 6 GeV/c. The protons lost energy each pass through the target and this caused the beam orbit radius to decrease. The protons spiralled in towards the center of the ZGS until a bending magnet steered the beam across the main ring and into more bending magnets which directed the beam to the experimental areas.

During "Resonant Extraction" a radiofrequency pulse perturbed the betatron oscillations of the beam after full acceleration causing the beam to enter the extraction bending magnets.

The "Energy Loss Extraction" method was used in this experiment, after testing, because it produced less beam motion and time structure, resulting in smaller transmission fluctuations.

(e) Motion

Spatial variation of the beam was the primary source of transmission fluctuations and could change coherently and incoherently with polarization reversal. This beam motion led to random and systematic error in the transmission measurement. The types of beam motion were:

i) Pulse to Pulse Motion

The beam centroid moved pulse-to-pulse, typically 1 mm. (See Figure 8 scatter plot) The transmission depended quadratically on the beam position because of the circular symmetry of the collimator aperture. The Figure 9 scatter plot shows this quadratic behaviour detected by scintillators and Figure 10 scatter plot by the ionization chambers. From these plots beam center was determined.

ii) Discontinuous Changes in the Average Beam Position

The average horizontal beam position run-to-run was usually constant; however, the beam delivered to the experimental areas was periodically interrupted because of minor technical problems such as magnet and water pump failures. After the problem was corrected a new average horizontal beam position would sometimes arise. Scatter plot Figure 11 shows a net horizontal shift of the beam position by 2.5 mm and scatter plot Figure 12 demonstrates the effect of this position change on the transmission detected by the ionization chambers. The quadratic dependence of the transmission on the beam position is apparent and the concentration of data points indicates the position of the beam was not optimal. These last two plots indicate that control of the beam position at the collimator was necessary. An analog position

Figure 8. Scatter Plot Showing the Distribution of Beam Pulse Positions in a Typical Run

Figure 9. Scatter Plot Showing the Quadratic Dependence of the Transmission, Measured by the Scintillators, on Beam Position. The concentration of points indicates the beam is centered.

Figure 10. Scatter Plot Showing the Quadratic Dependence of 1-Transmission, Measured by the Ion Chambers, on Position. The concentration of points indicates the beam is centered.

Figure 11. Average Horizontal Beam Position Moves by ~ 2.5 mm
After a Short Period Without Beam.

Figure 12. Scatter Plot of the Transmission Measured by the Ion Chambers for Beam Motion Shown in Figure 9. The transmission is clearly a quadratic function of position. The concentration of points indicates the beam is not centered.

signal taken from a position detector near the collimator was transmitted to a proton beam bending magnet power supply to stabilize the position of the incident beam.

iii) During the Spill Motion

Motion during the pulse was divided into two categories: fast motion or microstructure, which has frequencies greater than 60 Hertz; and slow motion, which has a frequency of about 1.5 Hertz. A slow variation of the mean horizontal beam position across the spill was controlled by adjusting bending magnet currents during the spill. This motion was typically 1-2 mm and was essentially zero after the magnet currents were properly adjusted. Fast motion caused the beam position to change by about 5 mm peak-to-peak and this was an intrinsic property of the beam which could not be removed.

(f) Beam Momentum

A false parity signal can result from a proton beam momentum which changes coherently with polarization reversal and a proton-nucleon total cross section which is sensitive to those small changes. The absolute proton beam momentum from the ZGS was constant to better than 4 parts in 10^4 at 6 GeV/c. The slope of the proton-nucleon cross section $\Delta\sigma/\Delta E$ was estimated to be $\sim 0.3 - 0.6$ mb/GeV, and at 6 GeV/c this gives an upper limit for $\Delta\sigma$ of $\sim 1 \times 10^{-3}$ mb.

The correlation between beam momentum and polarization was unobservably small³¹, and I have estimated 1% as an upper limit. Since $A_L \sim \Delta\sigma/2\sigma$, a rough upper limit of $\sim 2 \times 10^{-7}$ makes this source of a spurious parity signal negligible.

The unwanted effects on the transmission caused by beam properties (a)-(f) were minimized while taking data and a linear regression method performed in the offline analysis reduced fluctuations further by removing correlations between the transmission and beam variables horizontal (vertical) position, horizontal (vertical) position squared, and intensity. This is discussed further in the section ANALYSIS AND RESULTS.

RESIDUAL TRANSVERSE POLARIZATION

A small transverse component of polarization was observed in the nominally longitudinally polarized beam at the target. This transverse component reversed direction each ZGS pulse along with the beam polarization. A residual horizontal (vertical) polarization produced an up-down (left-right) scattering asymmetry given by

$$a(t) = P(t)A(t) \quad (6)$$

where $a(t)$ is the measured asymmetry, $P(t)$ the transverse polarization of the incident scattered proton, $A(t)$ the analyzing power of the scatterer, and t is the square of the four-momentum-transfer. The sensitivity of the downstream transmission detectors to the asymmetry $a(t)$ depended on the

position and angle of the beam at the collimator aperture. The general features of this effect are shown in Figure 13. The detector sensitivities were measured by increasing the magnitude of the transverse polarization using upstream solenoids and displacing the beam from center. Data were taken at the beam position of minimum sensitivity to this effect and with solenoid current settings which zeroed the residual transverse polarization at the target. Any remaining spurious parity signal is removed in the offline analysis. This is discussed in more detail in the sections EXPERIMENTAL PROCEDURE and ANALYSIS AND RESULTS.

BEAM-MATTER INTERACTIONS

A left-right scattering asymmetry was detected in the beam halo at the I detector. The vertically polarized proton beam interacted with air and ZGS beam monitors just upstream of the precession magnet and produced a scattering asymmetry which reversed sign with beam polarization each ZGS pulse. The magnitude of the spurious parity signal caused by this asymmetric beam halo depended on position and angle of the beam at the I detector. The sensitivity of the transmission detectors was measured by increasing the amount of scattering, inserting material in the region where the scattering occurred, and displacing the beam position from center. Data were taken at the beam position where the sensitivity to this

Figure 13. The first beam pulse in the top drawing has residual transverse polarization (R.T.P) up, while the next beam pulse shown in the lower drawing has R.T.P. down. Analyzing power of the H₂O target and the R.T.P. leads to a scattering asymmetry, measured by the YI detector, which changes sign with the incident polarization. A misaligned T detector shown above, or beam position off center, gives a transmitted beam intensity signal which changes in step with beam polarization, and therefore is a spurious parity signal. The I detector measures the incident beam intensity and the collimator C stops the scattered particles from striking the T detector.

asymmetric beam halo was minimal. The remaining false parity signal caused by beam-matter interactions is removed in the offline analysis. A more detailed discussion can be found in the sections EXPERIMENTAL PROCEDURE and ANALYSIS AND RESULTS.

HYPERONS

The proton beam helicity may be transferred to the hyperons produced in the target. The baryon intensity $I(\theta)$ per unit solid angle in a direction θ to the hyperon polarization is given by

$$I(\theta) \sim (1 + \alpha P \cos\theta) \quad (7)$$

where P is the hyperon polarization and α the asymmetry parameter. For example, in the lambda (Λ^0) decay, $\Lambda^0 \rightarrow p\pi^-$, the protons are produced preferentially along the direction of the Λ^0 polarization and the pions preferentially against it. If the helicity of the incident proton is transferred to the Λ^0 , the number of protons striking the transmission detectors can vary coherently with beam polarization and produce a transmission asymmetry. Further, since the perpendicular momentum of the proton is equal to that of the pion and the proton has most of the lambda longitudinal momentum, the greater mass proton will have an angular distribution peaked more forward in the laboratory frame than the lighter mass pion. Since the pion angular distribution is more spread out, the difference of this distribution for the two

polarizations of the lambda is larger than that of the protons. This can produce a transmission asymmetry caused by the pions. A collimator was inserted to reduce the solid angle subtended by the transmission detectors and a focusing magnet spectrometer was installed to transmit only beam momentum particles. These eliminated the decay products of polarized hyperons produced in the target and therefore removed the spurious parity signal caused by the protons and pions striking the transmission detectors.

POLARIZATION CORRELATION WITH PHASE SPACE

A correlation between the transverse polarization of protons and beam phase space, when scattered from the target, could lead to a helicity dependent transmission. This is true even when the average transverse component of polarization is zero. The main features of the effect are shown in Figure 14. The polarization distribution was measured for each quadrant of the beam. The measured sensitivity of the longitudinal asymmetry to residual transverse polarization is used to determine the correction resulting from a phase space correlation of transverse polarization.

Figure 14. The front view shows the polarization distribution within the beam for two incident beam pulses of opposite polarization. The left drawing shows the scattered protons missing the T detector and the right drawing the scattered protons striking the T detector. This leads to a false parity signal.

CHAPTER III

DESCRIPTION OF THE BEAM AND APPARATUS

POLARIZED PROTON BEAM PRODUCTION

To produce a high energy polarized proton beam, a source of polarized protons must be provided and eventually accelerated while maintaining the original polarization.³² The Zero Gradient Synchrotron (ZGS) used a ground state atomic beam source designed and built by ANAC of New Zealand.³³ The energy levels of the ground-state hydrogen atom as a function of an external magnetic field are shown on the Breit-Rabi diagram in Figure 15. The interaction between the electron and proton magnetic moments in the external field causes the energy levels to split. There are four energy levels associated with various combinations of nuclear spin projection m_i and electron spin projection m_j . In this source, a beam of hydrogen atoms was passed through an inhomogeneous field produced by a sextupole magnet. These neutral atoms moved towards the region of lowest potential energy and therefore an electron with spin up, $m_j = +\frac{1}{2}$, followed the weak field along the axis of the magnet, and electrons with spin down, $m_j = -\frac{1}{2}$, were attracted to the magnet poles. Emerging from the magnet were atoms with electron spins fully polarized with respect to the local field and protons that equally

Figure 15. Four Energy Levels of the Ground-State Hydrogen Atom in an External Magnetic Field B . Nuclear Spin Projection is m_i and Electron Spin Projection is m_j .

populated states 1 and 2 in Figure 13. The atoms then entered a uniform magnetic field which aligned the electron magnetic moments. A radiofrequency field of 1481 MHz was applied to the atoms which were in a magnetic field of ~ 15 gauss, and this flipped the spins of the electrons and protons in only the case where the spins were anti-parallel. This is a transition from state 2 to state 4 in Figure 13. After the atoms were ionized in an electron plasma the beam was accelerated to 20 kv. The beam current from the source was typically 50 microamps, 100 microamps peak, and was vertically polarized with an average polarization of 71%. The opposite proton polarization resulted when transitions 1 to 3 were selected by applying a 17 MHz radiofrequency field to the atoms in a 150 gauss magnetic field. A Cockcroft-Walton column accelerated the beam to 750 kev. It then entered a 50 MeV linac and after acceleration the beam was injected into the main ring and accelerated to 6 GeV/c. The first two stages of acceleration caused no depolarization of the beam. However, the ZGS (main ring) contained twelve serious depolarizing resonances. Resonant depolarization occurs when vertically polarized protons see periodically oscillating horizontal magnetic fields due to the vertical betatron oscillations. The horizontal fields were found in the fringe fields of the 8 octant magnets in the main ring. A method to

retain the polarization after full acceleration in the ZGS was suggested by Cohen.³⁴ The method proposed using pulsed quadrupoles around the main ring to rapidly shift the vertical betatron oscillation frequency at the appropriate energies. At 6 GeV/c there was no measurable loss in polarization due to these "intrinsic" resonances when this method was used.³⁵ The 6 GeV/c polarized proton beam was extracted from the main ring using an "Energy Loss Target" method previously described in the section TIME STRUCTURE of Chapter II.

BEAM TRANSPORT

A plan view of beam 2 is shown in Figure 16. The septum magnet X2SB1 separated the beam from the main beamline. The beam was divided roughly in half for use by the downstream experiments. A plastic bag filled with helium gas was inserted between X2SB1 and X2SB2 to reduce beam-air interactions. The magnets X2SB1 and X2B1 controlled horizontal position and angle of the beam through the apparatus.

The solenoid triplet X2S01 could rotate in a small horizontal component of spin (3.6°) from the nominally vertically polarized proton beam. This horizontal spin component rotated into the longitudinal direction during a 6° bend of the beam by magnet X2B1. Therefore, a small vertical component of polarization at the target could be controlled by adjusting the current in the solenoid triplet X2S01. The

Figure 16. Plan View of Beam 2 and Detectors Positioned on the Rails, A-A, B-B.
 SPIC - ZGS Segmented Proportional Ion Chamber, S₂-1, S₂-2, S₂-3, S₂-4
 SIC - ZGS Sensitive Ion Chamber

solenoid X2S02 was located after the horizontal bend in the beamline and therefore allowed the horizontal component of the beam-polarization to be amplified or cancelled at the target.

The quadrupole triplet X2Q1, X2Q2, X2Q3 focused the beam on the brass collimator aperture.

The proton beam entered the experimental area through an evacuated beam pipe of 19.05 cm diameter in a 2.44 meter long steel wall. A 7.75° upward bend of the beam by the magnet X2B2 rotated the transverse polarization to the longitudinal direction. The equation of precession for the proton polarization is

$$\phi = \theta \gamma \left(\frac{g}{2} - 1 \right) \quad (1)$$

where ϕ is the precession angle, θ is the vertical deflection, g the proton gyromagnetic ratio, and $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$. A proton with polarization up (down) rotated into a negative (positive) helicity state. It was necessary to regulate the power supply to better than 1 part in 10^4 in order to maintain a constant spin orientation at the target.

The brass collimator had an aperture 5.5 cm in diameter and was 46.3 cm in length. The purpose of the collimator was to transmit only unscattered beam. The spectrometer consisted of two bending magnets and four quadrupole magnets, and was designed to transmit only beam momentum particles. The inner

diameter of the channel was 22.9 cm and was completely evacuated. The momentum dispersion of the spectrometer was $1.1 \text{ cm}/\%(\frac{\Delta p}{p})$. The beam was focused onto the transmission detectors and had a spot size about 2.0 cm in diameter.

APPARATUS

Two independent detector systems, scintillation counters and ionization chambers, measured the beam intensity before and after the target. Auxilliary scintillation counters were used to measure properties of the polarized proton beam. All detectors were mounted on stainless steel rails of optical bench design. The detectors positioned on the rails are shown in Figure 17.

IONIZATION CHAMBERS

The ionization chamber system³⁶ consisted of three identically constructed ionization chambers, each with a cylindrical active volume 20 cm long and 10 cm in diameter. Inside a cylindrical container, there were twenty collector plates and twenty-one high voltage plates spaced 5 mm apart. The active volume was defined by the guard rings and by the two outermost high voltage plates. A gas mixture of 90% Argon and 10% methane was used at pressures between -1 and +2 atmospheres. An ionization chamber is shown in Figure 18.

Two of the ionization chambers, UDC (upstream difference chamber) and DDC (downstream difference chamber), were

Figure 17. Schematic of parity violation experiment shown in side view (not to scale). The vertically polarized proton beam enters from the left. The components are: SOL, a solenoid magnet (X2S02 in Figure 14) for rotating the plane of polarization by a few degrees; B1, a dipole magnet which bends the beam by 7.75° producing a longitudinally polarized beam; X2, Y1, Y2 arrays of scintillators arranged as polarimeters; P1, P2, P3 scintillator position monitors; MON, UDC and DDC, the ion chambers for measuring beam intensity and transmission; I and T, the scintillator detectors for measuring the transmission. The target was 81 cm of water and C is a brass collimator with a 5.5 cm diameter aperture. The spectrometer was designed to transmit beam momentum particles. S are four telescope counters which detect beam scattered in the spectrometer.

Figure 17.

Figure 18. IONIZATION CHAMBER ASSEMBLY. Inside a cylindrical container there were twenty collector plates and twenty-one high voltage plates spaced 5 mm apart. Each had an active volume 20 cm long and 10 cm in diameter.

operated in a null balance configuration. The collector plates of UDC and DDC were connected by a high impedance coaxial conductor. The ionization chambers had a common ground at the power supplies. The gas pressure of all three chambers could be adjusted from inside the counting house, but in practice only DDC was changed remotely in order to balance one integrated current against the other. The currents from UDC and DDC were subtracted, the net collected charge was then amplified and zero signal implied a balance. Any deviation from balance was interpreted as a change in transmission of the beam through the target. The third ionization chamber, MON, measured the beam intensity and was used to normalize the difference signal.

A signal flowchart for the ionization chamber balanced pair is shown in Figure 19 and for the monitor ionization chamber (MON) in Figure 20. The null current from UDC and DDC was measured with a low noise operational amplifier (ANCOM 15A-71) which converted the current to a voltage signal. A VIDAR voltage to frequency converter digitized the signal ($0.1 \text{ V/sec} = 10^5 \text{ Hertz}$). An isolation transformer was inserted as a precaution against current loops. A preset interval timer determined the time period during which the gate was closed and the signals were integrated. This was called the "beam on" interval. An "end of spill" pulse

Figure 19. Signal Flowchart for Ionization Chamber Balanced Pair

Figure 20. Signal Flowchart for Monitor Ionization Chamber

from the preset interval timer started an internal delay of 500 msec followed by a 500 msec electronic offset measurement called the "beam off" interval. The nominal gate lengths are shown in Figure 21. The pulse train from the VIDAR was counted by CAMAC scalars. A NOVA minicomputer read the scalars and recorded the data on magnetic tape after every ZGS pulse.

The transmission of the beam through the target fluctuated about a nominal value and consequently the current from the balanced pair could be positive or negative. Since the VIDAR required a signal of constant polarity, an offset voltage of about 150 mV was placed on the operational amplifier. Typical signal levels during the "beam on" interval were ± 15 mV and with intensity spikes about ± 40 mV.

The transmission asymmetry given by the balanced pair normalized by MON is

$$\frac{\delta Z2}{2G} = \frac{-1}{2G} \left[\left(\frac{\text{DIFF}}{\text{MON}} \right)_+ - \left(\frac{\text{DIFF}}{\text{MON}} \right)_- \right] \quad (2)$$

where

$$\text{DIFF} = \text{UDC} - \text{DDC} \quad (3)$$

and G is a constant relating the gain factors between UDC and MON. The asymmetry A_L is given by

$$A_L = \frac{-1}{P|\ln Z|} \frac{\delta Z2}{2\langle G \rangle} = \frac{1}{2GP|\ln Z|} \delta \left[\frac{\text{DIFF}}{\text{MON}} \right] \quad (4)$$

where P is the average longitudinal beam polarization, Z is the average transmission and equals $0.18 \pm .01$.

Figure 21. Gating Diagram for Ionization Chamber System.
The beam is on during Interval I and offsets are measured during Interval II.

SCINTILLATION COUNTERS

TRANSMISSION MEASUREMENT

The transmission of the beam through the target was measured by a pair of identically constructed scintillation counters. The detector is shown in Figure 22. A block of scintillator, 10.2 x 10.2 x 2.5 cm, was epoxied to four Lucite light guides, 15.1 x 10.2 x 2.5 cm, each followed by a 5 x 5 cm cylindrical Lucite guide and a photomultiplier tube (PMT). Ten stage DuMont 6292 PMT's were used with only five accelerating dynodes to reduce pulse height and maintain the linearity, which was about one part in 10^4 . A symmetrical arrangement of the detector about the beam direction helped to minimize signal position dependence. Beam intensity was measured by summing the four currents. Integral counting techniques were used in order to accept higher beam intensities and thus achieve the desired precision in the transmission measurement.

The transmission measured by the scintillation counter system is

$$Z1 = \frac{T}{I} \quad (5)$$

where T (I) is the beam intensity measured by the $T(I)$ detector, which is located downstream (upstream) of the water target. The difference in the transmission for positive and negative helicity incident protons is

Figure 22. This is one of a pair of identical detectors used to measure the intensity of the incident and transmitted beam.

$$\frac{\delta Z1}{2\langle Z1 \rangle} = \frac{\frac{T}{I_+} - \frac{T}{I_-}}{\frac{T}{I_+} + \frac{T}{I_-}} \quad (6)$$

where $\frac{T}{I_+}$ ($\frac{T}{I_-}$) is the transmission for positive (negative) helicity protons through the water target. The asymmetry A_L is related to the difference in transmission by

$$A_L = \frac{1}{P \ln 2} \left[\frac{\delta Z1}{2Z1} \right] \quad (7)$$

where P is the average beam polarization.

POSITION DETECTORS

The horizontal and vertical beam position, as well as angle of incidence, were measured by detectors with wedge shaped scintillators, P1, P2, and P3, every beam pulse. A position detector is shown in Figure 23. Two complementary wedges, cut from a block of scintillator, 10.2 x 10.2 x 2.5 cm, were each optically isolated and connected by Lucite light guides, 15.1 x 10.2 x 2.5 cm, to DuMont 6292 PMT's. Two such assemblies were mounted at right angles to each other and the incident beam direction. This formed one position detector (for example P1) which measured the horizontal and vertical beam position. The signals were integrated in the same manner as the transmission scintillators. After the beam was centered, the PMT gains were adjusted so the difference in the magnitude of the signal from the left and right wedge was

Figure 23. The wedge shaped scintillator position detector. Two such assemblies were mounted at right angles to each other and the incident beam direction. This formed one position detector (for example P1) which measured the horizontal and vertical beam position.

equal to within 5%. The calculated difference

$$\frac{L - R}{L + R} \quad (8)$$

represents the horizontal beam position where L (R) is the signal generated by the beam passing through the left (right) wedge. Relative position motion can be calculated from the scintillator width (10 cm) and the difference signal range. The wedge counter root mean square resolution was about 15 microns and the fluctuations of beam position were roughly 50 microns per pulse. The position fluctuations were larger in the horizontal direction by a factor of two. The difference in the beam position between positive and negative helicity protons as measured by wedge detector P1, averaged over all the data, is 0.98 ± 0.68 microns in the horizontal direction and -0.70 ± 0.42 microns in the vertical direction.

The instantaneous beam position was displayed on an oscilloscope, using a difference and summing amplifier, formed from the analog position signal

$$\left[\frac{L - R}{L + R} \right]_{\text{ANALOG}} \quad (9)$$

where L (R) is the output voltage from the left (right) wedge scintillation counter. This display was used as a visual diagnostic of beam motion and time structure during the spill.

An analog squaring circuit formed horizontal (vertical) position squared. This allows for the removal from the data of position motion during the spill in the offline analysis.

RESIDUAL TRANSVERSE POLARIZATION

The Y1 detector monitored residual transverse polarization by measuring the left-right and up-down scattering asymmetry of the beam after it interacted in the H_2O target. Residual transverse polarization was present at the target because the nominally vertically polarized beam was not precessed perfectly into the longitudinal direction. The Y1 detector is shown in Figure 24. It consisted of four $7.5 \times 7.5 \times 2.5$ cm plastic scintillators with centers 11 cm from beam center. Each scintillator was viewed by a 6292 PMT through a Lucite light guide. The left-right scattering asymmetry measured with the Y1 detector was $(2.35 \pm .095) \times 10^{-5}$ and the up-down asymmetry was $(-1.75 \pm .26) \times 10^{-5}$ averaged over all data runs. Using the measured analyzing power of 0.065 the residual horizontal polarization was $(3.62 \pm 1.46) \times 10^{-4}$ and the vertical polarization was $(-2.69 \pm 0.40) \times 10^{-4}$ throughout this experiment. The magnitude of this transverse polarization is to be compared to the longitudinal polarization of 0.71 ± 0.03 at the target.

BEAM-MATTER INTERACTIONS

The X1 and X2 polarimeters measured the scattering asymmetries at the entrance to the experimental area. The beam was nominally vertically polarized in this region and interacted with air and beam monitor detectors to produce a left-right scattering asymmetry. The Y2 detector monitored

Figure 24. The Y1 polarimeter measured the residual transverse polarization at the target.

scattering in the magnet spectrometer. A polarimeter detector is shown in Figure 25. It consisted of four $10.2 \times 10.2 \times 2.5$ cm plastic scintillators with the centers 10 cm from beam center. Each scintillator was viewed by an RCA 6342 PMT through a Lucite light guide. The beam was not scattered in the evacuated spectrometer channel as measured by the Y2 detector. The average left-right scattering asymmetry measured by the X2 detector was $1.75 \times 10^{-3} \pm 1.0 \times 10^{-6}$ throughout the experiment.

TIME STRUCTURE MONITOR

The instantaneous beam spill rate was monitored by summing and then squaring the voltage signal from the I detector with an analog circuit. The quantity formed is

$$\langle I^2 \rangle = \int dt [I(t)]^2 \quad (10)$$

where the integration is over the duration of the beam spill.

BEAM SPOT SIZE

Beam spot size was monitored in a previous version of this experiment with a detector which consisted of two cylindrically grooved plastic scintillators, one to monitor the horizontal spot size and the other to monitor the vertical spot size. A description can be found in reference 29. In that experiment, the beam spot size fluctuations correlated to polarization reversal made negligible contribution (of order 10^{-10}) to the longitudinal asymmetry, and therefore were not measured in this version of the experiment.

Front View

Top View

Figure 25. The X1, X2, or Y2 polarimeter measured parity allowed scattering asymmetries.

AUXILIARY BEAM MONITORS

The Accelerator Research Facilities Division provided four proportional chambers which measured the average beam position and beam spot size in the horizontal and vertical direction. Each had 48 wires with 2 mm spacing and a resolution of about 0.2 mm per pulse. Two ionization chambers measured the beam flux each pulse. These detectors were used to aid in steering the beam through the apparatus and monitoring beam transport efficiency. Their locations are shown in Figure 16. Table 2 lists the relative positions of all the detectors.

ASYMMETRY TELESCOPES

Six telescopes, each with three scintillation counters, monitored scattering of the transversely polarized proton beam in the spectrometer. Four were placed at right angles to the vacuum pipe between X2Q5 and X2Q6. Two telescopes viewed the downstream end of the spectrometer vacuum pipe at a lab angle of about 45° in the horizontal plane. The signals were processed using discriminators and coincidence circuits. Their locations are shown in Figure 16. The telescopes observed no scattering of the beam in the evacuated spectrometer during the test run.

PHOTOMULTIPLIER GAIN MONITORING SYSTEM

The relative gain of each photomultiplier tube, whose current was integrated, was monitored between every ZGS pulse.

TABLE 2

POSITIONS OF APPARATUS

DEVICE	DISTANCE FROM CENTER OF FIRST SIC (~ VACUUM WINDOW AT ENTRANCE TO CAVE), IN METERS
SIC	0
X1	0.11
SPIC	0.22
Gap	~ 0.25
X2S02	~ 0.70
BM105	~ 2.40
Gap	~ 0.49
X2	4.06
P1	4.26
MON	4.50
UDC	4.80
I	5.00
Gap	~ 0.24
Target	= 0.81
Gap	~ 0.76
TO	6.81
Y1	6.93
P2	7.03
SPIC	7.11
Gap	~ 0.10
Collimator	~ 0.46
Gap	~ 0.10
Spectrometer	~ 11.50
Gap	~ 1.35
Y2	~ 20.60
SPIC	20.70
DDC	20.90
T	21.20
P3	21.75
SPIC	22.05
SIC	22.15

The light from an incandescent 600 watt quartz lamp installed in a photographic enlarger was focused onto a matrix of acrylic optical fibers. Each PMT had its own optical fiber bundle encased in an almost opaque red plastic shield. An electronically controlled shutter (ILEX SHUTTER #4) opened between every ZGS pulse. The light was transmitted along a 22 meter fiber optic bundle to the Lucite light guide. The amount of light sent to each tube was adjusted to match the light generated from the beam by placing filter papers on the ends of the fiber bundles at the matrix. A reference scintillation counter located two meters from the photographic enlarger was installed with a ^{90}Sr source and an optical fiber. The source was inside a brass container with an electronically controlled brass shutter.

SCINTILLATION COUNTER SIGNAL PROCESSING

The signals from all scintillation detectors (except the six counter telescopes) were integrated. DuMont 6292 PMT's were linear to about 1 part in 10^4 and were used for detectors P1, P2, P3, I, T, Y1, and T0. The P1 and I detectors were exposed to the full intensity of the proton beam and therefore used only 5 accelerating dynodes which reduced phototube signal currents to levels compatible with the associated electronics but still maintained the linearity of the

PMT. Detectors which did not see the full intensity of the beam, P2, P3, Y1, and T, used 7 accelerating dynodes. Detectors X1, X2, and Y2 used ten stage RCA 6342 PMT's with the seventh stage being used as an anode.

A signal flowchart for the scintillation detectors operated in the integration mode is shown in Figure 26. The PMT current was converted to voltage by an operational amplifier located in the experimental area. The negative voltage signal was transmitted to the electronics house by signal cable, inverted by an operational amplifier, and digitized by a voltage to frequency converter (V/F). Dynamic Measurements 8413 V/F's were used for detectors I, T, P1, and T0, and Teledyne Philbrick 4705 V/F's for the other detectors. The V/F had an offset bias of 50 kHz to ensure a net positive input voltage. A potentiometer on each V/F module was used to match PMT gains on each detector assembly to within 5%. The V/F's were contained in NIM BINS which were gated on and off by a Field Effect Transistor (FET) located in a timing module. The V/F output pulse train was scaled by CAMAC scalers for slightly longer than the duration of the beam spill. A NOVA minicomputer read the scalers and wrote the raw data onto magnetic tape.

The scintillator gating diagram is shown in Figure 27. There were four intervals each cycle to read and record data.

Figure 26. Signal Flowchart for Integrated Scintillation Counters

Figure 27. Gating Diagram for Integrated Scintillation Counters. Beam is on during Interval I, electronic offsets are measured during Interval II, dark current is measured during Interval III, and lamp data is taken during Interval IV.

The duration of each interval was determined by the scintillator timing module once it received a beam start and stop pulse from the preset interval timer. The lengths of the scaler and FET gates were measured with a 20 MHz clock. The scaler gate enabled or disabled the CAMAC scalers while the FET gate enabled or disabled the voltage signals at the V/F inputs. The "beam on" signals were measured during the first interval. The scaler gate was opened about 50 msec after the FET gate was closed to ensure receiving the entire pulse train from the V/F, which had a time constant of 10 msec. The FET gate remained closed and the scalers were enabled for interval two, allowing the electronic offsets to be measured. The PMT dark current was measured during interval three.

The intensity signal I^x with electronic offsets and phototube dark current subtracted is calculated from these three measurements. Let I^x be given by

$$I^x = \left[\frac{I_{\text{measured}}^x(1)}{t_{\text{FET}}(1)} - \frac{I_{\text{offset}}^x(2)}{t_{\text{scaler}}(2)} \frac{t_{\text{scaler}}(1)}{t_{\text{FET}}(1)} \right] - \left[\frac{I_{\text{measured}}^x(3)}{t_{\text{FET}}(3)} - \frac{I_{\text{offset}}^x(2)}{t_{\text{scaler}}(2)} \frac{t_{\text{scaler}}(3)}{t_{\text{FET}}(3)} \right] \quad (11)$$

where $t_{\text{FET}}(1)$ was the length of the FET gate during interval one, $t_{\text{scaler}}(2)$ was the length of the scaler gate during interval two, $I_{\text{measured}}^x(1)$ was the scaler counts for phototube

x during interval one, and $I_{\text{offset}}^x(2)$ was the scaler counts for phototube x during the electronic offset measurement interval two.

The relative gain of each phototube operated in the integration mode was measured during the fourth interval. The signals were processed in an identical manner to the beam generated signals with interval four replacing interval one in equation 11.

POLARIZATION MEASUREMENTS

Beam polarization was measured at 50 MeV and at 6 GeV/c. The 50 MeV linac polarimeter consisted of two identical telescopes of three scintillators, viewing a needle-like carbon target. The elastically scattered protons were detected at a laboratory angle of 55° , where the analyzing power was $88 \pm 5\%$.³⁷ The beam polarization was measured to within a few percent in less than a minute. The high energy polarimeter was designed to give a fast relative measurement. It was located in the Main Ring building just after the extraction point of the beam from the ZGS. This polarimeter had a single arm and detected the recoil 500 MeV/c proton scattered from a thin piece of plastic. The beam polarization was measured to about 5% in 15 minutes. The signals from both polarimeters were converted to polarization by the Main Control Room computer and sent to the experiment each beam pulse.

LIQUID WATER TARGET

Distilled water was chosen as the target material because it allowed 80% absorption of the beam and for its homogeneity. The water was enclosed in an aluminum cylindrical container, 81 cm long and 15.2 cm in diameter. The container windows were made of 0.32 cm thick optically flat quartz glass and were aligned parallel to each other and perpendicular to the incident beam direction.

POSITION FEEDBACK

The beam centroid at position detector P1 was stabilized pulse-to-pulse with the aid of a feedback loop. The voltage signal from the two horizontal PMT's in scintillation counter P1 were combined to form

$$\left[\frac{L - R}{L + R} \right]_{\text{ANALOG}} \quad (9)$$

using analog summing and difference amplifiers. The signal controlled the current in magnet X2SB1. The time constant of the feedback loop, including the magnet response time, was ~ 100 ms.

CHAPTER IV

EXPERIMENTAL PROCEDURE

TUNING

The beamline magnet currents were adjusted, using beam position and intensity monitors supplied by the ZGS, to maximize the transmission of the beam through the apparatus. The detectors were centered with respect to the rails using plumb bob lines. The precession magnet, the front and rear rails, brass collimator, and magnet spectrometer were aligned by an optical survey. The beam was focused at the collimator, the smallest aperture in the beamline, to a minimum spot size of 2.3 cm horizontal and 2.6 cm vertical (full width at half maximum). Scintillation detector voltage signals at the output of the I/V were required to fall in the range 0.5 V to 1.0 V. This criterion determined the number of accelerating dynodes used in the phototube bases on each detector assembly. The PMT high voltage and the potentiometers on the V/F modules were adjusted to match scaler counts to within 5% from complementary detectors. The amplifier gains and gas pressures were adjusted in the ionization chamber system to give voltage signals of about 1.0 V from each chamber. The signal from the balanced pair was nulled to within 25 mV. The balanced signal voltage

could be displayed on an oscilloscope screen to indicate small changes in the transmission. Once the beam was nominally centered, the display was used as a monitor when trying to maximize the transmission of the beam through the magnet spectrometer.

The beam position, angle, and spot size were then adjusted slightly to minimize a transmission quality factor or Q-factor. This was a ratio of measured fluctuations in the difference in transmission through the target for positive and negative helicity beam pulses to those expected from statistical variations. The ratio is

$$Q = \frac{\text{MEASURED TRANSMISSION DIFFERENCE ERROR}}{\text{CALCULATED TRANSMISSION DIFFERENCE ERROR}} \quad (1)$$

and for the scintillation counters becomes

$$Q_{\text{SCINT}} = \frac{\Delta(Z1_+ - Z1_-)}{(Z1_+ + Z1_-)/2} \bigg/ \sqrt{\frac{2}{p}} \sqrt{\frac{1 - \tau}{\tau n}} \quad (2)$$

where $Z1_+$ ($Z1_-$) is the transmission through the target for positive (negative) helicity beam polarization, Δ signifies the error, p is the number of beam pulse pairs, n the average intensity/pulse, and τ the calculated transmission (0.18). This was a convenient online form of the Q-factor. The Q-factor for the ionization chambers is

$$Q_{\text{I.C.}} = \frac{\Delta \left[\frac{\text{DIFF}}{\text{MON}_+} - \frac{\text{DIFF}}{\text{MON}_-} \right]}{G} \bigg/ \sqrt{\frac{2}{p}} \sqrt{\frac{1 - \tau}{\tau n}} \quad (3)$$

where $\left[\frac{\text{DIFF}}{\text{MON}_+} - \frac{\text{DIFF}}{\text{MON}_-} \right]$ is the intensity normalized signal from the ionization chamber balanced pair and the constant G relates the signal in UDC to MON. Systematic minor adjustment of beam magnet currents resulted in online Q-factors between two and seven for both detector systems. The offline analysis could not remove these beam induced transmission variations satisfactorily if the online Q-factors were larger than about ten. It was therefore essential that online Q-factors were minimized.

FOUR TYPES OF DATA RUNS

Data consisted of four different measurements: "residual transverse polarization runs," "added absorber runs," "collimator runs," which determined transmission detector sensitivities to spurious parity signals, and lastly "data runs" representing 75% of the total data sample.

"Residual transverse polarization runs" were taken at various beam positions with increased transverse polarization at the target. Solenoids could rotate the vertical beam polarization by $\sim 4^\circ$ in either the horizontal or vertical direction. This changed the difference in the transverse scattering asymmetry, at detector Y1, between the positive and negative helicity beam by a factor of twenty-five from $\sim 1 \times 10^{-4}$ to $\sim 2.5 \times 10^{-3}$. Data were recorded at several beam positions with typical displacements a few millimeters

left-right for vertical polarization rotated or up-down for horizontal polarization. The data contained 18 "residual transverse polarization runs" of ~ 1600 pulses/run, with roughly an equal number of protons on target taken at two different periods during the experiment for a total of $\sim 7 \times 10^{12}$ protons on target.

"Added absorber runs" were taken with nominally 5 cm of Lucite placed about 2 meters upstream from the center of the precession magnet. The Lucite was positioned to intercept the entire beam. This absorber caused the difference in the scattering asymmetry between positive and negative helicity beam to increase by roughly a factor of ten from $\delta\text{TPLY} \sim 3.5 \times 10^{-3}$ to $\delta\text{TPLY} \sim 3.5 \times 10^{-2}$. (δTPLY is defined in the next section, ONLINE SOFTWARE.) The beam was moved a few millimeters left and right of beam center while the absorber still intercepted the entire incident beam. Lucite absorbers of 1 cm and 2 cm thickness were used to extrapolate the amount of scattering versus thickness to zero added absorber. The amount of scattering taking place during nominal data runs was equivalent to 5 mm of Lucite absorber. There were a total of 32 "added absorber runs" of ~ 1600 pulses/run, with about the same number of protons on target taken near the beginning and end of the experiment, for a total of $\sim 1.6 \times 10^{13}$ protons on target. For these runs the magnet currents in the

spectrometer were adjusted to transmit the lower energy beam caused by energy loss in the Lucite.

"Collimator runs" were taken with either the top, bottom, left or right half of the beam removed with a collimator. A cylindrical brass collimator, 30 cm in length and 10.5 cm in diameter, was inserted into and filled the aperture at the downstream end of solenoid X2S01. A combination of brass and styrofoam rods allowed the collimator to absorb one half of the beam while transmitting the other half. A total of 4 consecutive runs, one for each of the four halves, with ~ 1600 pulses/run were recorded.

There were 184 "data runs" with ~ 1600 pulses/run for a total of $\sim 9 \times 10^{13}$ protons on target. The "added absorber runs" and the "residual transverse polarization runs" determined beam positions (null axes) where these effects contributed minimally to the longitudinal transmission asymmetry. The beam was positioned on the added absorber null axis and the Q-factors were minimized by adjusting the incident beam angle and spot size during "data runs." Frequent adjustment of the beam steering magnets was necessary during the course of the experiment to maintain the minimal Q-factors.

ONLINE SOFTWARE

A NOVA minicomputer system recorded the data four times each ZGS beam pulse cycle. The raw data were:

- a) Integrated signal current from each integrating phototube along with the electronic offset, dark current, and relative gain;
- b) Integrated signal currents from the ionization chamber system and the electronic offsets;
- c) Number of counts from each of six counter telescopes;
- d) Analog and digital beam position and spot size from four ZGS proportional chambers, and beam intensity from two ZGS ionization chambers;
- e) Currents from ZGS extraction magnets and several beamline magnets;
- f) Beam polarization information from the 50 MeV and 6 GeV/c polarimeters;
- g) Two logic level signals of opposite sense indicating the direction of polarization (up or down) of the incident proton beam.

The online program calculated the average value, the corresponding error, the average difference value and its error for twenty chosen variables for every pair of beam pulses. This data plus both Q-factors were displayed on a CRT screen every 100 beam pulses, and a summary of 1600 pulses, one run, was photographed and recorded in the logbook. The variables most often displayed, with background and offsets subtracted, were:

a) MON: incident beam intensity/pulse measured by the monitor ion chamber.

b) DIFF/MON: normalized signal from balanced ion chamber pair defined by equation (2) and (3) in Chapter III.

c) I: incident beam intensity/pulse measured by scintillation detector I, given by

$$I = I_L + I_R + I_U + I_D \quad (4)$$

where I_L , I_R , I_U , and I_D refer to the integrated signal currents from the left, right, up, and down phototubes.

d) T/I: transmission measured by scintillator detectors, defined by

$$\frac{T}{I} = \frac{T_L + T_R + T_U + T_D}{I_L + I_R + I_U + I_D} \quad (5)$$

where T_L , T_R , T_U , and T_D refer to the integrated signal current from the left, right, up and down phototubes on the T scintillation detector.

e) POLX: up-down scattering asymmetry measured after the target by scintillation polarimeter, Y_l , defined by

$$POLX = \frac{Y_{lU} - Y_{lD}}{Y_{lU} + Y_{lD}} \quad (6)$$

where Y_{lU} (Y_{lD}) is the integrated signal current from the upper (lower) arm.

f) POLY: left-right scattering asymmetry measured after the target by scintillation polarimeter, Y_l , defined by

$$POLY = \frac{Y_{1L} - Y_{1R}}{Y_{1L} + Y_{1R}} \quad (7)$$

where Y_{1L} (Y_{1R}) is the integrated signal current from the left (right) arm.

g) P1Y: vertical beam position at P1, defined by

$$P1Y = \frac{P1U - P1D}{P1U + P1D} \quad (8)$$

where $P1U$ ($P1D$) is the integrated signal current from the upper (lower) scintillator wedge.

h) P1X: horizontal beam position at P1, defined by

$$P1X = \frac{P1L - P1R}{P1L + P1R} \quad (9)$$

where $P1L$ ($P1R$) is the integrated signal current from the left (right) scintillator wedge.

i) P2Y: vertical beam position at P2, defined similarly to g).

j) P2X: horizontal beam position at P2, defined similarly to h).

k) P3Y: vertical beam position at P3, defined similarly to g).

l) X1LR/I: left-right scattering asymmetry measured by scintillation polarimeter, $X1$, defined by

$$\frac{X1LR}{I} = \frac{X1L - X1R}{I_L + I_R + I_U + I_D} \quad (10)$$

where $X1L$ ($X1R$) is the integrated signal current from the left (right) arm, and I is defined in c).

m) TPLY: left-right scattering asymmetry measured by scintillation polarimeter X2, defined similarly to l).

n) T0/I: transmission measured by scintillation detectors T0 and I, defined similarly to d).

The remaining variables described the beam position along the beamline as measured by the ZGS proportional chambers.

Minimizing the Q-factors required both small adjustments in the beamline magnet currents and data cut such that improvements in the transmission could be seen in the calculations. The following were the most effective online cuts made on pairs of beam pulses:

a) I/V Saturation

The current from wedge detector PlR was divided in the ratio $\sim 10/1$. A beam intensity spike would saturate the I/V converter for the larger signal and not for the smaller signal. The ratio of the two signals was required to remain constant within 0.1%.

b) Spill Width

A beam spill width within 100 ms of the mean value is accepted.

c) Bad Spill Flag

This quantity indicated time structure and is defined by

$$\text{B.S.F.} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} * \frac{\langle I_L \rangle^2}{\langle I_L^2 \rangle} \quad (11)$$

where I is the integrated current signal from the I detector, defined in c), and I_L is the lamp signal for the I detector. The value of B.S.F. was typically 1.2. Beam pulses with values greater than 1.5 were discarded.

d) Polarization

The first pulse of every run was required to begin with an up polarization of magnitude greater than 60%.

e) Transmission

An upper and lower fluctuation limit was set about the mean transmission value for both detector systems.

Two beam pulses were cut each time because, in general, variables of interest were calculated from the difference between a pair of beam pulses of opposite helicity.

CHAPTER V

ANALYSIS AND RESULTS

INTRODUCTION

The measured beam properties and transmission of the beam through the target are combined into polarization independent sets of four beam pulses called quads. The value of each quad must lie within 2.5 standard deviations of the mean beam position, intensity, and transmission for a run in order to be selected for the final data sample. Transmission fluctuations from this data sample are reduced using a linear regression analysis, a method which uses the pulse-to-pulse variations of beam position, position squared, and intensity to determine the contribution of these beam properties to $\frac{\delta Z^*}{2Z}$. The asterisk indicates there are parity violating and also systematic contributions to the asymmetry. This regression method reduces fluctuations in $\frac{\delta Z^*}{2Z}$ caused by random and systematic (in phase with polarization reversal) changes in these beam properties and allows corrections to the transmission asymmetry to be applied to a block of data, called a run, taken with similar beam conditions. The measured transmission asymmetry is considered to be a sum of a parity violating signal (proportional to A_L) and two classes

of spurious terms caused by residual transverse polarization at the target and interactions of the vertically polarized beam with matter in the beamline channel (beam-matter scattering). The effects of transverse polarization and beam-matter scattering were enhanced in control runs and studied as a function of beam position and angle in order to measure the sensitivity of $\frac{\delta Z^*}{Z}$ to these effects. The transverse scattering asymmetries due to transverse polarization at the target and beam-matter interactions are measured each beam pulse and are statistically well determined after one run. The resulting corrections are applied to each data run using a chi-square minimization procedure. A correction for the correlation between transverse polarization and position in the beam is applied to the weighted average, determined from all the data runs, of A_L^* . The remaining value of A_L^* represents the helicity dependence of the effective total proton-nucleon cross section at 6 GeV/c.

OFFLINE VARIABLES

The following array of variables, used in the analysis, with offsets and background subtracted are:

- a) MON: incident beam intensity/pulse measured by the monitor ion chamber.
- b) Z2 = $\frac{\text{DIFF}}{\text{MON}}$: normalized signal from the balanced ion chamber pair defined by equations 2 and 3 in Chapter III.

- c) I: incident beam intensity/pulse measured by the scintillation detector I, given by

$$I = I_L + I_R + I_U + I_D$$

where I_L , I_R , I_U , and I_D refer to the integrated signal currents from the left, right, up and down phototubes.

- d) Z1 = $\frac{T}{I}$: transmission measured by the scintillation detectors defined by

$$Z1 = \frac{T}{I} = \frac{T_L + T_R + T_U + T_D}{I_L + I_R + I_U + I_D}$$

where T_L , T_R , T_U and T_D refer to the integrated current from the left, right, up and down phototubes on the T scintillation detector.

- e) POLY: left-right scattering asymmetry measured after the target by scintillation polarimeter Y1, defined by

$$POLY = \frac{Y1L - Y1R}{Y1L + Y1R}$$

where Y1L (Y1R) is the integrated signal current from the left (right) arm.

- f) POLX: like POLY only up-down scattering asymmetry, defined by

$$POLX = \frac{Y1U - Y1D}{Y1U + Y1D}$$

- g) P1X: horizontal position measured by position detector P1, given by

$$P1X = \frac{P1L - P1R}{P1L + P1R}$$

h) P1Y: vertical position, given by

$$P1Y = \frac{P1U - P1D}{P1U + P1D}$$

i) P2X: horizontal position at detector P2, like g).

j) P2Y: vertical position at detector P2, like h).

k) TPLY: left-right scattering asymmetry measured by scintillation polarimeter X2, defined by

$$TPLY = \frac{X2L - X2R}{I}$$

where X2L (X2R) is the integrated signal current from the left (right) arm, and I is defined in c).

l) I2: time structure monitor given by

$$I2 = \frac{\langle I^2 \rangle}{I} = \frac{\int dt [I(t)]^2}{I}$$

where $\langle I^2 \rangle$ is an analog signal from the I counter described in the section TIME STRUCTURE MONITOR, Chapter II.

m) product variables formed each beam pulse where

$$XTPY = P1X \cdot TPLY$$

$$XPLY = P1X \cdot POLY$$

$$YPLX = P1Y \cdot POLX$$

$$ATPY = (P2X - P1X) \cdot TPLY$$

$$P1X2 = P1X \cdot P1X$$

$$P1Y2 = P1Y \cdot P1Y$$

DATA SELECTION PROCEDURE

A value for each variable is calculated for every beam pulse. These values are initially arranged in sets of four consecutive beam pulses of helicity $H = +1, -1, +1, \text{ and } -1$. The four pulses are combined to form a single number for each variable by taking the value of the variable for the

1st pulse - 2nd pulse - 3rd pulse + 4th pulse.

This quantity is called a "quad," has "zero net polarization" and is not affected by a constant linear gain drift during the quad. Beam pulses with intensities below 5×10^7 , with incorrect beam polarization for the desired quad sequence, or with negative offsets are rejected, and any data point cut removes the entire quad.

The data selection procedure is applied to the "zero polarization" quad values of variables $PlX, PlX2, PlY, MON, Z1$ and $Z2$. The average quad value for each variable is calculated and the absolute values are sorted in ascending order (mean of the distribution is zero). The median quad is $M/2$, where M is the total number of quads, and its value divided by 0.69 gives the standard deviation for the quad distribution (assumed normal). This procedure is applied to all six variables and prevents any bias in calculating the standard deviation which normally arises from data containing "wild points." The quad value of any of the six variables which

lies greater than 2.5 standard deviations from the mean causes the data from the four beam pulses to be rejected. This method minimized the error in the transmission asymmetry by removing about 10% of the data from each run.

LINEAR REGRESSION ANALYSIS

The pulse-to-pulse fluctuations in the measured transmission of the beam through the apparatus were caused by detector noise, statistical variations in the absorption of the beam in the target, and from changes in various beam properties. To help reduce the effects of beam properties on the measured transmission, a regression analysis is employed in the offline program.

The smallest aperture (5.5 cm diameter) defining the beam was the collimator located between the target and the transmission detectors. The beam spot size was about one half the diameter of this aperture, and the pulse-to-pulse motion of the beam caused a varying intensity loss at this collimator. The circular geometry of the collimator aperture produced a quadratic dependence of the transmission on beam position and this is shown in scatter plot Figure 9.

The transmission measured by both detector systems is a quadratic function of beam position at the collimator and is given by

$$Z^* = Z_0 + a_1(X - X_0)^2 + a_2(Y - Y_0)^2 \quad (1)$$

where Z^* is the measured transmission, Z_0 a constant coefficient representing the "true transmission," $X - X_0$ and $Y - Y_0$ the horizontal and vertical distance from the aperture center X_0, Y_0 , and a_1 and a_2 are sensitivity coefficients. Neglecting terms proportional to X_0^2 and Y_0^2 , and absorbing constants by redefining the coefficients, equation 1 gives

$$Z^* = Z_0 + b_1 X^2 + b_2 X + b_3 Y^2 + b_4 Y \quad (2)$$

Using the variables defined earlier in this chapter, the transmission is given by

$$Z^* = Z_0 + b_1 P1X^2 + b_2 P1X + b_3 P1Y^2 + b_4 P1Y + b_5 I^2 \quad (3)$$

It was found that an extra term $b_5 I^2$ which represented the instantaneous spill rate of the beam is effective in reducing noise for both detector systems. Equation 3 can be written

$$Z^* = Z_0 + \sum_{i=1}^n c_i X_i \quad (4)$$

where Z^* and the X_i are measured quantities and equation 4 is solved for the c_i such that the X_i are uncorrelated to the constant coefficient Z_0 . The method of least-squares gives

$$\sum_{j=1}^n Z^* X_j = \sum_{j=1}^n Z_0 X_j + \sum_{i=1}^n \sum_{j=1}^n c_i X_i X_j \quad (5)$$

for a total of $n+1$ (5+1) simultaneous equations, and the sum over the number of observations is omitted. The constant coefficient Z_0 can be written in terms of the other coefficients, leaving $n(5)$ simultaneous equations to be solved. These

equations give

$$\sum_{j=1}^n Z^* X_j = \sum_{i=1}^n \sum_{j=1}^n d_i X_i X_j \quad (6)$$

where the d_i are coefficients related to the c_i . The algebra between equation 5 and 6 is lengthy and can be found in reference 38. Equation 6 is written as a matrix and gives

$$(Z^* X_j) = d_i (X_i X_j) \quad (7)$$

and

$$(X_i X_j) = \frac{1}{N} \sum_{k=1}^N X_i^k X_j^k \quad (8)$$

where X^k is a data point and N the total number of points. The coefficients are determined from equation 7 by multiplying by the inverse matrix such that

$$d_i = (Z^* X_j) (X_i X_j)^{-1} \quad (9)$$

The coefficients d_i are determined in this analysis using the quad values for each of the independent variables X_i . The object of the regression analysis is to reduce the fluctuations in the quantity

$$\delta Z^* = \delta Z_0 + \sum_{i=1}^n f_i \delta X_i \quad (10)$$

where δ is the operator which forms the difference of the variable between consecutive beam pulses of opposite helicity. For example,

$$\delta Z^* = Z_+^* - Z_-^* \quad (11)$$

where Z_+^* (Z_-^*) is the transmission through the target for a positive (negative) helicity beam. The regression coefficients d_i determined from the polarization independent quad data are used in equation 11 so as not to correct the difference signal δZ^* with a quantity containing implicit beam polarization information.

The data from the polarimeter scintillation counters X2 and Y1 are treated in a similar manner. The expressions

$$\delta \text{POLY}_0 = \delta \text{POLY} - e_i \delta \text{PLX} \quad (12)$$

and

$$\delta \text{POLX}_0 = \delta \text{POLX} - m_i \delta \text{PLY} \quad (13)$$

and

$$\delta \text{TPLY}_0 = \delta \text{TPLY} - p_i \delta \text{PLX} \quad (14)$$

are formed and the term with the subscript zero is the constant coefficient, and the e_i , m_i , and p_i are "quad regression coefficients."

BEAM-MATTER SCATTERING AND RESIDUAL TRANSVERSE POLARIZATION CORRECTIONS

The transmission asymmetry is considered to be the sum of a parity violating signal (proportional to A_L) and two classes of terms representing the effects of residual transverse polarization at the target and beam-matter scattering in the beamline channel where the beam is vertically polarized. Each term is the product of the polarization correlated

change in a variable and the sensitivity of $\frac{\delta Z^*}{ZZ}$ to that variable. The variables were monitored each beam pulse and the sensitivities were measured in control runs in which the effect of the relevant variable was enhanced. The contribution of residual transverse polarization and beam-matter scattering effects to $\frac{\delta Z^*}{ZZ}$ are minimal when the beam position and angle are on the symmetry axis (null axis), measured in the control runs, of the relevant detectors. The intensity detectors I and UDC observed intensity modulations coherent with polarization reversal from the beam-matter scattering and the transmission detectors T and DDC were affected by residual transverse polarization.

In the control runs measuring the effects of residual transverse polarization, the transverse components were increased at the target with solenoids in the beamline. In the runs measuring beam-matter scattering effects, the beam halo was increased by adding material upstream of magnet B1. During both types of control runs the beam positions and angle were varied.

The transverse scattering asymmetry is a function of the magnitude of the transverse polarization and the amount of scatterer. In the case of beam-matter scattering, the polarization is nearly totally transverse but the amount of

scatterer is small and for the residual transverse polarization effect the situation is just the opposite. The contribution of residual transverse polarization at the target to $\frac{\delta Z^*}{2Z}$ is

$$\delta \left[\alpha_2 (P2X - P2X_0) \text{ POLY} + \alpha_3 (P2Y - P2Y_0) \text{ POLX} \right] \quad (15)$$

where δ is the difference operator defined in the previous section, $P2X - P2X_0$ ($P2Y - P2Y_0$) is the distance of the average horizontal (vertical) beam position for a run from the horizontal (vertical) null position $P2X_0$ ($P2Y_0$), POLY and POLX are defined in OFFLINE VARIABLES, and α_2 and α_3 are coefficients measured during the "residual transverse polarization runs." Position detector P2 is used in equation 15 because the beam position at the collimator determined the acceptance of the transmission detectors to elastically scattered particles. Treating δ as a linear operator, equation 15 gives

$$\alpha_2 \delta (P2X \cdot \text{POLY}) - \alpha_2 P2X_0 \delta \text{POLY} + \alpha_3 \delta (P2Y \cdot \text{POLX}) - \alpha_3 P2Y_0 \delta \text{POLX} \quad (16)$$

or using previously defined product variables and combining coefficients this gives

$$\alpha_2 \delta XPLY - \beta_1 \delta \text{POLY} + \alpha_3 \delta YPLX - \beta_2 \delta \text{POLX} \quad (17)$$

The data taken during the control runs by the scintillation counters gave a χ^2 of 24 for 10 degrees of freedom.

The beam-matter contribution to the $\frac{\delta Z^*}{2Z}$ is the sum of a position and angle term given by

$$\alpha_4 \delta XTPY - \beta_3 \delta TPLY + \alpha_5 \delta ATPY - \beta_4 \delta TPLY \quad (18)$$

where

$$\beta_3 = \alpha_4 \cdot PlX_0 \text{ and } \beta_4 = (P2X_0 - PlX_0) \cdot \alpha_5 \quad (19)$$

The angle information provides a more accurate determination of the beam position at the intensity detectors than the Pl detector would because of its location. This angle term is important at the I detector where the output current signal changes across the surface of the scintillator, because of the $\sim 5\%$ gain imbalance between opposite phototubes. There is no gain imbalance in the ion chambers and it is found that the angle term did not improve the run to run consistency of the added absorber data which had a χ^2 of 39 for 30 degrees of freedom. The angle information improved the χ^2 of the added absorber data for the scintillation counters in cases where the beam position had been displaced from center. A χ^2/df (chi-square per degree of freedom) of 2.6 is obtained with only the position term included and a $\chi^2/df = 1.1$ resulted from adding the angle term to the model for the scintillation counters. Figure 28 shows the contribution of beam-matter scattering to $\frac{\delta Z^*}{2Z}$ as a function of position while there was 5 cm of Lucite, placed just upstream of magnet X2B2, intercepting the vertically polarized beam.

Figure 28. Spurious Parity Signal ($\frac{\delta Z^*}{Z}$) Versus Average Horizontal Position with 5.0 cm of Lucite intercepting the vertically polarized incident beam.

The beam-matter scattering halo can modulate the beam intensity striking the position detector P1 and the polarimeter detector Y1. The correction is given by

$$\delta\text{POLY} = c_1 + c_2\delta\text{TPLY}$$

for the Y1 detector and

$$\delta\text{PlX} = c_3 + c_4\delta\text{TPLY}$$

for the P1 detector. The coefficients are determined from a least-squares fit to the added absorber data and to an equal number of "data runs" and the resulting corrections to δPOLY and δPlX are negligible.

The complete expression for the transmission asymmetry for the scintillation counters is

$$\begin{aligned} \frac{\delta Z1^*}{2\langle Z1 \rangle} = & \alpha_1 + \alpha_2\delta\text{XPLY} - \beta_1\delta\text{POLY} + \alpha_3\delta\text{YPLX} \\ & - \beta_2\delta\text{POLX} + \alpha_4\delta\text{XTPY} - \beta_3\delta\text{TPLY} \\ & + \alpha_5\delta\text{ATPY} - \beta_4\delta\text{TPLY} \end{aligned} \quad (20)$$

where α_1 represents the transmission asymmetry resulting from parity-violating processes plus another possible systematic source (discussed later). The variables used in equation 20 have been corrected for position. All coefficients are determined simultaneously using a chi-square minimization procedure where "data runs," the "residual transverse polarization runs" and the "added absorber runs" are included in the data sample.

The complete expression for the transmission asymmetry measured by the ion chambers is

$$\frac{\delta Z^2}{2G}^* = a_1 + a_2 \delta XPLY - B_1 \delta POLY + a_3 \delta YPLX - B_2 \delta POLX + a_4 \delta XTPY - B_3 \delta TPLY \quad (21)$$

and the fitting procedure is identical to that used for the scintillators.

Runs with a χ^2 greater than 5 are rejected and this removes about 10% of the data runs. The final analysis used the P1 detector in forming variables $\delta XPLY$ and $\delta YPLX$ because P1 gave a lower χ^2/df for the fits and did not change A_L^* or the corrections appreciably.

STUDY OF THE BEAM-MATTER SCATTERING

The model used in the data analysis to determine the contribution to the longitudinal asymmetry by the asymmetric incident beam halo was studied using the computer programs TRANSPORT and TURTLE.

TRANSPORT is a computer program used to design charged particle beam transport systems. In TRANSPORT, the beamline magnets and drift spaces are represented to first order by a square matrix, called the transfer matrix, which describes the effect of the magnet or drift space on the particle. The particle is represented by a column matrix which contains the positions, angles and momentum of the particle with respect

to a reference trajectory. The particle coordinates are transformed along the beamline by matrix multiplication and are given by

$$X(1) = RX(0) \quad (22)$$

where R is the transfer matrix for a drift space or magnet, $X(0)$ is the vector containing initial particle coordinates, and $X(1)$ is that of the final particle coordinates. The effect of the entire set of elements on the particle coordinates is given by the matrix product of the individual transfer matrices. The coordinates of each particle passing through a magnet or drift space are transformed using the same transfer matrix.

TRANSPORT takes a given phase space distribution for the particles and provides only beam envelope information along the beamline and not particle distributions.

The beamline optics are reproduced by supplying TRANSPORT with the types of magnets in the beamline, the magnetic field of each magnet used during the experiment, the magnet positions, and drift space distances. TRANSPORT tracks the beam from septum magnet X2SB1 to the water target. The horizontal and vertical beam emittance is estimated to be ~ 2.5 $\mu\text{m}\cdot\text{cm}$ using beam spot sizes determined at several locations along the beamline. The beam has a minimal spot size or "waist" of ~ 3.0 cm diameter at solenoid X2S01 and the water

target. The typical angular divergence of the beam envelope is one to three milliradians at the waist.

The beamline design determined in TRANSPORT is used in the ray tracing computer program TURTLE. TURTLE generates rays with a Monte Carlo program and transforms the coordinates of each ray through the elements of beamline. TURTLE provides phase space distributions of the beam at each position along the beamline including the effects of collimators and magnet apertures.

Multiple scattering can be introduced into the ray tracing calculations in TURTLE. The angle of the original ray is increased by the root mean square addition of a randomly chosen angle between 0 and 50 mr. A typical perpendicular momentum of an elastically scattered proton is ~ 300 MeV/c, and the corresponding angle is $\sim 300/6000 \sim 50$ mr. The additional angle represents the change in direction of a proton having elastically scattered via the strong interaction.

The equivalent collision length of 5 cm of Lucite (0.10) is introduced into TURTLE at the position of detector X1, the same location where 5 cm of Lucite was placed during the "added absorber runs." The concentration of rays striking the X2 detector is compared for several different locations of the Lucite scatterer. The results of this study indicate that;

a) a large fraction of the beam scatters onto the X2 polarimeter arms with the Lucite placed at the detector X1;

b) the apertures at solenoids X2S01 and X2S02 remove large angle scatterers completely, and therefore the rays do not scatter onto the X2 polarimeter arms with Lucite placed at magnet X2SB2;

c) the amount of scattered beam reaching the X2 detector from the scattering of polarized protons with air and mylar windows in the region of X2SB2 is negligible;

d) the amount of scattering during nominal data taking can almost be reproduced by the scattering from the detectors and air located in that region.

The amount of material in this region of the beamline is

0.53 cm -- 7 aluminum plates in an ion chamber

300 cm -- air

.03 cm -- 4 mylar windows

for a total collision length of .0087 (compare to 0.01).

The conclusions are:

a) the asymmetric beam halo is caused by vertically polarized protons interacting with detectors and air located upstream of solenoid X2S02;

b) there is a negligible contribution to the longitudinal asymmetry by vertically polarized protons striking matter upstream of solenoid X2S01 since large angle scatterers

are removed during transport because of small magnet apertures. Further, small angle scatterers cannot be distinguished from unscattered beam particles because they strike both the upstream and downstream intensity detectors, and therefore do not contribute to the transmission asymmetry;

c) the initial phase space ellipse of the beam was not well known and this precluded any further detailed study of the beam-matter scattering and direct comparisons with data downstream of the target. Further, the technique of introducing nuclear scattering into the computer program via the Coulomb scattering parameters was only an approximation and again not suitable for detailed comparisons with the transmission data.

HYPERONS

The decay products of longitudinally polarized hyperons do not strike the transmission detectors. The computer program TURTLE was used to study the transport of the decay products of lambda hyperons from the production target to the transmission detectors. The (6.0 ± 0.5) GeV/c incident proton beam produces lambdas³⁹ with momenta in the range 3.2 to 5.3 GeV/c and at angles between ± 35 mr with respect to the beam direction. The pions from lambda decay are emitted with a mean momentum of 0.9 GeV/c, a maximum momentum of 1.2 GeV/c, and at angles between ± 200 mr with respect to the lambda direction. The protons have a momentum of 3.6 GeV/c, a maximum of 4.8 GeV/c, and are produced between ± 60 mr.

The collimator, located 1.58 m downstream from the center of the target, transmits 10% of the protons and 1% of the pions from lambda decays, and less than 0.5% of the lambdas. The first bending magnet of the spectrometer removes all the pions and 90% of the protons passed by the collimator. The remaining protons are stopped by the apertures of the final bending magnet in the spectrometer.

See Appendix A for a discussion of the results from an earlier version of this experiment.

DETECTOR GAIN

The gain of the scintillation counters and ionization chambers relates the integrated signal current from the detector to the incident beam intensity. This gain factor can change coherently and incoherently with reversal of the beam polarization.

The incoherent or random changes in gain can increase the magnitude of the error on a measurement. This type of gain fluctuation is reduced in this experiment by reversing the beam polarization between ZGS pulses, approximately every three seconds.

Coherent gain variations or a constant gain drift can produce a false parity signal. The data analysis computer program requires even and odd numbered runs to start with beam pulses with opposite polarization. Therefore any systematic drifts are reduced in the limit of many runs. The longitudinal asymmetry is calculated using the above method and also by starting even and odd numbered runs with pulses of the same polarization. The two methods give the same result which indicates the drifts are small and random throughout the experiment.

POLARIZATION CORRELATION WITH PHASE SPACE

The correction to the longitudinal asymmetry due to a polarization correlation with the beam phase space is made

using the sensitivity measured in the "residual transverse polarization runs" and the transverse polarization data taken in the "collimator runs." The average transverse polarization in the upper, lower, left and right halves of the beam determined in the "collimator runs" is presented in Table 3. The correction to the longitudinal asymmetry caused by a left-right or up-down scattering asymmetry produced at the target, is given in equation 16 by

$$\delta \left[\alpha_2 (P_{2X} - P_{2X_0}) \text{POLY} + \alpha_3 (P_{2Y} - P_{2Y_0}) \text{POLX} \right] \quad (16)$$

The correction due to a polarization correlation with phase space is made in analogy to this expression.

The polarization distribution in the beam which can lead to a helicity dependent transmission is given by

$$\iint dx dy (P_y x - P_x y) B(x, y) \quad (23)$$

where

$$P_y \equiv \frac{1}{2A(\theta)} \left[\delta \text{ POLY} \right] \quad (24)$$

and

$$P_x \equiv \frac{1}{2A(\theta)} \left[\delta \text{ POLX} \right] \quad (25)$$

are the average amount of transverse polarization for a given beam helicity. $A(\theta)$ is the target analyzing power as measured by the Y1 detector, $B(x, y)$ represents the spatial intensity distribution of the beam (taken as a gaussian), and x and y are particle coordinates at the collimator (beam center is $(0, 0)$).

TABLE 3

RESULTS FROM COLLIMATOR STUDY OF BEAM
 PHASE SPACE CORRELATION WITH POLARIZATION
 (in units of 10^{-4})

HALF OF BEAM TRANSMITTED	POLY	POLX
UPPER	2.75 ± 0.15	0.60 ± 0.35
LOWER	-2.65 ± 0.20	1.60 ± 0.40
RIGHT	0.50 ± 0.15	0.70 ± 0.15
LEFT	0.55 ± 0.20	1.45 ± 0.15

POLX (POLY) is the up-down (left-right) scattering asymmetry measured 1.3 m downstream of the target by detector Y1. POLY and POLX are defined in the section OFFLINE VARIABLES, CHAPTER 5.

During the "collimator runs" the Y1 detector measured the scattering asymmetry

$$\text{POLX} = A(\theta) \langle P_x \rangle \quad (26)$$

where $\langle P_x \rangle$ is the average horizontal component of beam polarization at the target. This can be written

$$\text{POLX} = \frac{A(\theta) \int \int_{\text{half circle}} dx dy P_x B(x,y)}{\int \int_{\text{half circle}} dx dy B(x,y)} \quad (27)$$

where the vertical intensity distribution is

$$B_y(y) = \frac{1}{\sqrt{2\pi} \Sigma_y} e^{-y^2/2\Sigma_y^2} \quad (28)$$

and Σ_y is related to the root-mean-square beam radius σ_y by

$$2 \Sigma_y = \sigma_y$$

The horizontal polarization is taken to be a linear function of position given by

$$P_x = \alpha y \quad (29)$$

where α is a coefficient. Substituting equations 28 and 29 into equation 27 and integrating gives

$$\langle P_x \rangle = \frac{2\Sigma_y \alpha}{\sqrt{2\pi}} \quad (30)$$

Therefore

$$\langle P_x \rangle_+ - \langle P_x \rangle_- = \frac{4\Sigma_y \alpha}{\sqrt{2\pi}} \quad (31)$$

where + and - denote the helicity of the incident proton beam. The transverse component of polarization which

averages to zero when both halves of the incident beam are scattered can produce a spurious parity signal. The magnitude of this component is determined by forming

$$\overline{\langle P_x \rangle_+ - \langle P_x \rangle_-} = \frac{1}{2A} \left[\text{POLX}_{\text{LOWER}} - \text{POLX}_{\text{UPPER}} \right] \quad (32)$$

where $\text{POLX}_{\text{LOWER}}$ ($\text{POLX}_{\text{UPPER}}$) is the up-down scattering asymmetry measured by the Y1 detector when the lower (upper) half of the incident beam was transmitted during the "collimator runs." From equation 31 this gives

$$\overline{\langle P_x \rangle_+ - \langle P_x \rangle_-} = \frac{4\Sigma_y \alpha}{\sqrt{2\pi}} \quad (33)$$

Similarly,

$$\overline{\langle P_y \rangle_+ - \langle P_y \rangle_-} = \frac{4\Sigma_x \beta}{\sqrt{2\pi}} \quad (34)$$

and β is defined by

$$P_y \equiv \beta x \quad (35)$$

Substituting equations 35 and 29 into equation 23 gives

$$-\alpha \Sigma_y^2 + \beta \Sigma_x^2 \quad (36)$$

Using equations 33 and 34 this can be written

$$\begin{aligned} \iint dx dy (P_y x - P_x y) B(x, y) &= -\Sigma_y \frac{\sqrt{2\pi}}{4} \overline{\langle P_x \rangle_+ - \langle P_x \rangle_-} \\ &+ \Sigma_x \frac{\sqrt{2\pi}}{4} \overline{\langle P_y \rangle_+ - \langle P_y \rangle_-} = \epsilon \end{aligned} \quad (37)$$

where ϵ represents the first moment of the polarization distribution.

The correction to the longitudinal asymmetry is

$$\frac{\delta Z}{2Z}^* = \alpha_2 \epsilon \quad (38)$$

where α_2 is taken from equation 16. The sensitivity coefficients α_2 and α_3 are equal because of the circular symmetry of the collimator after the target, and therefore α_2 or α_3 can be used in equation 38. The value of $\Sigma_x = \Sigma_y = 1.0 \pm 0.1$ cm and $\alpha_2 = \alpha_3 = -0.02 \pm 0.01$. This leads to a correction of $-(0.40 \pm 0.30) \times 10^{-6}$ to A_L^* .

UNPOLARIZED DATA

The asymmetry determined from the average of the "quad transmission $\delta Z/2Z$ " is $(0.5 \pm 0.6) \times 10^{-6}$. See page 81 for the definition of a quad variable. Here the operator δ takes the difference between consecutive quad variables. The null result implies there are no parity-violating backgrounds from this "unpolarized" data.

ELECTRONIC BACKGROUND

The asymmetry A_L^* , calculated with the beam off, was less than 10^{-8} throughout the experiment.

RESULTS

The raw value of $A_L^* = \frac{1}{P \ln Z} \frac{\delta Z}{Z}$ is calculated for each run and the weighted average of 184 runs gives

$$A_L^* = (4.37 \pm 0.64) \times 10^{-6}$$

for the scintillation counters and

$$A_L^* = (5.47 \pm 0.72) \times 10^{-6}$$

for the ionization chambers. The average beam polarization P was 0.71 ± 0.03 and the average transmission Z^* , determined from the ratio of the gas pressures in the UDC to DDC ion chambers, was 0.18 ± 0.01 . The quoted errors in A_L are the root mean square values.

A small reduction in the statistical fluctuations of A_L^* is obtained after the regression analysis. This noise reduction process did not appreciably change A_L^* , indicating the regression variables are independent of polarization. The value of A_L^* after regression for the scintillation counters is

$$A_L^* = (4.15 \pm 0.56) \times 10^{-6}$$

and

$$A_L^* = (5.11 \pm 0.69) \times 10^{-6}$$

for the ion chambers. Table 4 summarizes the contributions of beam properties of A_L^* .

TABLE 4

SUMMARY OF CONTRIBUTIONS TO A_L^* FROM
BEAM PROPERTIES IN UNITS OF 10^{-7}

PROPERTY	SCINTILLATORS CONTRIBUTION TO A_L^*	ION CHAMBERS CONTRIBUTION TO A_L^*
Horizontal Position	-0.74 ± 3.8	-2.6 ± 2.8
Vertical Position	-1.8 ± 2.7	-0.96 ± 1.7
Time Structure	0.35 ± 0.25	0.05 ± 0.07
Sum	-2.2 ± 4.7	-3.5 ± 3.3

The corrections for contributions to $\frac{\delta Z^*}{2Z}$ from residual transverse polarization and beam-matter effects are made using equations 20 and 21. Table 5 shows the weighted averages of the variables used in equations 20 and 21 and Table 6 shows the values of the coefficients. This data is combined and displayed in Table 7 such that the contribution to A_L^* is the product of $\gamma(\text{cm}^{-1})$, the measured sensitivity of A_L^* to beam position and angle in the presence of a transverse scattering asymmetry ΔH , $d(\text{cm})$, the distance of the beam position and angle from the measured symmetry axis, and ΔH . The data are consistent with the model since $\chi^2/\text{df} = 1.17$ for both detector systems. The scintillation counters find that

$$A_L^* = (2.40 \pm 0.66) \times 10^{-6}$$

and the ion chambers find

$$A_L^* = (4.08 \pm 0.81) \times 10^{-6}.$$

The correlation of polarization with beam phase space gives a contribution to A_L^* of $(-0.40 \pm 0.30) \times 10^{-6}$ for both detector systems.

Table 8 summarizes the values of A_L^* at each stage of the analysis and gives the final result

$$A_L = (1.99 \pm 0.73) \times 10^{-6}$$

for the scintillators and

$$A_L = (3.66 \pm 0.87) \times 10^{-6}$$

TABLE 5

Summary of the weighted average of variables and the root-mean-square errors used in computing contributions to A_L for the residual transverse polarization and beam-matter scattering effects. See equations 20 and 21.

Variable	Value
$\delta XPLY^+$	$(2.80 \pm 0.39) \times 10^{-6}$
$\delta POLY^+$	$-(4.70 \pm 0.19) \times 10^{-5}$
$\delta YPLX$	$-(1.10 \pm 0.75) \times 10^{-6}$
$\delta POLX$	$(3.50 \pm 0.53) \times 10^{-5}$
$\delta XTPY$	$(2.10 \pm 0.0019) \times 10^{-4}$
$\delta TPLY$	$-(3.50 \pm 0.0019) \times 10^{-3}$
$\delta ATPY$	$(1.20 \pm 0.0045) \times 10^{-4}$

[†] Product variables are in units of cm/5.

⁺ The analyzing power of the target as measured by the Y1 detector is 0.065.

TABLE 6

Summary of the values of coefficients in units of 10^{-2} determined from a chi-square minimization procedure applied to equations 20 (scintillation counters) and 21 (ion chambers).

COEFFICIENTS FROM THE SCINTILLATION DATA	VALUE	COEFFICIENTS FROM THE ION CHAMBER DATA	VALUE
α_2	-1.93 ± 0.81	a_2	-1.95 ± 1.10
$P2X_0^\dagger$	1.40 ± 3.30	$P2X_0^\dagger$	0.18 ± 3.40
α_3	-3.10 ± 3.70	a_3	-2.20 ± 4.20
$P2Y_0^\dagger$	-24.0 ± 8.0	$P2Y_0^\dagger$	-10.0 ± 7.0
α_4	2.85 ± 0.17	a_4	2.99 ± 0.18
$P1X_0$	-8.20 ± 3.90	$P1X_0$	-7.01 ± 0.36
α_5	0.96 ± 0.15		
$(P2X-P1X)_0$	$-1.8 \begin{smallmatrix} + 3.0 \\ -61.0 \end{smallmatrix}$		

[†] The P1 detector was used in the determination of this coefficient. See text p.91.

NOTE: $P2X_0$, $P2Y_0$, $P1X_0$ and $(P2X-P1X)_0$ are in units of cm/5.

All other coefficients are in units of 5/cm.

TABLE 7

CONTRIBUTIONS FROM RESIDUAL TRANSVERSE POLARIZATION
AND BEAM-MATTER SCATTERING TO $\delta Z/2Z^*$

<u>Scintillation Counters</u>			
<u>Source</u>	<u>Beam-Matter</u>	<u>Horizontal Residual Transverse</u>	<u>Vertical Residual Transverse</u>
γ	(0.0057 ± 0.00034)	(-0.0039 ± 0.0016)	(-0.006 ± 0.004)
d	(0.09 ± 0.024)	(-0.36 ± 0.15)	(1.1 ± 0.40)
ΔH	$-(3.5 \pm 0.002) \times 10^{-3}$	$-(4.7 \pm 0.20) \times 10^{-5}$	$(3.5 \pm 0.53) \times 10^{-5}$
$\gamma d \Delta H$	$-(1.8 \pm 0.49) \times 10^{-6}$	$-(0.066 \pm 0.039) \times 10^{-6}$	$-(0.23 \pm 0.18) \times 10^{-6}$
<u>Ion Chambers</u>			
γ	(0.0058 ± 0.00036)	(-0.0039 ± 0.0022)	(-0.0044 ± 0.0084)
d	(0.058 ± 0.029)	(-0.27 ± 0.15)	(0.29 ± 0.35)
ΔH	$-(3.5 \pm 0.002) \times 10^{-3}$	$-(4.7 \pm 0.19) \times 10^{-5}$	$(3.5 \pm 0.53) \times 10^{-5}$
$\gamma d \Delta H$	$-(1.18 \pm 0.60) \times 10^{-6}$	$-(0.049 \pm 0.039) \times 10^{-6}$	$-(0.045 \pm 0.10) \times 10^{-6}$

TABLE 8
SUMMARY OF A_L^* RESULTS IN UNITS OF 10^{-6}

Stage of Analysis	Scintillation Counters	Ionization Chambers	Combined
Raw Asymmetry	4.37 ± 0.64	5.47 ± 0.72	4.86 ± 0.47
After Regression	4.15 ± 0.56	5.11 ± 0.69	4.54 ± 0.43
Corrected for:			
Transverse [†] Polarization	3.90 ± 0.55	5.04 ± 0.68	4.37 ± 0.43
Beam-Matter [†] Scattering	2.40 ± 0.66	4.08 ± 0.81	3.06 ± 0.51
Polarization Correlation with Phase Space	1.99 ± 0.73	3.66 ± 0.87	2.65 ± 0.60
Final Results	1.99 ± 0.73	3.66 ± 0.87	2.65 ± 0.60

[†] The control run data are included in the data sample.

for the ion chambers. The correlation coefficient between A_L for the two detector systems is 0.20 and is determined from the average A_L for each run after all the corrections to the A_L are made. Figure 29 shows a scatter plot of

$\frac{\delta Z_2}{2G}$ vs $-\frac{\delta Z_1}{2Z_1}$. Since the correlation coefficient between the A_L for the two systems indicate the measurements are independent, a combined fit gives

$$A_L = (2.65 \pm 0.60) \times 10^{-6}.$$

CONCLUSIONS

This experiment measured A_L with an accuracy of better than 6×10^{-7} in about a six week period of data taking. The error is roughly 3 times greater than expected from the statistical fluctuations of the beam absorption in the target (Q-factor ~ 3). This Q-factor precluded a more precise measurement of A_L in a reasonable amount of time with these detectors since the error on the transmission did not decrease as $\sqrt{N}$, where N is the number of incident protons, with a beam intensity greater than 5×10^8 protons/pulse. The extra fluctuations in the transmission measurement in each detector system are uncorrelated and therefore do not originate from a common source, such as a contribution to A_L from a beam property not considered in the analysis (e.g., beam motion during the spill).

Figure 29. Scatter plot of $\frac{\delta Z_2}{2G}$ vs $-\frac{\delta Z_1}{2Z_1}$ in units of 10^{-6} using data after the regression analysis and corrected for residual transverse polarization and beam-matter scattering effects. The correlation coefficient for this plot is -0.20 . The final result is displayed with error bars at $(2.4 \pm .8, -4.5 \pm 1.0)$.

The regression analysis and the model describing the contributions to A_L^* from residual transverse polarization and beam-matter scattering have been tested thoroughly and describe the data accurately. The phase space correlation with beam polarization provided a small correction to A_L^* . More control run data should have been taken in order to reduce the error on these contributions to A_L^* . The decays from polarized hyperons are adequately removed with the collimator and magnetic spectrometer.

The combined result from two independent measurements give a value for A_L nearly 5 standard deviations from zero. The most probable explanation for this helicity-correlated transmission is the parity-violating interference between the weak and strong interaction scattering amplitudes.

The result of this experiment is larger than expected from our present knowledge of the weak and strong interaction at 6 GeV/c. Henley and Krejs calculate A_L to be $\sim 1.0 \times 10^{-7}$ at 6 GeV/c.²⁵ Modifications to the calculation by Holstein²⁴ suggest the sign of A_L is positive at 6 GeV/c, but it does not provide any substantial change in the magnitude of A_L . More recently, Henley has estimated⁴⁰ A_L to be positive but failed to find a large increase in the magnitude. The calculation is made more difficult because of the nuclear target and the role of the neutrons. The neutrons may enhance the parity signal in some as yet unknown manner as

seems to be the case in the anomalously large results of Lobashov, et al., in $n + p \rightarrow d + \gamma$.¹⁶ The effect of neutrons can be studied at LAMPF, now that the ZGS is closed, where an experimental search for parity violation between nucleons will be undertaken at 1.5 GeV/c in the near future. Of course the LAMPF data should see any energy dependence in the parity signal being suggested by the 6 GeV/c data. The outcome of the LAMPF experiment will be very interesting, and should it corroborate the ZGS data, the failure of the calculations may be of a more fundamental nature. New calculations are being considered by several theorists⁴⁰ and hopefully these results will aid in the understanding of the interactions between nucleons.

The results of this experiment are illustrated in Figure 30.

Figure 30. Parity conservation implies the laws of physics are identical for an experiment and its mirror image. The above figure illustrates the results of this experiment, which do not conserve parity because we can distinguish between the measurement on the left and the mirror image shown at the right.

DISCUSSION

The result of this experiment, $A_L \sim 10^{-6}$, indicates a strong energy dependence associated with the weak and hadronic interaction between nucleons since the low energy measurements of A_L are $\sim 10^{-7}$. The next information on this energy dependence will come from a transmission experiment designed to search for parity violation in proton-proton scattering at 1.5 GeV/c, with an accuracy in the measurement of A_L of about 10^{-7} .

Within a couple of years a polarized beam with a momentum range up to 28 GeV/c will be available for experiments at the Alternating Gradient Synchrotron Brookhaven National Laboratory. The experience gained from the ZGS experiments can provide guidelines for further experimental investigation of the energy and isospin dependence of the weak hadronic interaction.

DETECTORS

The most attractive design feature of the ZGS experiment is the ability to make two simultaneous independent measurements of A_L . Two detector systems with different properties can increase the confidence in the final result by aiding in the understanding of systematic and random backgrounds. The scintillation counter and ionization chamber transmission detectors used in this experiment operated with a signal to

noise ratio of about 3 (Q-factor ~ 3) at an incident beam intensity of $\sim 4 \times 10^8$ protons/pulse. Beam motion during the spill, 60 Hz and greater, contributed to this noise. To improve the Q-factor a regression analysis removing beam motion from the transmission and a data selection procedure, during the spill, can be accomplished by electronically dividing the beam spill into small time segments. The gain drifts of both detector systems were random and negligible. Randomly selecting the sign of the initial polarization is a method that can be used to reduce the effects of long term drifts.

The next measurement of A_L at high energy should have an accuracy at the 10^{-7} level. This would require at least 10^{15} protons on target and therefore an intense beam relative to the beam received in the ZGS experiment. Ion chambers perform well in intense beams but scintillation counters do not because of radiation damage to the plastic scintillator. The use of liquid scintillator in place of plastic scintillator is a possible solution to this problem. Alternatively, an experiment that measures only the scattered beam from the target²⁰ with scintillation counters and the transmitted beam with ion chambers could receive high beam intensities.

SYSTEMATICS

There is no global test to determine the presence of a systematic contribution to A_L . An experiment measuring A_L at

the 10^{-7} level will consider systematics that were negligible in this experiment. Therefore, classes of systematics should be studied as a check on A_L , as is possible with unpolarized beam data.

Transporting a longitudinally polarized beam to the experimental area would eliminate the largest contribution to A_L^* in this experiment -- the beam-matter interaction.

The method used in this experiment to measure residual transverse polarization contributions to A_L^* could be repeated in a more sensitive measurement of A_L^* . Control runs in general should be repeated frequently during the experiment to compensate for changing conditions.

The correlation of polarization with phase space should be measured at the target and can be determined by collimating a portion of the beam or by passing a thin scatterer through the beam and measuring the resulting transverse scattering asymmetry.²¹

A position feedback loop controlling the current in an upstream bending magnet is necessary to minimize beam motion and maintain the beam position on the symmetry axis for residual transverse polarization effects.

PHYSICS

In the next decade polarized beams at Fermilab and Isabelle may allow the search for parity violating front-back asymmetries in high-transverse-momentum proton-proton

collisions. This would measure more directly, than in a total cross section measurement, the interference between the weak and strong scattering amplitudes of quarks and therefore aid in discriminating among strong interaction models.⁴¹

APPENDIX A

DISCUSSION OF RESULTS FROM AN EARLIER VERSION OF THIS EXPERIMENT

The purpose of the T0 (Figure 16) detector was to repeat the measurement of A_L taken in an earlier version of this experiment²⁹ where A_L was found to be $(-15.0 \pm 2.4) \times 10^{-6}$. This value of A_L could be attributed to the production of polarized hyperons in the target (discussed in EXPERIMENTAL CONSIDERATIONS -- HYPERONS, page 31). A study³⁰ of the decay distribution of polarized lambdas with a Monte Carlo computer program, in which the longitudinal polarization transfer to the lambdas was assumed to be (0.26 ± 0.18) , produced a cross section asymmetry $\frac{\delta Z}{2Z} = (31 \pm 23) \times 10^{-6}$.

The result of this experiment does not confirm the large negative asymmetry for the value of A_L but finds $A_L(T0) = (3.9 \pm 0.72) \times 10^{-6}$ after all corrections.

The previous experiment³⁰ measured a transverse scattering asymmetry due to the beam-matter interaction six times greater than the present experiment. This reduction is due to the addition of vacuum along the beamline where possible, helium elsewhere, and the enlarged aperture at the entrance to the experimental area just upstream of magnet X2B2 (see

Figure 14, p. 38). The largest contribution to A_L^* in the present experiment comes from the beam-matter interaction. The correction to A_L^* , with the beam carefully positioned on the symmetry axis, was $\sim 2 \times 10^{-6}$.

The effects of beam-matter scattering were not realized until the end of the previous experiment.³⁰ Therefore, the data, from the experiment in which $A_L = (-15.0 \pm 2.4) \times 10^{-6}$, was not corrected for beam-matter scattering, nor was there an attempt to position the beam on the symmetry axis. The factor of six in the transverse asymmetry and the known strong position dependence of the contribution to A_L^* (see Figure 26, p. 89) can produce the observed result.

The first measurement at the ZGS²⁷ found $A_L = (5.0 \pm 9.0) \times 10^{-6}$. This result, because of its large uncertainty, is consistent with the present experiment and previous experiments indicating large negative asymmetries. However, it is tempting to speculate that the positive value A_L reflects the small effect of the beam-matter scattering to A_L^* when the beam is positioned on the symmetry axis.

APPENDIX B

PHOTOTUBE GAIN MONITORING SYSTEM

The gain monitoring system was not used to reduce the noise caused by phototube gain fluctuations in the scintillation counter signals because the optical fibers were radiation damaged. The effect of radiation on the optical fibers is to reduce the amount of light transmitted to the phototube. Since the magnitude of this change is unknown, phototube gain changes cannot be monitored accurately throughout the experiment.

Figure 31 shows the exponentially decreasing light output from the optical fiber connected to the YLU phototube as a function of the total beam intensity accumulated during the experiment, and Figure 32 is a similar plot for the IU optical fiber. The steeper exponential of the YLU optical fiber damage reflects the greater amount of radiation in the region just downstream of the target. Figure 33 shows that the TU optical fiber has less damage than the IU and YLU fibers and the dependence on beam intensity is linear. Since the transmission of the proton beam through the target is 0.18, and the spectrometer focuses the beam at the T detector,

the damage to the TU optical fiber is expected to be less than the IU and Y1U fibers.

The structure seen in the TU and Y1U plot at $\sim 83.2 \times 10^{12}$ protons represents the recovery of the optical fiber from radiation, since during this period the proton beam was off for one week. This partial recovery phenomena has been observed before in control experiments studying the gamma-radiation damage of scintillators.⁴²

In this experiment a quantitative analysis cannot be performed because the positions of the optical fibers on each phototube relative to the beam and the backgrounds, consisting of many kinds of radiation which varied throughout the experimental area and during the course of the experiment, are unknown.

It is evident from this data that plastic optical fibers, located within ~ 30 cm of an intense proton beam, will be severely damaged by radiation, eventually become opaque, and therefore be of no use as a light guide.

Figure 31. Exponentially decreasing light output from the optical fiber connected to the YIU phototube as a function of the incident beam intensity.

Figure 32. Exponentially decreasing light output from the optical fiber connected to the IU phototube as a function of the incident beam intensity.

Figure 33. Linearly decreasing light output from the optical fiber connected to the TU phototube as a function of the incident beam intensity.

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