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**Measurement of the Free Neutron-Proton
Analyzing Power and Spin-Transfer Parameters
In the Charge-Exchange Region at 790 MeV**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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Measurement of the Free Neutron-Proton Analyzing Power and Spin-Transfer Parameters In the Charge-Exchange Region at 790 MeV

Ronald Dean Ransome*

DISCLAIMER

The following table shows the results of the regression analysis for the dependent variable "Number of children in the household" (N = 1,000). The independent variables are "Age of the head of household" and "Gender of the head of household". The results are presented in the following table:

*The University of Texas at Austin, Austin, TX 78712.

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MEASUREMENT OF THE FREE NEUTRON-PROTON ANALYZING POWER AND
SPIN TRANSFER PARAMETERS IN THE CHARGE EXCHANGE REGION AT 790 MEV

by

Ronald Dean Ransome

ABSTRACT

The free neutron-proton analyzing power and the spin transfer parameters (K_{NN} , K_{SS} , K_{SL} , and K_{LL}) were measured at the Los Alamos Meson Physics Facility at 790 MeV between 165° and 180° center of mass. A 40% polarized neutron beam incident on a liquid hydrogen target was used. The recoil protons were momentum analyzed with a magnetic spectrometer to isolate elastic scatters. A large solid angle carbon polarimeter was used to measure the proton polarization. The measurements are the first at this energy and are in basic agreement with pre-existing phase shift solutions. The proton-carbon analyzing power was measured between 500 and 750 MeV. An empirical fit to the proton-carbon analyzing power between 100 and 750 MeV was done.

CHAPTER ONE-INTRODUCTION AND BACKGROUND

A. Introduction

A large portion of the physics research of this century has been devoted to the study of subatomic particles. The discoveries of the electron and of the atomic nucleus and its constituents, the neutron and proton, led to a tremendous effort to understand the interactions of these particles and the structure of the nucleus. Beginning in the 1930's, primarily due to the development of electron and proton accelerators, a large number of subatomic particles were discovered. It was soon realized that these particles had two different interactions, called the "strong" and "weak" forces. This brought the total number of forces known to four; these two and the previously known electromagnetic and gravitational forces. Both the proton and neutron are strongly interacting particles (hadrons), while the electron is a weakly interacting particle (lepton). The strong force is responsible for binding the nucleus, while the weak force is manifest in certain decays (for example, β decay of a neutron). Although the hadrons also interact weakly, the predominant force is the strong one, and most experiments with hadrons are designed to further understand its characteristics.

Despite nearly 50 years of research on the strong interaction between nucleons (the neutron and proton), the interaction is still not well understood. Further complicating the issue have been

suggestions in the last 20 years or so that the proton and neutron are not "elementary" particles, but are composed of even smaller particles. The most popular version of this is the "quark" theory, which holds that the nucleons are composed of three quarks each. This theory has had some success in predicting different families of hadrons, and is substantiated to a degree by scattering experiments. In the basic quark model, there are a few particles which can combine to form all of the hadrons. Baryons (hadrons with half-integer spin) are composed of three quarks, while mesons (hadrons with integer spin) are composed of a quark-antiquark pair. The quarks differ from all observed (at this time) particles in one important aspect; they carry a fractional electrical charge. Originally, three quarks were introduced (usually called up, down and strange quarks). The up quark has charge $2/3$, the down charge $-1/3$, and the strange charge $-1/3$. All three have spin $1/2$ and baryon number $1/3$. The up and down quarks have strangeness 0, and the strange quark has strangeness -1 . For each quark there is a corresponding anti-quark. By combining two up and one down quark, one gets a charge 1, baryon number 1, spin $1/2$ particle, the proton. Similarly, the neutron is composed of two down and one up quark. Strange particles, such as the Σ 's, contain the strange quark. One of the early successes of the quark model was the prediction of a particle with strangeness -3 , composed of three strange quarks. Such a particle, the Ω^- , was later observed. The model also predicts the correct value of the ratio of the neutron magnetic moment to the proton magnetic moment. Although the initial

model had successes, it had to be modified. Since the quarks are fermions, the Pauli principle forbids two identical quarks from being in the same state. This led to problems in baryons composed of three identical quarks. Another property, called color, was introduced to circumvent this. New particles were discovered, such as the J/ψ meson, which required additional quarks. Despite complications, the model still gives a good phenomenological description of many of the hadron properties. Some questions do remain. For example, no free fractionally charged particle has ever been observed in a scattering experiment (although there have been claims of the observation of fractional charges in a Millikan oil-drop type experiment¹). Why isn't a quark occasionally knocked out of a baryon in high energy collisions? The model also fails to explain why four or five quark states are not observed. Despite these questions, the model has gained wide acceptance.

Although the quark model explains some of the general features of the strong interaction, it is still not able to predict the details of hadron scattering. Since it is not possible to do free quark-quark scattering, the nature of the quark-quark interaction must be explored by studying hadron scattering. The majority of hadron scattering experiments have been nucleon-nucleon scattering experiments, since the nucleons are the most easily accessible hadrons. Many of the experiments, the majority at higher energies, have been of total and differential cross sections. Recent experiments exploring the spin dependent nature of the strong interaction have found that spin is

important at energies of at least of few GeV, where some thought the effect of spin would be negligible. The cross section measurements provide little information on the spin dependence of the interaction. It is important, therefore, to do further experiments which are sensitive to this spin dependence. The information provided will help in the development of "fundamental" theories, and will provide a more stringent test of models than do the cross section measurements.

The experiment described in this work is one that explores the spin dependence of the strong interaction for neutron-proton elastic scattering in the charge exchange (CEX) region. For a neutron beam incident on a proton target, the CEX region is that part of the scattering in which the recoil proton comes out in the forward direction, with roughly the same energy as the incident neutron beam. The interaction is thought to proceed through the exchange of a charged pion, represented by the following diagram

In this model, the neutron scatters at a small angle, but is changed into a proton due to the absorption of a π^+ . The particular interest

of this interaction, and the nucleon-nucleon formalism will be given in the next two sections.

B. Motivation for the Experiment

The experiment reported in this work is the measurement of the Wolfenstein parameters K_{NN} , K_{LL} , K_{SS} , K_{SL} and K_{LS} , and the analyzing power for free elastic n-p scattering at 790 MeV, between 167° and 180° center of mass (see Sec. C and Fig. 1-2 for a description of these parameters). This is the first measurement of these parameters in this angular region at this energy, and one of the first at any energy. Previous data are given in Table 1-1. In addition to the free data, there are the quasi-elastic measurements for pd+npp for K_{LL} and K_{NN} , also shown in Table 1-1. These measurements are part of a program to understand the nucleon-nucleon interaction at medium energies and to explore the neutron-proton charge exchange (n-p CEX) region specifically.

The medium energy range is of interest for two reasons. First, it is the region in which theories from both low energy (below pion production threshold, ~ 290 MeV) and high energy (where multiple particle production is possible, > 1 GeV) can be tested. It is probably still possible to use some potential model, a normal low energy technique, with some mechanism for pion production included, while our measurements indicate that Regge theory techniques, normally used at high energies, may also be applicable. Second, phase shift analysis, which provides a method of correlating measurements of different parameters at different energies and angles, can still be

Table 1-1

Previous Data

Param.	T (MeV)	θ_{cm}	Value	Ref.
K_{NN}	520	180.0	.12 $\pm$.33	Surko-29
K_{NN}	600	180.0	-.05 $\pm$.84	Surko-29
K_{SS}	520	180.0	-.22 $\pm$.18	Leung-30
K_{SS}	600	180.0	-.06 $\pm$.15	Leung-30
K_{NN}	128	170.0	-.28 $\pm$.21	Collins-31
K_{NN}	50	180.0	-.05 $\pm$.08	Woolverton-32
A_H	1731	166.5	-.17 $\pm$.05	Robrisch-33
		171.0	-.03 $\pm$.06	"
		175.5	-.03 $\pm$.12	"
K_{NN} (q.e.)	800	180.0	-.15 $\pm$.03	Riley-23
K_{LL} (q.e.)	800	180.0	-.64 $\pm$.03	Riley-23

used. This provides a phenomenological tool for investigating the nature of resonances and the effects of inelasticities.

The n-p CEX region is of interest for several reasons. First, the differential cross section shows a pronounced peak in the CEX region (Fig. 1-1). Simple one pion exchange (OPE), would give a dip in this region. This peak can be parameterized by the function

$$\frac{d\sigma}{dt} = \alpha_1 \exp(\beta_1 t) + \alpha_2 \exp(\beta_2 t)$$

where t is the four momentum transfer (see Sec. D). This form describes the cross section quite well over a very large energy range²⁻⁵ (roughly 200 MeV to over 60 GeV), possibly indicating a single mechanism is responsible. In addition, the $t = 0$ slope ($\alpha_1 \beta_1 + \alpha_2 \beta_2$) is almost independent of energy. Since the small angle scatters are believed to be dominated by a few light particle exchanges (primarily one pion exchange), the region should be the simplest to calculate.

This measurement was also inspired by a suggestion from Gibbs⁶. The phase shift analyses at this energy predicted the parameter K_{NN} would be close to zero at 180° c.m. Conventional OPE predicted the cross section would be zero and K_{NN} would be -1. Gibbs suggested the peak in the cross section might be due to one pion exchange, if the vertex function were changed slightly to allow S wave pions, which are forbidden in the conventional model because of the

Figure 1-1 n-p CEX differential cross section.

pion's negative parity. This model also gave the definite prediction of $K_{NN}=1$ at 180° . Although this idea was quite intriguing, the measurements more or less confirmed the phase shift predictions.

The lack of information about the nucleon-nucleon system not only impedes development of fundamental theories of the strong interaction, but also affects related areas of physics, such as interpretation of nucleon-nucleus scattering. For example, experiments have been recently done at the Los Alamos Meson Physics Facility (LAMPF) which use proton-nucleus scattering to attempt to extract the density of neutrons in nuclei. Ray⁷ has used the KMT optical model approach to interpret the data. The KMT approach uses the free nucleon-nucleon scattering amplitudes to describe nucleon-nucleus scattering. According to Ray, the lack of accurate nucleon-nucleon amplitudes at 800 MeV is one of the largest uncertainties in the extraction of neutron densities in these experiments.

C. Nucleon-Nucleon Formalism

Soon after the discovery that the nucleus is composed of protons and neutrons, the general features of the nuclear (strong) force were understood. First, it is primarily attractive (or else there would be no nuclei), and it is short range, indicated by the fact that the binding energy per nucleon is relatively constant for large numbers of nucleons. At short range it must be quite strong, since the Coulomb repulsion between protons is overcome. It is believed that all interactions obey the principles of conservation of

momentum and energy, with the strong interaction being no exception. The force is also known to be spin dependent, as indicated by the single two nucleon bound state (the deuteron), which has spin one. If there were no spin dependence, one would expect bound states with both spin one and zero. In addition, the strong force appears to conserve parity and isospin, and be invariant under time reversal, at least at the 1% level or better. For most analyses, these conservation principles are considered absolute.

If these properties are assumed exactly true, a general scattering matrix can be derived. The scattering matrix transforms the initial wave function into the final in a linear fashion, thus

$$\chi_f = M \chi_i$$

If the following coordinate system is defined

$$\hat{k} = \frac{\hat{k}_f + \hat{k}_i}{|\hat{k}_f + \hat{k}_i|} \quad \hat{m} = \frac{\hat{k}_f - \hat{k}_i}{|\hat{k}_f - \hat{k}_i|} \quad \hat{n} = \frac{\hat{k}_i \times \hat{k}_f}{|\hat{k}_i \times \hat{k}_f|}$$

where $\hat{k}_i$ and $\hat{k}_f$ are unit vectors in same directions as the initial and final momenta of the scattered particle, the M matrix for identical particles can be written as

$$M(k_f, k_i) = .5((a+b) + (a-b)(\sigma_1 n)(\sigma_2 n) + (c+d)(\sigma_1 m)(\sigma_2 m) \\ + (c-d)(\sigma_1 \ell)(\sigma_2 \ell) + e(\sigma_1 + \sigma_2)n)$$

σ_1 and σ_2 are the Pauli matrices acting on the first and second nucleon wave functions, with $\sigma_1 n$ equal to $\vec{\sigma}_1 \cdot \hat{n}$. That this is the most general form for the M matrix was shown by Wolfenstein⁶. The notation followed here is that of Lehar⁹. This matrix applies for the n-p system as well as for the p-p and n-n system if isospin invariance is assumed. However, the n-p system is composed of both isospin 1 and isospin 0 terms, so even with isospin invariance the n-p amplitudes will differ from the p-p and n-n amplitudes. If isospin invariance is not assumed, the np system has one additional term, $f(\sigma_1 - \sigma_2)n$. Since isospin invariance is known to be true at least to the 1-2% level, this term is usually neglected in the analysis of nucleon-nucleon scattering data. Since a, b, c, d, and e are all complex numbers, there are a total of 10 parameters to be determined. Since the overall phase is unimportant, 9 experiments must be done to uniquely determine all amplitudes. The amplitudes are functions of both energy and angle, so 9 experiments must be done at each energy and angle. To separate the isospin 0 and 1 terms in n-p scattering, data from a pure isospin 1 system (the p-p system, for example) must be used in conjunction with the n-p data, making a total of 19 experiments (5 I=0, and 5 I=1 complex amplitudes for a total of 20 parameters) necessary. As will be explained later, certain assumptions can be made which help simplify the situation.

Another system, the helicity formalism, has been developed by Jacob and Wick¹⁰. In this system states are labeled by the spin

projection onto the particle momentum. This formalism is quite useful at high energies and for massless particles with spin. Its application to nucleon-nucleon scattering has been described in detail by Goldberger, Grisaru, MacDowell, and Wong¹². Table 1-2 relates the helicity amplitudes to those used by Lehar.

Although each of the many formalisms in the literature may have advantages for different types of analysis, the goal of each is to provide a method of unifying experiment and allowing a comparison of theory to experiment. Models of the interaction can be used to calculate the relative importance of different amplitudes, rather than attempting to directly calculate all observables.

Once a formalism is decided upon, a set of observables must be defined and expressed in terms of the scattering matrix amplitudes. A number of different notations have been used, and different observables have been defined in both the center of mass and laboratory. Those pertinent to the experiment described in this work will be given here. Relevant quantities in terms of Lehar's amplitudes are given in Table 1-2.

Lehar uses the notations D_{pqik} and K_{pqik} for the spin transfer parameters, where $pqik$ stands for the polarizations of the scattered, recoil, beam, and target particles, D indicates the scattered particle polarization is measured and K indicates the recoil particle polarization is measured. For example, an experiment which scattered a polarized neutron beam from an unpolarized proton target and measured the scattered neutrons polarization would be denoted by

Figure 1-2 Spin transfer (Wolfenstein) parameters.
Dashed line indicates recoil particle.

Table 1-2

Observables in terms of Various Amplitudes

Laboratory Observables in terms of Lehar's amplitudes

$$\sigma = .5(a^2 + b^2 + c^2 + d^2 + e^2)$$

$$\sigma_{NN} = D = .5(a^2 + b^2 - c^2 - d^2 + e^2)$$

$$\sigma_P = \sigma_{A_N} = \text{Re}(a^* e)$$

$$\sigma_{SS} = \sigma_R = \text{Re}(a^* b) \cos(\alpha + \theta/2) + \text{Re}(c^* d) \cos(\alpha - \theta/2) \\ - \text{Im}(b^* e) \sin(\alpha + \theta/2)$$

$$\sigma_{LS} = \sigma_A = -\text{Re}(a^* b) \sin(\alpha + \theta/2) + \text{Re}(c^* d) \sin(\alpha - \theta/2) \\ - \text{Im}(b^* e) \cos(\alpha + \theta/2)$$

$$\sigma_{SL} = \sigma_{R'} = \text{Re}(a^* b) \sin(\alpha + \theta/2) + \text{Re}(c^* d) \sin(\alpha - \theta/2) \\ + \text{Im}(b^* e) \cos(\alpha + \theta/2)$$

$$\sigma_{LL} = \sigma_{A'} = \text{Re}(a^* b) \cos(\alpha + \theta/2) - \text{Re}(c^* d) \cos(\alpha - \theta/2) \\ - \text{Im}(b^* e) \sin(\alpha + \theta/2)$$

$$\sigma_{NN}^K = \sigma_{T_t} = .5(a^2 - b^2 + c^2 - d^2 + e^2)$$

$$\sigma_{SS}^K = \sigma_{R_t} = -\text{Re}(a^* c) \cos(\beta + \theta/2) - \text{Re}(b^* d) \cos(\beta - \theta/2) \\ + \text{Im}(c^* e) \sin(\beta + \theta/2)$$

$$\sigma_{LS}^K = \sigma_{A_t} = \text{Re}(a^* c) \sin(\beta + \theta/2) - \text{Re}(b^* d) \sin(\beta - \theta/2) \\ + \text{Im}(c^* e) \cos(\beta + \theta/2)$$

$$\sigma_{SL}^K = \sigma_{R_t'} = -\text{Re}(a^* c) \sin(\beta + \theta/2) - \text{Re}(b^* d) \sin(\beta - \theta/2) \\ - \text{Im}(c^* e) \cos(\beta + \theta/2)$$

$$\sigma_{LL}^K = \sigma_{A_t'} = -\text{Re}(a^* c) \cos(\beta + \theta/2) + \text{Re}(b^* d) \cos(\beta - \theta/2) \\ + \text{Im}(c^* e) \sin(\beta + \theta/2)$$

$\alpha = \theta/2 - \theta_1$ $\beta = \theta/2 + \theta_2$
 $a^2 = a^* a$, etc. $*$ = complex conjugate
 θ = c.m. scatt. angle θ_1 and θ_2 = lab. scatt. and recoil angles
(all greater than zero)

Helicity Amplitudes in terms of Lehar amplitudes

$$\begin{aligned}M_1 &= (a \cos \theta + b - c + d + i \sin \theta)/2 \\M_2 &= (a \cos \theta - b + c + d + i \sin \theta)/2 \\M_3 &= (a \cos \theta + b + c - d + i \sin \theta)/2 \\M_4 &= (-a \cos \theta + b + c + d - i \sin \theta)/2 \\M_5 &= (-a \sin \theta + i \cos \theta)/2\end{aligned}$$

where

$$\begin{aligned}M_1 &= \langle ++ | M | ++ \rangle \\M_2 &= \langle ++ | M | -- \rangle \\M_3 &= \langle +- | M | +- \rangle \\M_4 &= \langle +- | M | -+ \rangle \\M_5 &= \langle ++ | M | +- \rangle\end{aligned}$$

where + or - indicates the nucleon helicity,
with M the scattering matrix

Laboratory Observables in terms of helicity amplitudes

$$\begin{aligned}\sigma &= .5(M_1^2 + M_2^2 + M_3^2 + M_4^2 + 4M_5^2) \\ \sigma_{NN} &= \text{Re}(M_1^* M_3 - M_2^* M_4) + 2M_5^2 \\ \sigma_{AN} &= -\text{Im}(M_5^* (M_1 + M_2 + M_3 - M_4)) \\ \sigma_{SS} &= -\text{Re}(M_5^* (M_1 - M_2 + M_3 + M_4)) \sin \theta_1 \\ &\quad + \text{Re}(M_1^* M_3 + M_2^* M_4) \cos \theta_1 \\ \sigma_{LS} &= \text{Re}(M_5^* (M_1 - M_2 + M_3 + M_4)) \cos \theta_1 \\ &\quad + .5(M_1^2 - M_2^2 + M_3^2 - M_4^2) \sin \theta_1 \\ \sigma_{SL} &= -\text{Re}(M_5^* (M_1 - M_2 + M_3 + M_4)) \cos \theta_1 \\ &\quad - \text{Re}(M_1^* M_3 + M_2^* M_4) \sin \theta_1 \\ \sigma_{LL} &= -\text{Re}(M_5^* (M_1 - M_2 + M_3 + M_4)) \sin \theta_1 \\ &\quad + .5(M_1^2 - M_2^2 + M_3^2 - M_4^2) \cos \theta_1 \\ \sigma_{KN} &= -\text{Re}(M_1^* M_4 - M_2^* M_3) + 2M_5^2 \\ \sigma_{KS} &= -\text{Re}(M_5^* (-M_1 + M_2 + M_3 + M_4)) \sin \theta_2 \\ &\quad - \text{Re}(M_1^* M_4 + M_2^* M_3) \cos \theta_2\end{aligned}$$

$$\sigma K_{LS} = -\text{Re}(M_5^*(-M_1 + M_2 + M_3 + M_4))\cos\theta_2 \\ + .5(-M_1^2 + M_2^2 + M_3^2 - M_4^2)\sin\theta_2$$

$$\sigma K_{SL} = \text{Re}(M_5^*(-M_1 + M_2 + M_3 + M_4))\cos\theta_2 \\ - \text{Re}(M_1^*M_4 + M_2^*M_3)\sin\theta_2$$

$$\sigma K_{LL} = -\text{Re}(M_5^*(-M_1 + M_2 + M_3 + M_4))\sin\theta_2 \\ - .5(-M_1^2 + M_2^2 + M_3^2 - M_4^2)\cos\theta_2$$

(Quasi-elastic pd spin transfer parameters

$$\gamma K_{NN} = -2M_4^2 - 2M_1^2 - 4\text{Re}(M_4^*M_1)$$

$$\gamma K_{LL} = -4M_2^2 + 2M_4^2 + 2M_1^2 + 4\text{Re}(M_4^*M_1)$$

$$\gamma = 2M_4^2 + 2M_1^2 + 4M_2^2 + 4\text{Re}(M_4^*M_1)$$

D_{poio} , while one which measured the proton's polarization would be K_{oqio} , with p, q, and i being the directions measured. "o" indicates either an unpolarized state for the initial particles or that the polarization is not measured for the final particles.

An older notation, defined by Wolfenstein, defines parameters in the laboratory, relative to each particle's momentum and the scattering plane. These are expressed in the form Z'_t . Z indicates the beam polarization and is replaced by A for initial spin longitudinal, R for initial transverse in scattering plane, or D for transverse and perpendicular to the scattering plane. "t" is present if the recoil particle polarization is measured, absent for the scattered particle. The prime is present for final polarization longitudinal, absent for transverse. Since parity conservation prohibits polarization transfer between components in the scattering plane and those perpendicular to the scattering plane, the notation is unambiguous.

A newer notation, the "Ann Arbor" convention¹¹, has been introduced to cover both of the above cases. Like Lehar, it uses D and K to specify whether the scattered or the recoil polarization is measured. Like the Wolfenstein notation, polarizations are defined relative to each particle's momentum and the scattering plane. If the parameter being referred to is in the laboratory frame, capital letters N, L, and S are used, in the center of mass, lower case n, l, and s are used, where in each case n is normal to the scattering plane, s sideways, and l longitudinal with respect to the momentum of

the particle. This is the notation used in this paper. The experiment described in this work was designed to measure the parameters K_{NN} , K_{SL} , K_{SS} , K_{LS} , and K_{LL} for the charge exchange region in n-p elastic scattering. Fig. 1-2 shows the spin orientations for the spin transfer parameters.

One additional parameter is also measured, the free np analyzing power. This is denoted A_N in the Ann Arbor convention and A or P by Lehar (A if the asymmetry is measured and P if the polarization is measured, with $A=P$).

As stated earlier, a unique determination of the scattering amplitudes requires 9 experiments at each energy and angle. In the real world, experiments are done only at discrete energies and angles, and it is rare that 9 experiments are all done at exactly the same energy and angle. A common phenomenological technique, phase shift analysis, helps overcome this problem by using conservation of angular momentum and wave mechanics to describe the data. The basic idea is that an interaction takes place in discrete angular momentum states. The incoming particle is described by a plane wave, which can be expressed as an infinite sum of partial waves, each of a fixed angular momentum. Each partial wave has its phase shifted by some amount δ . The greater the shift, the stronger the elastic interaction in that angular momentum state. Classically, the angular momentum is the cross product of the distance between two particles and their relative linear momentum, so higher angular momentum states correspond to longer distance interactions for a fixed relative linear momentum.

Because of the short range nature of the nucleon-nucleon force, only a finite number of partial waves actually contribute to the reaction cross section. At low energies this may be only the $\ell=0, 1$, and 2 waves, with all others making no significant contribution. At 800 MeV partial waves with ℓ as high as 7 or 8 are needed to fit the data. In practice, the phases of some predetermined number of partial waves are allowed to vary to fit the data, with the phases of higher partial waves being set by theory (usually the calculated one pion exchange phases). The angular dependence of each partial wave is given by a Legendre polynomial of order ℓ . For the simplest case of pure elastic scattering of two particles without spin, the relation of the scattering amplitude and phase shifts is given by

$$f(E, \theta) = \sum_{\ell=0}^{\infty} (2\ell + 1) P_{\ell}(\cos(\theta)) \exp(i\delta_{\ell}) \sin(\delta_{\ell}) / p$$

where P_{ℓ} is a Legendre polynomial, p is the center of mass momentum and δ_{ℓ} is the phase shift for the ℓ th partial wave. $f(E, \theta)$ is the scattering amplitude and corresponds to the $(a+b)$ term in the scattering matrix formula given above. If inelastic reactions are also possible, an additional term, η_{ℓ} must be included in the product. η varies from 0 to 1 and represents the fraction of elastic scattering for each partial wave. When the scattering is of two particles with spin, the relations between the phase shifts and amplitudes become more complicated. Only total angular momentum is conserved, so initial states with one orbital angular momentum can couple to final

states with a different value (for example, an initial 3P_2 state can couple to a 3F_2 final state). For nucleon-nucleon scattering, the Pauli principle puts additional restrictions on initial and final states. Although this complicates the calculation, the basic idea is the same as for the simple case where spin is not involved. Details of phase shift analysis for particles with spin are given in Ref. 13-15.

Given the relation between the amplitudes (and observables) and the phase shifts, the data at a fixed energy can be fit by doing a phase shift analysis (that is, determining the δ for each partial wave) so the need to have all data at the same angle is eliminated. Also, assuming that the phases vary smoothly as a function of energy, data at different energies can also be correlated. This approach works quite well at lower energies (below 400 MeV) where only a limited number of partial waves enter, and the scattering is almost entirely elastic. In the intermediate energy range (400 MeV to a few GeV) phase shift analyses are still done. However, inelasticities, the increasing number of partial waves which must be considered, and the general lack of data make the analysis more difficult and less reliable. Despite these problems, fairly stable phase shift solutions have been obtained.

Of course, the goal of all this is to correlate data for comparison with theory, which it is hoped will determine the underlying principle of the interaction. At this time, the only such theory is that of particle exchange. This was proposed by Yukawa in

1935. It was known that the electromagnetic force could be described in terms of the exchange of a photon between the interacting particles. Yukawa suggested that the nuclear force could be described in an analogous manner, except that the particle exchanged had a mass, unlike the massless photon of electromagnetic theory. Although the emission of a particle by a single nucleon violates conservation of energy, it is allowed for a limited time by the Heisenberg uncertainty principle. This states that $\Delta E \Delta t \leq \hbar$. By inserting the range of the nuclear interaction and assuming the exchanged particle travels at the speed of light, Δt can be determined and an estimate of ΔE (the particle mass) can be made. This gave an estimated mass of 100-200 MeV. About 10 years later a strongly interacting particle with a mass of ~140 MeV was discovered, the pion. Since that time, nearly all models of the nuclear force have been within the framework of exchanged particles. Although the pion alone is not adequate for description of the nuclear force, it is still believed to be responsible for most of the long range part of the force.

At lower energies, especially below pion production threshold, the most common technique has been to use a potential model to calculate phase shifts and compare these to those obtained by fitting the data. The different aspects of the potential are interpreted in terms of different meson exchanges. Some models, notably the "Paris Potential"¹⁶, have been remarkably successful in describing the data below 400 MeV. However, once pion production becomes an important part of the cross section, the models have difficulty.

High energy data (above a few GeV) has been fit reasonably well using Regge theory analysis. Although this method is not usually applied in the intermediate energy range, this experiment and others¹⁷⁻¹⁸, give some indication that it may be valid in the range of 500 to 1000 MeV. The basic ideas of Regge theory are fairly simple. Since it is desired to interpret the data given in this dissertation in terms of Regge theory, these basic principles will be described.

D. S-Matrix and Regge Theory

Many of the experiments in hadron physics involve scattering one particle off another. In elastic scattering the final particles are the same as the initial, while in inelastic collisions new particles are created. The transition probability from a certain initial state to a given final state is described by a matrix whose elements give the probabilities for each transition. This is usually expressed in the following form

$$P_{fi} = |\langle f | S | i \rangle|^2$$

P_{fi} is the transition probability from initial state i to final state f . The elements of the S matrix can be calculated from models of the fundamental interaction and compared to those determined from experiment. Of course, one hopes eventually to develop a theory in which all possible transitions can be calculated, although no such theory exists today.

The elements of the S-matrix are functions of both the relative linear and angular momentum of the initial particles. In a physical system, both the linear and angular momentum must be real numbers, and the angular momentum is restricted to integral or half-integral values. Despite this fact, treating both of these momenta as complex variables and observing the behaviour of the S-matrix provides information about the physical system. Regge showed in 1959¹⁹ that poles in the complex angular momentum plane could be related to physical states. In a potential model, such as the Coulomb potential, the poles which occurred at real, integral values of the angular momentum (ℓ), corresponded to bound states. As the total energy of the system increases, the position of the pole moves. One then sees a "trajectory", on which bound states occur. For example, in the Coulomb potential, the S matrix element is given by²⁰

$$S(\alpha, k^2) = \Gamma(\alpha + 1 + i\gamma) / \Gamma(\alpha + 1 - i\gamma)$$

where $\gamma = \mu e^2 / \hbar p$ and $p^2 = 2\mu E$, and α is used to represent the complex angular momentum. Since the Γ function has no zeros and simple poles for the argument equal to a real integer less than or equal to zero, the S matrix has only simple poles for

$$\alpha + 1 + i\gamma = 0, -1, -2, -3, \dots$$

For E greater than zero, there are no poles. If the energy is less

than zero, p is pure imaginary and there will be solutions of the above equation, with α being purely real. The energies at which α is also an integer correspond to the energies of bound states. There are an infinite number of energies for each value of α which will give poles. These correspond to different principal quantum numbers. A plot of several Coulomb potential trajectories is shown in Fig. 1-3. In potentials which do not have an infinite number of bound states, the trajectory will move off the real axis as the energy gets closer to zero. A trajectory for an attractive Yukawa potential is shown in Fig. 1-4. If the trajectory is not purely real, but does pass close to an integral value of α , a resonance will be observed.

Physicists working in high energy hadron physics became interested in Regge theory when it was found that baryon resonances could be described as lying on Regge trajectories.²⁰ A plot of the spin against the mass² of known baryons (known as a Chew-Frautschi plot) showed that the baryons could be grouped into families lying on straight lines (Fig. 1-5). The lines are assumed to be Regge trajectories. It was found later that mesons could also be grouped into families lying on Regge trajectories.

Regge theory has one additional feature, it allows description of dynamical properties of hadron scattering. Before discussing this a few things need to be defined.

First, three Lorentz invariant variables are defined for the reaction $1+2 \rightarrow 3+4$ (Fig. 1-6). Each particle has a four-momentum p_i . The variables, called Mandelstam variables, are

Figure 1-3 Regge trajectories for the Coulomb potential, with dots indicating the locations of bound states.

Figure 1-4 Typical Regge trajectory for a Yukawa potential, with α being the complex angular momentum.

Figure 1-5 A Chew-Frautschi plot for baryons, showing the relation between mass and spin. The lines are assumed to be Regge trajectories. Fig. from Perl (Ref. 15).

$$s = (p_1 + p_2)^2$$

$$t = (p_1 + p_3)^2$$

$$u = (p_1 + p_4)^2$$

For elastic scattering of two equal mass particles where particle 2 is initially at rest, s is just equal to $4m^2 + 2Tm$, where T is the kinetic energy of particle 1 and m the common mass. Both t and u are negative for physical values of the p_i . Two other related reactions are also defined by replacing various particles with their anti-particles. These reactions are (along with the original) called the s , t , and u channels and are defined as

$$1 + 2 \rightarrow 3 + 4 \quad s \text{ channel}$$

$$1 + \bar{3} \rightarrow \bar{2} + 4 \quad t \text{ channel}$$

$$1 + \bar{4} \rightarrow 3 + \bar{2} \quad u \text{ channel}$$

The three variables can be conveniently expressed by a diagram with three axes, as shown in Fig. 1-7, called a Mandelstam diagram. The physical regions for each channel are shaded. This diagram is for the elastic scattering of two equal mass particles (mass m). The physical regions will be different if all four particle masses are not equal. The value of s for the t channel is $(p_1 + p_3^-)^2$. The p_i are defined as positive for a particle going into a reaction and negative for one

Figure 1-6 Labelling of particles for two body initial and final states.

Figure 1-7 Relations between Mandelstam variables for elastic scattering of equal mass particles.

leaving. Since an anti-particle entering a reaction is the same as the particle leaving, an anti-particle entering a reaction as a negative value of p_i . Thus, s in the t channel acts like t in the s channel and vice versa. In Regge theory, the dynamics of the s channel can be understood by examining the poles in the t and u channels. For example, consider the s channel reaction $np \rightarrow np$. The t channel is then $n\bar{n} \rightarrow p\bar{p}$ and the u channel $n\bar{p} \rightarrow \bar{n}p$ (see Fig. 1-8). The t channel will have poles whenever $t = m_5^2$, with m_5 representing the mass or a resonance. In the case of $n\bar{n} \rightarrow p\bar{p}$, the first pole will be the π^0 , while for the $n\bar{p} \rightarrow \bar{n}p$ reaction, it will be the π^- . Thus, in the s channel, the exchange of a π^0 is called a t channel exchange, and a π^- exchange is called a u channel exchange. The particles found on the Chew-Frautschi plot are assumed to be the exchanged particles in hadron scattering. In the original Regge proposal only poles (single particle exchanges) were considered important. Later, it became clear that cuts in the complex k plane also had to be considered. A cut results when a "particle" without a definite mass is exchanged. This is usually thought of as two particles being exchanged simultaneously. The presence of cuts makes calculations more complicated, but they seem to be required to explain experiment. These poles and cuts are often represented as in Fig. 1-9. The closer a pole is to the physical region, the stronger the effect. In the case of nucleon-nucleon scattering, the pion pole is very close to the physical region, and is therefore expected to dominate small t and small u scattering.

Figure 1-8 s, t, and u channels for np scattering. by the exchange of particle 5. Arrows at the side of the s channel and top of the t channel indicate the direction of the reaction.

Figure 1-9 Poles and cuts in the t plane for np scattering.

The final result of the Regge theory for pion exchange is that a t channel pion will contribute equally to the two helicity amplitudes M_2 and M_4 and, in the small t region, is proportional to

$$\frac{t}{t-m_\pi^2} (s/s_0)^\alpha$$

where α is equal to $(t-m_\pi^2)$, and s_0 is a constant, usually taken to be 1 GeV^2 . This is very similar to the first Born approximation for a Yukawa potential, with a pseudoscalar particle exchange, which gives the $t/(t-m^2)$ term, but not the (s/s_0) term. Both clearly lead to zero cross section for $t=0$. Neutron-proton scattering shows a peak in the cross section in the charge exchange region. Different models have been proposed to explain this discrepancy of one pion exchange and the observed cross section. Two of these models will be discussed here.

Before continuing, one slightly confusing point should be clarified. In the literature, the reaction $np \rightarrow np$ at 180° is usually referred to as $np \rightarrow pn$ scattering at 0° . The helicity amplitudes for the two reactions transform as follows

$$M_1(\theta) \rightarrow M_1(\pi-\theta) \quad M_2(\theta) \rightarrow M_2(\pi-\theta)$$

$$M_3(\theta) \rightarrow -M_4(\pi-\theta) \quad M_4(\theta) \rightarrow -M_3(\pi-\theta)$$

$$M_5(\theta) \rightarrow -M_5$$

For example, $M_3(180)$ for $np \rightarrow np$ is equal to $-M_4(0)$ for $np \rightarrow pn$. The spin

transfer parameters K_{NN} , K_{LL} , etc., become D_{NN} , D_{LL} , etc., $A \rightarrow -A$, and $u \rightarrow t$. To remain consistent with the models being described, the helicity amplitude convention is used when comparisons are made with these models, although the parameters will still be referred as K_{NN} , etc.

The most common technique for explaining the cross section peak is to assume that absorption of low partial waves in the interaction modifies the pion contribution, such that M_2 is no longer zero for $t=0$ (M_4 must be zero at $t=0$ because of angular momentum conservation). Several prescriptions for doing this have been given. The most popular of these is known as the "poor man's absorption" model (PMA). Some recent calculations using this were done by Gotsman and Maor²¹. The prescription of the PMA model is to leave alone all amplitudes required to be zero by angular momentum conservation, but modify those that have no such requirement by replacing the t in the numerator with m_π^2 . Gotsman and Maor include additional modifications plus higher mass exchanges (such as the ρ and A_2). This technique gives reasonably good fits to the differential cross section data over a large energy range (6-260 GeV) for n - p CEX scattering, and also works reasonably well for other reactions, such as $\pi^+p \rightarrow \rho^0 \Delta^{++}$ and $\pi^-p \rightarrow \rho^0 n$. This model is used because it does give good fits to the data, although even its proponents¹⁶ acknowledge the uncertainty of its theoretical soundness.

Another model, proposed by Chia²², suggests the structure in

the small t region can be explained as a pion-pomeron cut. Chia evaluates the diagram

assuming the σ to be scalar-isoscalar meson. The pomeron is a rather mysterious particle which was originally introduced to explain diffractive scattering. It has the quantum numbers of the vacuum ($S, B, I, Q=0$) and its properties are deduced from the high energy behaviour of total and elastic diffractive cross sections. The true nature of the pomeron is still unknown. Despite this, calculations can be made using models of the pomeron which agree with the cross section data. Chia has done this and found the cut to contribute to the correct amplitudes to explain the n - p CEX cross sections, and has fit data between 2 and 20 GeV. Chia finds the cut contributions to be

$$h(i) \cong \gamma(\tau) \exp(-i\pi(\phi(\tau)-\lambda)/2) (s/s_0)^{\phi(\tau)/\ln(s/s_0)}$$

where the $h(i)$ are helicity amplitudes, $\gamma(i)$ residue functions, $\phi(\tau)$ the trajectory function, and λ a phase factor. This equation is valid for small values of t and large values of s . Chia has made some assumptions to simplify the calculations. The model can be followed

as is to calculate lower energy amplitudes, as will be discussed in Chap. 5. Chia adjusted the trajectory function in order to fit 10 GeV/c data, so the validity at lower energies is uncertain. Chia's model also gives reasonably good fits to the $\pi^+p \rightarrow \rho^0\Delta^{++}$ and $\pi^-p \rightarrow \rho^0n$ reactions. Despite the reasonably good fits to the data, there is still some question about the model, since the nature of both the pomeron and the σ are uncertain.

Both of these models give qualitatively identical results for the amplitude structure in small t n - p scattering. Both models predict that the helicity amplitude M_2 accounts for most of the $t=0$ cross section, then decreases rapidly while M_4 increases to give the drop off of the cross section with subsequent leveling off. The predictions of Chia are shown in Chap. 5, along with the data from the experiment described in this work.

E. Quasi-free Scattering

Since the most precise spin transfer data in the n - p CEX region are the quasi-free measurements of Riley²³, it is worth considering how they may be related to the free parameters. This relation has been considered before by several authors²⁴⁻²⁶. Two aspects of quasi-elastic scattering may cause it to be different from free scattering, the Pauli principle restriction of the final states of the remaining protons and modifications due to double scattering and the effect of the deuteron wave function.

Cromer²⁴ describes a method for determining the effect of the deuteron wave function. The technique is simply to calculate form

factors using the deuteron wave function and assuming only the final state interaction in the S state is important. The integral

$$F(q,k) = \int [\bar{\varphi}_k]^* \varphi_0(r) \exp(i\vec{q} \cdot \vec{r}/2) d\vec{r}$$

is evaluated by replacing $\bar{\varphi}_k(r)$ with a plane wave, except for the S wave contribution. "q" is the momentum transfer, φ_0 is the deuteron wave function, and k is the relative momentum of the remaining protons. The final integral then becomes

$$F_S = (2\pi)^{-1/2} \int \frac{\sin(kr+\delta)}{kr} \varphi_0 \frac{\sin(qr/2)}{qr/2} dr$$

$$F_O = (2\pi)^{-1/2} \int \frac{\sin(kr)}{kr} \varphi_0 \frac{\sin(qr/2)}{qr/2} dr$$

$$F_B = (2\pi)^{-3/2} \int \exp(-k \cdot r) \varphi_0 \exp(i\vec{q} \cdot \vec{r}/2) dr$$

with

$$F(q,k) = F_S + F_O + F_B$$

$$\varphi_0 = -.26(\exp(-\alpha r - \beta r)/r)$$

and δ is calculated from the effective range formula

$$k \cot \delta = -1/a + r_0 k^2/2, \quad a = -23.7 \text{ F and } r_0 = 2.65 \text{ F}$$

These form factors are integrated over all values of k, then used to calculate relative contributions of charge exchange singlet (final protons in 1S_0 state) and free scattering. Although Cromer

applied this to the case in which a proton leaves with a high momentum, Reay²⁵ shows the same technique can be applied to the case in which a neutron leaves the interaction with high momentum. The measured value for the quasi-elastic case is shown to be

$$K_{ij} d\sigma/d\Omega = a I^{np} K_{ij} + 2b I^{ces} K_{ij}^{ces}$$

where ces stands for charge exchange singlet and np for the free case. I is the cross section and K_{ij} is the spin transfer parameter under consideration. Using Cromer's method, a and b can be calculated. At 800 MeV this method gives a to be negligible compared to b . Double scattering is also felt to be negligible for high energy 0° scattering. The modification due to the Pauli principle can be calculated and has been done so by Reay²⁵ and Phillips²⁶, who give the combinations of free amplitudes needed for the determination of I^{ces} and K_{ij}^{ces} . Their results are shown in Table 1-2. A comparison of the free and quasi-elastic results using this method is given in Chap. 5.

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CHAPTER TWO-THE EXPERIMENT

This chapter is divided into two main sections. The first section deals with the measurement of the n-p spin transfer parameters. The second section concerns the calibration of the recoil polarimeter. Details common to both measurements will be given in the spin transfer section.

The measurements were performed in three sections. The spin transfer part was performed during January, 1980, the 800 MeV calibration during March, 1980, and the lower energy calibrations between July and October of 1980. The spin transfer section was LAMPF experiment 403. A number of people assisted in various phases of these measurements. Those primarily responsible were as follows:

B. E. Bonner	LASL
M. W. McNaughton	LASL
C. L. Hollas	Univ. of Texas at Austin
R. D. Ransome	Univ. of Texas at Austin
P. J. Riley	Univ. of Texas at Austin

Section I

A. Introduction and Overview

The spin transfer parameters K_{NN} , K_{SS} , K_{SL} , K_{LL} , and K_{LS} are traditionally called "triple scattering parameters", because (not surprisingly) three scatters are involved in making the measurement. The first scatter provides the polarized beam, the second is the interaction of interest, and the third is used to measure the polarization of one of the outgoing particles. The name was applied before the use of polarized targets and beams, which can reduce the number of scatters required. This experiment still requires three scatters.

The first scatter is a polarized proton beam on an unpolarized deuterium target. This produces neutrons with a broad range of momenta. Those produced via the quasi-elastic reaction $pd \rightarrow np$ are the only ones of interest in this experiment. For a longitudinally polarized proton beam, a polarization transfer to the neutrons of about .64 is achieved. A 3.66 meter steel collimator is used to produce a sharp beam of neutrons at zero degrees relative to the incident proton beam. A combination of two magnets is used to orient the neutron polarization to the desired direction. These neutrons then impinge on a liquid hydrogen target. Recoil protons are momentum analyzed by a magnetic spectrometer, allowing the rejection of those resulting from inelastic interactions in the hydrogen target and/or

from neutrons produced by non quasi-elastic reactions in the deuterium (for example, the reaction $pd \rightarrow npp\pi^0$). The third scatter is of the recoil protons on carbon, to determine their polarization. This polarization relative to the neutron polarization is the quantity of interest.

The following sections will give a more detailed description of the experiment.

B. The Accelerator and Proton Beam

The proton beam is produced by the Los Alamos Meson Physics Facility (LAMPF) 800 MeV linear accelerator. This accelerator is capable of accelerating two beams simultaneously, one H^+ and the other polarized or unpolarized H^- . The experiments reported in this work (both the spin transfer and calibrations) use the polarized H^- beam. The polarized beam is produced by a Lamb-shift ion source. Initial acceleration from the source is by a 750 keV Cockcroft-Walton injector. This beam is then accelerated to 100 MeV by a 201.25 MHz Alvarez-type standing wave accelerator. The final energy of 800 MeV is achieved by an 805 MHz side-coupled cavity linear accelerator. The beam from this type of accelerator has a time structure, since particles can only be accelerated during one phase of the RF. Since the initial frequency is 201.25 MHz, there is a pulse (called a micro-pulse) every 5 nsec. The micro-pulse is very sharp, with a FWHM of about .25 nsec. Because of power limitations and problems with klystron heating, particles are accelerated only for a small fraction of the time. The usual mode at LAMPF is to accelerate 120 500- μ sec

pulses per second (each called a macro-pulse). This means the accelerator is only running about 6% of the time (the duty-factor).

After acceleration, the H^- beam is split for use in three different experimental areas. The spin transfer experiment and lower energy calibrations were performed in area BR of the Nucleon Physics Laboratory (NPL). The 800 MeV calibration was performed in EPB. Fig. 2-1 shows these two areas, along with some of the beam line instrumentation and beam control magnets.

The proton beam current was typically 10 nano-amps with a polarization of 70-75%. The beam diameter is about one centimeter.

Orientation of the polarization depends on the needs of the various experimental areas. The direction of polarization before acceleration can be set to any desired value to produce the desired orientation in any one of the three beam lines. There is not, however, the freedom to give each area a desired polarization orientation independent of the others merely by adjusting the orientation at the source. For example, if the spin orientation is "normal" (transverse to the beam momentum and vertical) all of the areas will have normal beam. This is, in fact, the usual mode of operation. This experiment requires a longitudinally polarized beam at the liquid deuterium target. Both of the other lines required a normal polarization. Some method is needed, therefore, to change the polarization after the line B-EPB split. This is accomplished by use of a solenoid and two bending magnets. The field of the super-conducting solenoid (LB-SO-01) is parallel to the beam momentum,

thus precessing the spin from transverse vertical to transverse horizontal without changing the proton's direction. Precession from transverse to longitudinal is accomplished by two bending magnets. Since both the spin and momentum are now in a plane perpendicular to the magnetic fields, both change in direction. For an 800 MeV proton they change in the ratio $(\theta_p - \theta_b)/\theta_b = 3.32$. The total bend by LB-BM-04 and LB-BM-05 is 32° (16° each), giving a net spin precession of 106° , 16° further than desired. This is not a serious problem, since $\cos(16^\circ) = .96$, thus producing a neutron beam with nearly the full polarization produced by an exactly longitudinal beam (see sec. C).

To facilitate eliminating systematic errors in the experiments using polarized beam, the polarization direction of the beam is flipped at a fixed interval. That is, the magnitude of the polarization is unchanged but the direction is reversed 180° . Averaging over the two spin states then gives a net unpolarized beam. During the spin transfer experiment the flip time was three minutes, with a ~15 sec pause between states. During the lower energy calibrations the flip time was one minute with about 10 seconds between states.

After passing through the deuterium target, the main proton beam is bent away from the zero degree line into a beam dump.

C. Neutron Beam

As described earlier, the neutron beam is produced by striking a deuterium target with a proton beam. A number of reactions are possible. Two classes can be defined: quasi-elastic ($pd \rightarrow npp$) and non-quasi-elastic (primarily single pion production). The zero degree neutron spectrum from the pd reaction for 800 MeV protons has been studied in detail by Bjork¹. Fig. 2-2 shows this spectrum, with the quasi-elastic peak, near 1450 MeV/c (795 MeV), being quite distinct. Bjork found the intrinsic width of this peak to be about 10 MeV. The use of a 25 cm LD_2 target increases this width to about 13 MeV. Since the energy resolution of the spectrometer (sec. G) is on the order of 10 MeV and there is no reason to believe the parameters being measured will vary rapidly over this small energy range, the spread is acceptable. Bjork found the centroid of the peak to be about 6-7 MeV below the proton energy. The mean energy loss of the proton beam in the LD_2 target is 3-4 MeV, so that the centroid of the neutron quasi-elastic peak is at about 790 MeV.

Previous measurements by Riley² determined the polarization of the zero degree neutron beam as a function of neutron energy for the pd reaction with 800 MeV protons. Figs. 2-3,4 show the transfer of polarization as a function of neutron energy. Maximum transfer occurs for a longitudinally polarized proton beam. Riley found a transfer in the quasi-elastic peak of $-.64 \pm .03$ for the longitudinal case and $-.15 \pm .03$ for the transverse case. As mentioned in the previous

Figure 2-2 Spectrum of neutrons incident on LH_2 target.

section, the proton polarization is not longitudinal at the target, but 16° off. This then produces a quasi-free peak polarization of:

$$P_n = P_B (K_{LL}^2 \cos(16^\circ)^2 + K_{NN}^2 \sin(16^\circ)^2)^{.5} = .617 P_B$$

For the typical beam polarization (P_B) of 70%, the neutron polarization is about 43%. The polarization in the lower energies is somewhat lower, and no attempt was made to use these neutrons in these experiments.

The neutron beam is defined by a collimator consisting of a tapered hole through 3.66 m of steel. The hole is 2.54 cm in diameter nearest the deuterium target and 5.08 cm in diameter at the exit, giving a beam diameter of about 10 cm at the LH_2 target. The tapered hole provides a sharper beam definition than a hole of constant diameter.

After the beam is collimated, the neutron spin must be oriented to the desired direction: transverse vertical (N), transverse horizontal (S), or longitudinal (L). This is easily accomplished by use of two dipole magnets, one with a vertical field, the other with a horizontal field. Since the neutron is electrically neutral, the spin may be precessed without affecting the momentum. Due to the passage of the neutrons through the sweep magnet field (LB-BM-06 in Fig. 2-1), the spin direction is already precessed $\sim 50^\circ$ at the collimator exit. By adjusting the field strength and direction of M1 (Fig. 2-5), the polarization may be oriented either sideways or

Figure 2-3 Quasi-free spin transfer K_{NN} .

Figure 2-4 Quasi-free spin transfer K_{LL} .

Figure 2-5 Area B and experimental setup.

longitudinal. M2 may be either turned on to produce a transverse vertical polarization or turned off to leave the polarization sideways or longitudinal. The correct field strengths for both magnets were determined by use of QPAN (sec. E). These two magnets have the added benefit of sweeping out charged particles produced in the collimator or elsewhere along the beam path. The spin orientation of protons and neutrons along the beam line for the original polarization "up" is shown in Fig. 2-6.

D. Targets

Two targets are used: a liquid deuterium target, built in the early 1970s specifically for use as a neutron producer ("LD₂" LB-TW-01 in Fig. 2-1); and a liquid hydrogen target, built for use in this and other neutron experiments ("LH₂" in Fig. 2-5). The deuterium target is 25.4 cm long with .0762 mm stainless steel windows. The refrigeration system used is fully described by Bjork³.

The hydrogen target is a 12.5 cm diameter cylinder with hemispherical end-caps. The total length is 30 cm. This "bullet" shape is used because of its great strength against internal pressure. The vessel is made of .254 mm mylar wrapped in 10 layers of super-insulation (.063 mm aluminized mylar). Liquid hydrogen is kept at a pressure of 15 psi within the vessel. An outer cylinder with .254 mm mylar walls provides the outer vacuum jacket (Fig. 2-7). Hydrogen is liquified and kept cold by a CTI 10 watt compressor-refrigerator system, using helium as a coolant. The target was built at LASL. Systems similiar to it have been used in a number

Figure 2-6 Polarization orientation for initial spin "up"

of experiments at LAMPF. Fig. 2-8 shows the plumbing layout for the refrigeration system.

The target has marks on each end indicating the center. These were aligned along the beam line to within .75 mm. Since the target is larger than the beam by about 2.5 cm, alignment is not crucial.

E. QPAN (Quick Polarization Analyzer for Neutrons)

As mentioned in Sec. C, the fields of magnets M1 and M2 must be properly adjusted to provide the desired orientation of neutron polarization. The approximate magnet currents needed can be calculated, but the fields and the path of the neutrons through the fields, particularly through the sweep magnet (LB-BM-06), are not known well enough to allow a confident setting of the fields.

The solution to the problem is a neutron polarimeter. If one can be designed which will be sensitive primarily to high energy neutrons and used in such a way that only a null value need be determined, an accurate setting of the precession magnets may be determined without needing an absolute calibration. Such a system was developed and reported by Hollas⁴. A piece of CH_2 acts as an analyzer and two scintillation telescopes count recoil charged particles. The telescopes are mounted at 30° relative to the beam, the angle at which the free n-p analyzing power peaks. A trapezoidal shaped piece of brass is mounted between two scintillators to absorb low energy particles (Fig. 2-9), but allow transmission of the elastically scattered recoil protons. In addition, the accelerator RF signal is used to discriminate against low energy particles by determining the

Figure 2-7 Top view of LH₂ target.

Figure 2-8 Liquid hydrogen target plumbing layout. Some valves and gauges have been omitted for clarity.

flight time between the LD_2 target and QPAN within a modulus of 5 nsec, and rejecting those which do not fall within set limits. The circuit for this is shown in Fig. 2-10.

QPAN may be used with the telescopes in a horizontal or vertical plane. This allows both vertical and horizontal polarizations to be measured. Depending on the direction of polarization desired, the magnetic field is adjusted to produce either a maximum or minimum asymmetry in QPAN. There is never any need to know the absolute value of the analyzing power. Figs. 2-11 and 2-12 show sample asymmetries. The device was used in previous experiments, where the proper settings for M1 and M2 to give longitudinal and vertical polarization were determined. With this system the polarization could be oriented within about 4° of the desired value.

F. Beam Line Polarimeter and Monitors

Since all measurements described herein require knowledge of the proton beam polarization and of the relative amount of beam between the two polarization states, some method must be used to measure beam polarization and intensity.

Proton beam polarization and intensity are measured by the same system. The polarimeter consists of a .0254 mm CH_2 analyzer and four scintillator telescopes⁵. Each telescope consists of two photo-detectors: one mounted at 17° relative to the beam, the other mounted at 68° . These are the conjugate angles for pp elastic scattering near 800 MeV at the maximum of the pp elastic analyzing power. A coincidence of the two detectors defines a single telescope

Figure 2-9 Schematic of QPAN.

Figure 2-10 Logic for QPAN with RF discrimination.

Figure 2-11 Asymmetry in QPAN as a function of magnet current.

Figure 2-12 Asymmetry in QPAN as a function of magnet current.

event. The telescopes may also register non pp elastic scattering events, such as pC quasi-free scattering, inelastic pp scattering or accidental (uncorrelated) coincidences. The first two are a constant fraction of the total events and only change the effective analyzing power of the system (such that is slightly different than the elastic pp analyzing power). Since the polarimeters are calibrated with a beam of known polarization, these events are not a problem. Accidental coincidences can be a problem since their intensity increases as the beam intensity squared, while the number of true coincidences increase linearly with the beam intensity. The level of these accidental events can be determined by adding a delay (40 ns) to one arm of a telescope. This accidental rate is subtracted from the measured rate to find the true rate of coincidences. This value is used in calculating the beam polarization.

Two telescopes are positioned in a horizontal plane for measurement of the left-right asymmetry, and two in a vertical plane for measurement of the up-down asymmetry. The left-right (or up-down) asymmetry is directly related to the polarization via the relation $P = A\epsilon$. A is the analyzing power and ϵ is defined by the relation $(L-R)/(L+R)$ where $L = \sqrt{L_N R_R}$ and $R = \sqrt{L_R R_N}$, the subscripts N and R indicating the two beam orientations. These definitions for L, R, and ϵ eliminate instrumental asymmetries to high order (see, for example, Ohlsen⁶). Calibration of the polarimeter was done by LAMPF personnel using the quench ratio method⁵ (see also Sec. II-C).

In this experiment, the polarimeter was downstream of the solenoid and the first 16° bending dipole. This means that the transverse polarization component is in the horizontal plane, 53° away from perpendicular. The asymmetry measured is thus in the up-down direction and 60% of the full asymmetry ($\sin(53^\circ)=.60$).

In addition to measuring the polarization, the polarimeter can be used as an intensity monitor. Since the polarization is in the horizontal plane, the number of events counted by the left and right telescopes is directly related to the amount of beam. If the two spin states differ only in sign, there is negligible beam movement between states, and each telescope has the same efficiency the up and down telescopes will be accurate as intensity monitors, since the sum (up plus down) will remain constant. In practice, the sum of all four telescopes is used to normalize the amount of beam in each spin state.

Although the number of neutrons produced is directly related to the number of protons incident on the deuterium target, it is desirable to monitor directly the number of neutrons entering the experimental area. This is accomplished by a system similar to QPAN. Like QPAN, a CH_2 analyzer with two scintillator telescopes is used. Each telescope consists of two scintillation counters in coincidence with a piece of brass between them to range out low energy particles. In addition, there is an in-beam telescope, consisting of a scintillation counter, the CH_2 , and two more counters. The first counter vetos charged particles, and the last two are in coincidence. The entire monitor system is located directly at the exit of the

collimator. It differs from QPAN primarily in the thickness of CH_2 used (.635 cm vs. 5.08 cm) and in the lack of RF discrimination against low energy particles.

These two systems (proton polarimeter and neutron monitor) provide three methods of normalizing the two spin states: sum of polarimeter counters, left plus right counters of neutron monitor, and the in-beam counter. The neutron monitors agree with each other within .1% and the proton monitor agrees with the neutron monitors within 1%.

G. Spectrometer

The spectrometer (Fig. 2-5) is basically the same as has been used for many previous experiments (Bjork³, Newsom⁷). It consists of two wire chambers (W1 and W2), a magnet (M3), and the first three chambers of the polarimeter (see Sec. H). It differs from previous experiments in the use of the drift chambers of the recoil polarimeter downstream of M3, rather than multi-wire proportional chambers (MWPC). The electronics for the front MWPCs are described in Ref. 8. The front chambers (W1,W2) each consist of one "x" and one "y" plane. Both chambers are 25.6 cm wide by 19.2 cm tall with a wire spacing of 2 mm. The magnet (M3) is an 18D36, with a maximum field strength of 18 kilo-gauss and length of 36 in (91.4 cm), hence the name. The maximum bend angle for an 800 MeV proton is about 23° .

As mentioned earlier, the back of the spectrometer is the front of the recoil polarimeter. Different bend angles can be examined by moving the polarimeter relative to M3. Two different

positions were used in this experiment: a 21° setting for a magnet current of 600 amps and a 11° setting for a magnet current of 200 amps. These angles are the nominal bend angles for an 800 MeV proton at the stated magnet currents. The exact angle is not critical.

H. The Polarimeter

The critical piece of apparatus for this experiment is the recoil polarimeter (called the recoil polarimeter to distinguish it from the beam line polarimeter). This is the first neutron experiment to use the polarimeter.

Fig. 2-13 shows a schematic side view of the polarimeter, along with critical dimensions. Six drift chambers are used, three in front of a carbon analyzer, three in back. Two scintillators—one front, one back—provide the event trigger and timing for the chambers.

Fig. 2-14 shows the overall view of the polarimeter. The frame is composed of steel angle with aluminum plates on the ends. The frame is rigid enough to allow moving the entire assembly by crane. Fig. 2-15 shows a back view of the polarimeter, along with a close-up of the side rails. Both scintillators and chambers are mounted on movable frames. Four semi-circular bearings, one in each corner, slide over the bars shown in Fig. 2-14. Small rings with set screws are slid on before and after each frame on diagonal corners. These can be tightened to prevent movement of the chamber frames. Chambers themselves are removable even after the frame has been fixed. One side of the frame opens to allow the chamber to be slid out quite

easily. While the polarimeter is being used, this side is tightened to prevent any chamber movement within the frame.

The carbon analyzer consists of a 25.4 cm thick, 60 cm square block of commercial grade ATJ graphite, with a measured density of 1.75 g/cm^3 . The 25.4 cm thickness is obtained by bolting together three 6.35 cm thick plates and two 3.18 cm thick plates of carbon. Using several thin plates rather than a single piece of carbon allows for different thicknesses of carbon to be used (as is required for lower energy protons) and provides for easier handling of the carbon outside of the polarimeter. The carbon is mounted in a frame similar to the chamber frames and can be removed without disturbing the chambers.

The scintillators (SF and SB) each consist of two .476 cm x 30.5 cm x 61.0 cm pieces, individually wrapped. Front and back scintillators are identical. Each plate has a photo-detector on each end, making a total of eight photo-tubes. Fig. 2-15 indicates the labeling of the tubes. Anode signals are used to form the main trigger (Sec. I-1).

Six identical drift chambers are used to trace the protons through the system. The nominal active area is 60 cm x 60 cm. Each chamber consists of two signal planes, three ground planes, and two cover planes. The sequence is cover-ground-signal-ground-signal-ground-cover plane.

Ground planes consist of .0127 mm aluminum foil. Signal planes consist of alternating cathode and anode wires (Fig. 2-16).

The wires are evenly spaced with a .4064 cm separation. Anode wires are .02 mm gold-plated tungsten, cathode wires are .076 mm gold plated aluminum. Plane spacing is 4.76 mm, so that the "x" plane is 9.52 mm in front of the "y" plane. A positive 2250 volts is applied to the anode wires, while the cathode wires are at ground.

A standard "magic" gas mixture of 62% argon, 38% iso-butane, .1% iso-propyl alcohol, and .03% Freon is used. The gas pressure is kept slightly above atmospheric pressure by submerging the end of the exit line in about 3 mm of low vapor pressure oil. The flow rate is such that the gas in a chamber is replaced every few hours. The gas handling system is shown in Fig. 2-17.

Each anode wire is attached to a 200 ns long delay line, with a nominal 2.8 ns per wire separation. Signals from the delay line ends are fed to a discriminator located at the polarimeter. A discrimination level of about 2.7 mvolt is used to obtain precise signal timing. These discriminated signals are delayed about 200 ns, then used to stop TDCs (see Sec. I-I).

Alternating cathode wires are attached to two bus lines (Fig. 2-16). These are referred to as "odd" and "even" lines. These two lines are fed into an electronic unit which adds and subtracts the pulses. This is also located at the polarimeter. These pulses are also delayed about 200 ns. This device ("odd-even" box) allows resolution of the left-right ambiguity present in drift chambers (see Ch. 3 and Walenta⁹ and Breskin¹⁰). The details of the odd-even box are given in Ref. 11. Signals from the odd plus even (O+E) output

DIMENSIONS IN cm

Figure 2-13 Polarimeter side view.

Figure 2-14 Top view of polarimeter.

Figure 2-15 Back view of polarimeter, showing scintillator labeling.

0 10 20 cm

Figure 2-16 Drift chamber schematic.

Figure 2-17 Gas handling system for wire chambers.

are clipped by a 3.22 m line attached with a tee at the output. This reduces the dead time of the system substantially by reducing the pulse width from about a micro-second to about 200 nsec.

The odd-even box has an adjustable gain and DC offset for the odd minus even (O-E) output. These were adjusted to give a -.3 volt DC offset and maximum gain. This caused most signals to saturate at either zero volts or -1.5 volts. Since the only purpose is to distinguish positive-going signals from negative-going signals, this gave the clearest results. It was thought early on that the pulse heights might provide a useful correction to the anode position for time-walk effects. No strong correlation was found, however, so no attempt was made to keep pulses from saturating.

Pulses from the O-E output are fed into a charge sensitive analog to digital converter (ADC). This integrates total charge, with negative pulses being added. Integration time is 100 nsec. Pulses from the O+E output are fed into a time to digital converter (TDC) and used for drift time determination.

I. Electronics

The electronic logic is shown in Figs. 2-18,23. The logic can be divided into four main sections: spin logic, event trigger, fast clear, and data. Each of these will be outlined.

The spin logic (Fig. 2-22) has two purposes: trigger a scaler read at the time of the spin change and to inhibit data acquisition during spin changes or at times of faulty spin signals. Two spin signals are supplied from the ion-source control room. These are, by

convention, called "normal" and "reverse," and were 10 volt signals, allowing them to be used in TTL systems. Under normal circumstances one signal will be 10 volts and the other zero volts. When the spin is being flipped both drop to zero volts. Under no circumstances should both be 10 volts. Whenever both signals are up or both down, data taking is inhibited. In addition, when the signals go from a one-up-one-down state to both down, a single pulse is generated which triggers a read of the scalers. The circuit has a one second delay built in for two reasons. First, one spin signal will occasionally drop then immediately return to its proper state. A delay prevents a scaler read trigger on those occasions. Second, there is quite a bit of noise in the circuit when the signal drops. A delay lets the noise die down and prevents multiple triggering.

The "master" trigger (Fig. 2-18) is a coincidence of S1, SF, SB, 3/4 "x" and 3/4 "y" planes of W1 and W2, all in anti-coincidence with a "master inhibit" signal. SF and SB (Fig. 2-19) are "or"s of the top and bottom paddles. The coincidence helps insure that the system will not be triggered by cosmic rays, noise in the scintillators, or low energy charged particles which do not pass through the entire system. The master inhibit (Fig. 2-20) is an "or" of the "gross inhibit" (Fig. 2-21), the LAMPF trigger module (LTM) busy, and master and event trigger busies. The master trigger busy is triggered by a master trigger and inhibits further master triggers long enough for a decision to be made about accepting the event. If the event is accepted, the event trigger busy inhibits further master

triggers long enough for the computer read to begin. Once the computer read begins, the LTM sends out an inhibit pulse until all modules are read, a process which takes about 400 μ sec. The gross inhibit prevents master triggers except during a macro-pulse (signaled by the "beam gate") and when the spin signal is in an allowed state.

The "event" trigger (lower part of Fig. 2-23) differs from the master trigger only if the fast-clear (see next paragraph) is being used. If the fast-clear system is being used, the coincidence of the master trigger and no fast-clear forms the event trigger. The dotted line in Fig. 2-23 shows the first condition (fast-clear not in use). The event trigger signal is fed into the LTM to initiate reading of an event (see Sec. J).

It was realized early on that many events would not scatter at a large angle in the carbon. Since the analyzing power of carbon must be zero at zero degrees, and small for small angle scatters, it is desirable to use a hardware reject system to eliminate small scatters. At high event rates this would allow more good events to be recorded. At low event rates it does not increase the number of good events, but does increase the percentage of good events written to magnetic tape, thus allowing a reduction in the amount of tape needed for the experiment. The system used to clear small angle scatters is shown in Fig. 2-23. Signals from the delay line ends of a chamber are used to start and stop a time to amplitude converter (TAC). This is done for the first, third, fourth, and sixth chambers. If the delay lines are linear, the TAC output pulse height will be linearly related to the

wire number. Relative slopes of the incoming and outgoing rays can then be computed by using a pulse summer. This sum, $(X_6 - X_4) - (X_3 - X_1)$, will have a series of peaks, corresponding to a slope differential of no wires, one wire, two wires, and so on. This will work well only if the delay lines are linear, TACs have the same gain, and the delay per wire is the same in all lines. If these conditions are not satisfied, the peak positions will change as a function of position in the chambers. To help minimize this problem, the gain of each TAC is adjustable. In fact, adjusting the gain of only one TAC is sufficient to cancel all linear differences between TACs and delay lines.

Once the sum is formed, the pulse is fed into a linear gate. The linear gate allows only the center portion of the pulse to be output, since the ends of the summed pulse have large spikes where the pulses do not quite cancel. This output pulse is then fed into a single-channel analyzer (SCA). This outputs a pulse only if the input pulse is within some adjustable range. For this experiment, the range is adjusted to allow events with a zero or one wire differential to give an output. Identical setups are used for both the "x" and "y" planes. A coincidence of the SCA outputs is then formed, corresponding to an event with a small angle scatter in both the "x" plane and "y" plane. This is the signal to clear the event. This entire procedure takes about 8 μ sec, allowing the event to be cleared and another one taken in the same macro-pulse.

In addition to this clear, a coincidence of the valid stop output of the TACs is formed. This eliminates any event in which one

delay line end did not fire. This signal is put in coincidence with the previously mentioned fast-clear signal to provide the final fast-clear signal.

Although discrete spacing of the anode wires prevents the system from being 100% efficient, the fast clear does provide substantial enhancement of good events on tape. A further discussion of this enhancement can be found in Chap. 4.

Once an event is triggered in the hardware, it is read by the computer (a PDP 11/60) and written to tape via the "Q" system (see Sec J).

Four CAMAC devices are read in for each polarimeter plane: three TDCs and one ADC. The start for each TDC is the event trigger, which also provides the gate for the ADC. TDC stops are provided by the delay line end pulses and the O+E pulse. Two coincidence buffers are also read. These contain a normal-reverse tag, the polarimeter scintillators which fired, and a fast-clear tag. The fast clear tag is used when the fast-clear is not being used, allowing the characteristics of events which would have been cleared to be examined. The wire information from the MWPCs is also read in, in a manner described in Ref. 8. Finally, the S1 pulse height, the time of flight between S1 and SB, and the time of the event relative to the RF signal are read. A total of about 80 words (varying with the number of words for MWPCs) are read for each data event. As mentioned earlier, this takes about 400 μ sec, effectively limiting the maximum event rate to the number of macro-pulses per second, since each

Figure 2-18 Master trigger logic.

Figure 2-19 SF and SB logic.

Figure 2-20 Master Inhibit logic.

Figure 2-21 Gross Inhibit logic.

Figure 2-22 Spin enable and scaler read logic.

Figure 2-23 Fast clear and event trigger logic.

macro-pulse is only about 500 μ sec. Actual beam intensities for the neutron beam are such that only 20-30 events per second are recorded.

Finally, scalers are read in at each spin flip. A total of 100 scalers are read. These contain singles counts for each delay line end, the MWPC signals, the O+E signals, all scintillators, the beam line polarimeter telescopes, the neutron monitor, and three real times. Each time is hardware gated slightly differently, such that one counts during all data taking, one during beam normal times, and the third during beam reverse time. This allows scalers to be split into normal and reverse sets without duplicating all modules and hardware gating them.

J. "Q" System and Data Acquisition

In order to make writing data acquisition programs easier for the experimenter, the LAMPF computer support group (MP-1) has written a data acquisition system called "Q". This system allows experimenters to write programs in Fortran and a very simple "Q" language called QAL, rather than having to write in assembly language code. It also has a histogramming package available. The main Q system has been modified by MP-10 (the high resolution spectrometer group) to incorporate several valuable features not present in the original Q system. This experiment was done using the MP-10 version of Q. Details of Q can be found in Ref. 12. Only experiment dependent details will be described here.

One of the greatest virtues of Q is the ease with which it allows the transfer of data from CAMAC to magnetic tape. The basic

procedure is as follows. First, a QAL program is written. This program contains a list of the devices which are to be used, including their location in CAMAC and a short identifier (for example, a scaler located in crate 1, module 5, address 3 might be called S153). After all devices have been specified, the "events" desired are specified. An "event" is a listing of devices to be read whenever a hardware or software trigger for that event is received. In addition, a listing of all Fortran subroutines which are to be called is given. This allows events be partially analyzed during the data taking.

Once the QAL program is written, it is compiled, with two machine language codes being generated. One code contains the Fortran subroutines to be called, the other contains the MBD (micro-programmable branch driver) code. The MBD is a small computer which handles the transfer of data from CAMAC to the PDP 11/60. The first code is then compiled with the appropriate Fortran code desired for on-line analysis. Once this procedure is finished, the experimenter is ready to begin data acquisition.

The events are signaled to the MBD via the LAMPF Trigger Module (LTM). This is a module with a series of inputs numbered 4 to 11. Whenever a NIM signal is received at the LTM, the event of the same number as the input is triggered. This experiment uses three events: 6, 7, and 4. Event 6 is the data event, Event 7 is the scaler event, and Event 4 an MBD dump. Event 4 is simply a pulse at the end of each macro-pulse which requires the MBD to dump whatever data it has stored to the PDP 11.

Whenever an event is triggered, the data is read then written to tape. The data record contains the run number, event type, and number of words in the event. Each physical record also contains the time. A physical record is about 800 words long (roughly 8 events).

There are three modes of running with regard to on-line analysis: "must", "may", and "no" process. Must process requires that all events be processed, i.e., analyzed by the on-line analyzer. This mode is not normally used because data taking is inhibited while the event is being processed, thus reducing the amount of data taken. May and no process do not impede data taking. In may process mode events are only analyzed when the computer is free. No process, of course, means the data is only written to tape and not analyzed. The normal situation is to run Event 6 as may process and Event 7 as must process. Since there is only one Event 7 every three minutes, data taking is not hindered, and at the end of each run a complete set of scalars can be output, a very useful diagnostic tool. Beam polarizations can also be computed at the end of each run.

The data analysis will be described in Chap. 3.

Section II

A. Introduction

This section deals with the calibration of the polarimeter. As mentioned in the previous section, the purpose of the recoil polarimeter is to determine the polarization of recoil protons. All that can actually be measured in the polarimeter is an azimuthal asymmetry in the scattering of particles from the carbon. This asymmetry is related to the polarization via the relation $\epsilon = AP$, where P is the polarization, A is the analyzing power and ϵ the asymmetry. The analyzing power is a function of both energy and scattering angle, and must be empirically determined by using a proton beam of known polarization. In this experiment, the polarimeter calibration (determination of the analyzing power) was done by placing the polarimeter directly in the proton beam at LAMPF. Calibrations were done for energies between 550 and 800 MeV. Slightly different techniques were used between lower energy calibrations and the 800 MeV calibration. Each of these will now be described.

B. 800 MeV Calibration

Fig. 2-1 shows the setup for this experiment. The polarimeter is located in EPB, directly in the beam line. The super-conducting solenoid (LB-SO-01) was moved from line B to EPB line. A beam line polarimeter (EP-PO-01) is located just downstream of the recoil polarimeter. This beam line polarimeter is identical

the one described in Sec. I-I. Signals from both polarimeters (EP-PO-01 and LB-PO-01) are recorded.

Under normal circumstances, beam intensities of a pico-amp to a few nano-amps are used in EPB. This corresponds to 10^6 - 10^{10} protons per second, far higher rates than can be run directly through the recoil polarimeter. It was necessary, therefore, to use a much reduced beam intensity. This was accomplished by using three strippers (thin foils) in series. When H^- passes through the foil, the electrons are knocked off, converting H^- to H^+ . The H^+ beam is bent down line B, while the H^- continues down EPB. The third stripper is jaw-shaped and can be opened different amounts to control the amount of beam into EPB. Combining strippers in series allows a greater beam ratio between line B and EPB. An extremely large stripping ratio was required, since line B needed a few nano-amps, while EPB required only about 100 protons per second. This was accomplished, although a few problems did turn up.

With normal beam intensities, the beam cross section is a sharp spot a few millimeters in diameter. With very low intensity a sharp spot still appeared, but with a great deal of background, including a secondary spot a few centimeters wide and a few centimeters away from the main spot. The exact nature of the background was not determined, but the particles did have a time relative to the RF signal different from that of the main beam, indicating a production via inelastic processes somewhere in the line. Tests showed that even with the strippers entirely closed, such that

nothing should have been seen in EPB, the rate of these particles was not reduced. Since it is possible to eliminate nearly all of these particles with software cuts, it was decided that they presented no serious problem.

In order to check for systematic problems in the recoil polarimeter, two beam orientations were used. First, the polarization was oriented in the appropriate direction at the ion-source to give a sideways polarization at the polarimeter. Next, LB-SO-01 was turned on to provide normal (vertical) polarization. Also at this time magnets EP-BM-01,02,03 were turned on. These magnets are part of a system to provide arbitrary spin orientation in EPB¹³. In this case they were used in an attempt to remove the aforementioned background. Their mode of operation is straightforward. BM-01 bends the H^- away from the beam line. EP-ST-00 strips the H^- to H^+ , then BM-02 and BM-03 bend the beam back to the proper direction. Since the spin is in a vertical direction, it is not affected by this procedure. This process eliminated virtually all of the background.

In addition to changing the polarization orientation, the polarimeter was placed in three different positions during the vertical polarization measurements: beam 15 cm from the left edge, beam centered, and beam 15 cm from the right edge. This served as a check for instrumental asymmetries and other problems in the polarimeter.

Analyzers used during the 800 MeV calibration were a 25.4 cm thick, 60 cm square block of carbon (the same used in the spin

transfer experiment) and a 10 cm thick, 7.5 cm square piece of beryllium. The beryllium analyzing power measurement was done using vertical polarization, with the beam centered on the polarimeter.

The EPB beam line polarimeter is located directly behind the recoil polarimeter. It was designed to run with beam intensities of a few pico-amps. Thus, it could not be used during the actual calibration. To monitor beam polarization during these runs, the line B polarimeter was used. Before and during the calibration runs, the polarization was measured using the EPB polarimeter and compared with the line B polarimeter. This gave a comparison of the two measured polarizations and helped make certain that there were no dramatic changes in the polarization during the calibration.

C. Lower Energy Calibrations

Between July and October of 1980, the H^- beam was, for the first time, run at a wide range of energies. During this time calibrations of the recoil polarimeter were made at some of the lower energies. The basic procedure used was the same as for the 800 MeV calibration, but with some differences. First, the calibrations took place in area B. During this time area B was being used as a proton line, rather than a neutron line. Another experiment, which used a polarized target, was also being run in the area. At the time of each energy change, time was allotted for calibrating the beam line polarimeters and the recoil polarimeter. The polarized target was left in place during the calibrations, with the polarimeter about 4 meters downstream. Coulomb multiple scattering in the target and air

caused the beam to be blown up from one cm diameter to about 10 cm diameter. Multiple scattering does not affect the polarization, and larger angle nuclear scatters can be eliminated by software cuts, so this blowup is not felt to be a problem.

The most important difference in the lower energy calibration was in the measurement of beam polarization. Instead of using a beam line polarimeter, the quench ratio technique was used. This method is available because of the nature of the LAMPF polarized ion source. The source is a Lamb-shift type, which uses a meta-stable state ($2s$) of H^0 in the production of polarized beam. The H^0 is brought into a chamber which has both electric and magnetic fields present. The presence of these fields shifts the energy levels of the H^0 , such that two of the $2s$ states have the same energy as two of the $2p$ states (see Fig. 2-24). These quickly decay to the ground state. An RF signal is used to induce transitions between a third $2s$ state and the $2p$ level. This leaves only one hyperfine $2s$ state, with the protons aligned in one direction. The frequency needed to induce the transition is dependent on the values of both the magnetic and electric fields. If either is changed, the preferential "quenching" will not occur and the remaining beam will be unpolarized, with all atoms being quenched to the ground state.

The H^0 then enters a charge exchange cell where the excited (polarized) H^0 is preferentially ionized. Some of the ground state H^0 is also ionized, giving a background of unpolarized H^- . If the magnetic or electric field (usually the electric field) is changed to

Figure 2-24 Level structure of H^0 used in
Lamb-shift ion source.

quench all H^0 , the beam will be entirely unpolarized. The ratio of intensities of this beam and the polarized beam is directly related to the beam polarization⁶ by the formula

$$P = 1. - 1/Q + P_q/Q$$

where P is the beam polarization, Q the intensity ratio of polarized to quenched beam, and P_q the quenched beam polarization, usually very small ($\sim .03$).

This quenching can be done quickly and repeated at fixed intervals. Signals from the ion-source identical to the normal-reverse signals are supplied to the experimental areas. If some beam intensity monitor is gated with both polarized and quenched signals, the beam polarization can be extracted. This was done for the lower energy calibrations using the coincidence of SF and SB, along with two gated times to normalize the amount of time spent in each state. The procedure during these calibrations was to alternate polarized and quenched beam every 10 seconds, and flip the spin every minute. Runs were also taken with no beam to allow a correction for the cosmic ray background.

Two thicknesses of carbon were used in this section. The thickness must be decreased for lower energy protons to keep Coulomb multiple scattering from extending into the region of interest. Carbon thicknesses are chosen to keep the mean coulomb multiple

scattering angle to less than one degree. The following energies and carbon thicknesses were used:

Energy	C thickness
800 MeV	25.4 cm
750	25.4
650	25.4
580	12.7
550	12.7

Typical polarizations during these runs were about 80%. All of the lower energy calibrations were carried out with vertical polarization and with beam centered on the polarimeter.

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CHAPTER THREE-ANALYSIS

The analysis consists of five basic parts: calibrations of the polarimeter drift chambers, extraction of the asymmetry, extraction of the carbon analyzing power, extraction of the np analyzing power, and extraction of the np spin transfer parameters.

A. Drift Chamber Calibration and Checks

As can be seen from Chapter 2, the electronics for the polarimeter are relatively simple. Only four words of data are recorded per plane per event, i.e., three TDC outputs and one ADC. These data must be used to calculate the position of the event in that plane. The combined data from all twelve planes allows the determination of the scattering angles.

The calibration has three basic objectives: to establish the correct anode wire, to find the distance of the interaction from the anode wire and side on which it occurred, and to software align the chambers so the true scattering angle can be determined. A total of 10 constants (R_1 - R_{10}) need to be determined for each plane, making a total of 120 calibration constants. Once the calibrations are done, checks are made on each event to establish the internal consistency of the data obtained.

1. Anode Wire Determination

Ideally, the correct anode wire could be determined simply from the difference in the arrival times of the delay line end signals

relative to the event trigger. This can be seen from the following equations:

$$T_1 = S + d + nD$$

$$T_2 = S + d + (N-n)D$$

$$T_1 - T_2 = -ND + 2nD$$

where S is a constant offset, d is the drift time, D the delay per wire, N the number of wires, and n the wire number. The difference in times to the two ends, $(T_1 - T_2)$, is linearly related to the wire number, such that the wire number is found from the relation

$$n = (T_1 - T_2 + ND)/2D$$

where the constants ND and $2D$ can be empirically determined. In practice, the situation is not quite so simple. The two TDCs may have different calibration constants, pulses traveling most of the delay line distance may be distorted enough to give an effective value of D different than for pulses with short travel distances, the TDCs may have non-linear effects and so on. If any of these effects were large, it would be difficult to determine the wire number. They were found to be fairly small, enabling the use of an empirical correction formula of the form

$$AP = R_1 + R_2 AA + R_3 AA^2 + R_4 AA^3$$

where AA is $(T_1 - T_2)$. The constants R_{1-4} are determined to give values of the anode position (AP) equal to n times the wire spacing in centimeters, with n being an integer.

The constants R_{1-4} are determined as follows. First, a truncated anode position (TAP) is calculated by the relations

$$NAP = AP/GAP + 50.5 \quad (NAP \text{ is integer truncation})$$

$$TAP = (NAP - 50)GAP$$

where GAP is the wire spacing. TAP is then the nearest integer to AP. If AP falls on integral multiples of GAP, TAP and AP will be equal. By summing the value of $(TAP - AP)$ and $(TAP - AP)^2$ for many events, the average discrepancy of $(TAP - AP)$ and the mean width of the peaks can be found. If the sum of $(TAP - AP)$ is zero for each value of TAP, the peaks are centered on integral multiples of GAP. A minimization program is used to search over reasonable values of R_{1-4} to find the combination which minimizes the sum of $(TAP - AP)^2$. R_1 , for example, is allowed to vary over plus or minus one wire spacing. R_2 can be estimated from the nominal delay per wire and channels per nsec of the TDCs and is allowed to vary within a few percent of this value. The results are checked by plotting the sums of $(TAP - AP)$ and $(TAP - AP)^2$ as a function of TAP. Figs. 3-1 and 3-2 show sample plots of these two sums. The "D"s are the sums of $(TAP - AP)$ and the "*"s sums of $(TAP - AP)^2$. Fig. 3-1 shows a well calibrated delay line, Fig. 3-2

Figure 3-2 Poorly calibrated delay line.

one in which the constants are incorrect. The rise on the right side of Fig. 3-2 followed by a sudden drop occurs when the value of AP are not integral multiples of GAP, so eventually a wire number is skipped. For example, if one wire has an AP value of 19.4, the value of TAP will be 19.0 and the difference -.4. If the next wire has an AP value of 20.6, the value of TAP will be 21.0 and the difference .4, taking GAP to be 1.0 in both cases. The small variations seen in Fig. 3-1 are not important, since the correct wire is being identified but the position of TAP relative to the center of the AP peak is shifting slightly. Figs. 3-3 and 3-4 show AP over the whole range of a chamber and a close up of one end. The clear separation of the peaks can be seen, indicating that misidentification of the anode wire number should not be a problem.

2. Drift Time and Left-Right Determination

Once the correct wire has been identified, the chamber could be used in the same way as individual wire readout chambers are used, i.e., take the point of the interaction to be at the wire with an uncertainty of one-half the wire spacing. In the case of this system, which has a wire spacing of .8128 cm, resolution of scattering angles would be rather poor unless the chambers had a very wide separation. Fortunately, much finer resolution can be obtained by using the drift time.

When a charged particle goes through matter it leaves a trail of ions and free electrons. When this occurs inside a chamber the electrons gradually drift toward the anode wire, colliding with atoms

Figure 3-3 Anode position. The wavy pattern is simply a binning effect.

Figure 3-4 Anode position, one end of the chamber.

along the way. This drift proceeds at a fairly uniform average rate, such that the time of travel is nearly proportional to the distance of interaction from the anode wire. At a distance of 100 microns or so the fields become intense enough to accelerate the electron to energies high enough to ionize more atoms. These newly freed electrons ionize additional atoms and soon a large pulse of electrons reach the anode, generating a signal pulse. This "avalanche" process takes place quite quickly, on the order of one nsec. During the avalanche a large number of positive ions are created and pushed toward the cathode wires. This process distorts the electric fields around the anode wire inducing pulses on the neighboring cathode wires. Thus, at the time of an avalanche pulses are detected from both the anode wire and the cathode wires. By comparing the time of arrival of these pulses with that of the scintillator trigger the drift time can be determined. As mentioned in Chap. 2, the sum of the pulses from the two cathode bus lines is actually used for timing.

Fig. 3-5 shows a single drift time spectrum. If the drift time were linearly related to the distance of the interaction from the wire, the spectrum would be rectangular (for uniform illumination over one wire spacing). As can be seen, this is approximately true for the real spectrum. Two features stand out in the real spectrum: a long tail at the end and a sharp peak at the start. Both of these features can be explained in a fairly simple fashion. If an interaction occurs near midway between two anode wires the electric field will be rather weak. The electron will take a while to "decide" which way to go and

Figure 3-5 Corrected drift time spectrum,
single channel.

Figure 3-6 Corrected drift time spectra from
all 12 planes.

will move slowly at first. This "indecision" of the electrons spreads out the time of arrival for them, giving the long tail. The peak at the first results from the avalanche occurring at a small distance (.1 mm or so) from the wire. Any time ions are created within some critical distance a near immediate avalanche will occur and all events will appear to have the same time.

At this point some method must be used to transform the drift time into a position. This is done by assuming the distribution of events across one wire spacing is uniform, and that increasing times correspond to increasing distance of the interaction. If both of these conditions are fulfilled, the first 10% of the events, for example, will correspond to the first 10% of the distance between the anode wire and cathode wire. By dividing the drift time spectrum into bins with equal numbers of events and relating each bin to a fixed increment of distance, a flat distribution of distances from the anode wire can be made. If all drift time spectra look the same, one simple look-up file can be made to transform the time into a distance. As might be expected, the spectra are not quite identical, mainly because of differences in TDC calibration constants. A number of corrections can be made to produce a set of nearly identical drift time spectra.

First, a correction for the change in drift time with respect to the anode position is made in the form

$$DTIM = DTIM + R_5AP.$$

This accounts for the finite travel time across the chamber, such that all events occurring at the wire appear to have zero drift time. The correction is made by plotting the drift time against anode position and adjusting the value of R_5 until the line formed by minimum drift times at each anode is horizontal.

Next, a correction is applied to account for the different calibration constants of the TDCs. This takes the form

$$DTIM = (DTIM)R_6.$$

R_6 is calculated by measuring each TDC calibration constant and normalizing to one arbitrarily chosen TDC. Thus, if TDC_1 had a constant of 10 channels/nsec and TDC_2 had a constant of 11 channels/nsec, all values from TDC_1 would be multiplied by 1.1 to give the same effective calibration constant as TDC_2 .

Finally, an offset, R_7 , is applied to make all spectra start at the same value. This gives 12 drift time spectra which appear nearly identical (Fig. 3-6). Without these corrections 12 different tables for time to distance conversion would be needed, instead of the one required for the corrected spectra.

Once the corrections have been made, a time to distance look-up table is generated as described above. The drift time spectrum is divided into roughly 300 bins, corresponding to .027 mm divisions, well below the resolution needed (or possible). Once the table is made, the drift position is simply looked up with a direct

correspondence between drift time channel and distance. A drift position spectrum is shown in Fig. 3-7.

Once the drift position is determined, the side of the wire on which the event occurred must be determined. This is done with the "odd-even" system described in Chap. 2. Although pulses are induced on each of the nearest cathode wires at the time of an avalanche, the pulses are not equal. As discussed in Ref. 10 of Chap. 2, the pulse on the cathode wire which is on the same side as the event will be larger than the opposite cathode wire pulse by 20-30%. By subtracting the two pulses, a determination can be made of the side on which the event occurred. Fig. 3-8 shows the O-E spectrum, with the two peaks being quite distinct. About 94% of the events are in the peaks. An offset, R_0 , is applied to the spectrum so that half the events have a negative value and half a positive value. The correct sign of the drift position can be determined simply from the sign of the adjusted ADC spectrum, thus

$$DPOS = (-1)^n (\text{sign}(ADC)) (DPOS),$$

where n is the wire number and $DPOS$ the drift position determined above. The first phase factor is needed because a positive value for the ADC will correspond to the right side of wire n but the left side of wire $n+1$. There are two problems with this system: getting the correct phase and making sure that the ADC sign is truly indicative of the side on which the interaction occurred.

Figure 3-7 Event position spectrum deduced from drift time.

Figure 3-8 Odd-even pulse height spectrum.

The phase correction is fairly straightforward in this system, since there are six chambers all looking at the same particles. First, the final position in each plane (XY) is determined by the formula

$$XY = TAP + DPOS$$

where DPOS is the signed drift position. The final x (y) position in one chamber can be compared to the final x (y) position in an adjacent chamber. One of the following conditions must exist: both chambers have correct phase, both incorrect, or one correct and one incorrect. Examples of all three cases are shown in Figs. 3-9,11. The case for both correct gives a nice sharp straight line. One phase incorrect give a cross-hatched pattern, since as one position increases, the other decreases, with both giving the same value at the wire. At first, it might be thought that it would be impossible to tell if both chambers were out of phase. Indeed, if all particles were parallel and all planes were aligned so that if a particle went through one wire, it would go through the corresponding wire in all planes, then it would not be possible to tell if both planes were out of phase. In the real situation the particles are diverging and the planes are not perfectly aligned. This gives a set of parallel lines, as shown in Fig. 3-11.

Once it is determined that one or more planes are out of phase, a correction is applied to R_1 in the calculation of AP. This

Figure 3-9 Both 0-E
phases correct.

Figure 3-10 One 0-E phase
incorrect.

Figure 3-11 Both 0-E phases incorrect.

consists of the addition or subtraction of one wire spacing, which shifts the wire number by one. In the case where only one plane is out of phase, this must be done for one plane, then checked to see if the proper plane was corrected.

After this procedure is completed, the correct position in each plane is known, with the possible exception of a sign error from the ADC. The check for this will be described in sub-section 4.

3. Chamber Alignment

The next step in the calibration procedure is the alignment of the chambers. The chambers are physically aligned such the first wire of each chamber is within a few millimeters or so of being on a straight line drawn through the chambers. Except for the hardware fast clear (see Chap. 2), this is not of great importance because the anode position calculation (including phase correction) effectively shifts the wire positions. It is necessary, therefore, to include an alignment adjustment of the form

$$XY = XY + R_9.$$

As with the phase adjustment, the use of six planes makes the determination of R_9 fairly easy. The first step is to calculate a quantity called the residual. This is simply the difference between the best fit line to the three points of one set of planes ($X1-X3$, $Y1-Y3$, $X4-X6$, or $Y4-Y6$) and the measured position in the middle plane of that set. The histogram of this should show a peak centered on

zero. R_9 is adjusted for X2 and Y2 until the front (1-3) plane residuals are indeed centered on zero.

A similiar procedure is done for the back planes. A position at each plane is calculated from the front planes and the difference between this and the actual position is histogrammed. Again, this should show a peak centered on zero. R_9 is then adjusted for each of the back planes until each front-back residual is centered on zero. This is, of course, done with the carbon analyzer removed. These residual peaks are broader than the front residuals because of the greater distances involved. Once this is done a back residual can be calculated (that is, the difference between plane 5 and the fit to planes 4-6). This should again be a sharp peak centered on zero. If it is not, the above procedure is repeated until it is. Although it was not used for this analysis, a program now exists which will perform this procedure automatically.

4. Checks for Good Events

Once the chambers are calibrated, various checks can be made to determine internal consistency of the polarimeter before calculating scattering angles. This involves calculating a quantity known as the "checksum", and a left-right determination check.

The checksum is a check as to whether the anode and cathode signals agree on the drift time and the two delay line ends agree on the wire number. The checksum is defined as

$$CKSM = T_1 + T_2 - 2T_{OE}.$$

T_1 and T_2 are the delay line end times and T_{OE} is the cathode O+E time. That this should be constant for a good event is seen from the following equations:

$$T_1 = D_{tm} + nD + K_1$$

$$T_2 = D_{tm} + (N-n)D + K_2$$

$$T_{OE} = D_{tm} + K_3$$

$$CKSM = ND + K_1 + K_2 - 2K_3$$

D_{tm} is the drift time, D the delay per wire, n the wire number, N the number of wires, and the K s are constant offsets. As long as the values of D_{tm} and n measured by the different TDCs are identical, checksum will be a constant.

Since checksum involves different TDCs, there is again the problem of different calibration constants. This gives a dependence of checksum on the drift time. This is corrected by the following relation

$$CKSM = CKSM + R_{10}DTIM.$$

If the value for $DTIM$ is the corrected time derived above, checksum will not have much dependence on the anode position. Making this correction is not really essential, but does allow a tighter cut on checksum, hence eliminating more bad events.

Figure 3-12 Checksum spectrum.

Figure 3-13 Checksum spectrum, expanded scale.

The resulting checksum spectrum shows two peaks (see Figs. 3-12,13), one corresponding to good events, the other to events in which none of the TDCs received a valid stop. There is a long tail of events beginning at the good event peak and trailing toward smaller values of checksum. The cause of this will be described later.

Once the checksum is calculated, a cut can be made so as to eliminate the time-out peak and most of the tail. This should eliminate most of the bad signals. Next, a check is made on the residual.

The residual, described earlier, shows a sharp peak at zero, with a full-width-half-max of about .2 mm. There is, however, a plateau with a width of about 1.2 cm containing about 5% of the events. This is the result of incorrect left-right identification. The use of three planes to determine the ray allows for correction of this. For each plane the residual is calculated using both the subtracted and added drift position. This is done for one plane at a time, with the other two of a set using the position indicated by their ADCs. The combination that gives the lowest value is then used. This almost completely eliminates the plateau. The peak itself is not made any sharper. It has been found that between 1% and 2% of the time per plane this procedure will produce a better residual. The drift positions for the events benefiting from this procedure tend to be near the wire and the ADC values tend to come from the valley (the valley accounts for only 6-8% of the events, but 20% of those which benefit from changing the ADC sign come from the valley). This

indicates that the ADC probably actually fails to give the correct side of the interaction about 1% of the time. After this procedure a cut is made on the residual of ± 1 mm.

Even after the odd-even check, 2-3% of the events per plane (about 30% overall) which passed good checksum do not pass good residual. Since a good checksum seems to indicate a good check on the internal consistency of each plane, one might wonder why events with good checksums would ever have a bad residual. As it turns out, the tail on the checksum and the bad residuals are closely related. Both seem largely due to delta rays (high energy electrons). This and other problems will now be discussed.

There are several possible causes of a bad checksum. For example, failure of one or more TDCs to receive valid stops, noise giving too early a stop on one or more TDCs, double hits caused by two high energy protons going through the system at nearly the same time, and double hits from charged particles knocked out by protons will all give a bad checksum. The first two causes (noise and failure of TDC to fire) are rare. These give values for checksum far away from the main peak and were found to contribute only about .2% of the total events per plane (about 20% of the bad checksum events). Double proton hits are very unlikely at the event rates of these experiments, since the rate was never more than about one event per two macro-pulses. Since each macro-pulse is about 500 μ sec long, the chances of two events occurring within the same 300 nsec period is negligible. This leaves secondary charged particles, primarily

electrons, as the culprit for most bad checksums. If an ionizing electron triggers an adjacent wire with a drift time such that one TDC records one wire and the other TDC the second wire, the checksum value will be slightly low, since the drift times will not quite agree and the wire sum will be too small. This gives a long tail on the checksum (see Fig. 3-13). If the drift time for the second wire is sufficiently low so that all three TDCs record the second wire and associated drift time, the checksum will be good but the residual will be bad.

The question remains as to whether enough high energy electrons are generated to account for the observed levels of bad checksum and residual. Calculations of this have been made by Sauli¹. An 800 MeV proton will generate an electron with energy greater than 15 keV about 1% of the time in 1 cm Argon and .0013 cm Al, the amount of material in the ground plane and gas before the signal plane. A 15 keV electron has a range of about 3 mm. These can cause problems by either going on the opposite side of a cathode wire as the proton, and thus giving a signal one wire off, or by being knocked toward the anode wire causing the signal to arrive too soon. The normal drift rate is about .05 mm/nsec, while a 15 keV electron travels at a rate of 71 mm/nsec. Thus, even a 15 keV electron may travel far enough at a high velocity to decrease the total drift time by a few nsec. This can be enough to give the wrong position by close to a millimeter, the maximum allowed discrepancy. For an 800 MeV proton can generate electrons with energies up to 2.5 MeV. These have have mean travel

distance of a few grams/cm² of material. Although the maximum energy electrons are generated an insignificant amount of the time, 1 MeV electrons will be generated by 1% of the protons per gram/cm². Since the front scintillators are about .6 gram/cm², these will occur for about .6 % of the events. Such high energy electrons will also be generated in the carbon analyzer and thus affect the back chambers. It has been observed that that back chambers have a slightly higher failure rate for the residual and checksum tests, consistent with the larger amount of material in which delta rays may be generated. Since a faulty signal, either bad checksum or bad residual, occurs for about 4% of the events per plane, the number of high energy electrons seems at about the right level to explain them. Further tests showed bad checksum to be moderately correlated between x and y planes in one chamber, with about 35% of the events with bad checksum in x also having bad checksum in y. There was some correlation between chambers, with about 8% of the events having bad checksum in X1 also bad in all three front x planes. Since this is only about .1% of all events, they can be explained as very high energy delta rays, or x-rays from various sources. Although the probability for higher energy electrons decreases, the range in which they can be generated and still cause problems increases, thus giving the few percent failure rate for the residual test observed.

The problem of bad residuals for events with good checksums was investigated with the calibrations runs. Since the beam during calibrations is isolated to one small section of the chamber, the

Figure 3-14 Distance of closest approach distribution.

Table 3-1

Acceptance Cuts for Polarimeter and Spectrometer

<u>Parameter</u>	<u>Range</u>	<u>Units</u>
XCLOSE	-28.0 to 26.8	cm
YCLOSE	-27.8 to 29.0	cm
ZCLOSE	-16.0 to 16.0	cm
DCLOSE	0.0 to 5.0	mm
X-Target	-4.4 to 4.8	cm
Y-Target	-5.8 to 4.0	cm
XSB	-28.0 to 28.8	cm
YSB	-27.8 to 29.0	cm
Residuals	-1.0 to 1.0	mm

checksum peak is very narrow, allowing a tight cut to be made on it. Cuts could be made on the first and third chambers such that only protons going through both and within a one centimeter square on each were accepted. The positions in the second chamber for events with a good checksum were examined. Although most were within a one centimeter square on the second chamber, a few were as much as 10 cm away. Further, a drift time histogram of those events with a bad residual showed the times were very biased toward short times. This gives support to the idea that the chamber did not malfunction, but recorded another particle going through, with a drift time less than that associated with the proton.

Although these secondarily scattered particles decrease the efficiency of the polarimeter, there is no evidence for them inducing instrumental asymmetries (see App. E).

A few other cuts are made for good polarimeter events. These are on XCLOSE, YCLOSE, and ZCLOSE, the coordinates of the point of closest approach of the initial and final rays, which assures that the event came from the carbon, and on DCLOSE (Fig. 3-14), the distance of closest approach. The only cut which has any real effect is that on DCLOSE. Checks were done to see the effect of DCLOSE cuts on the analyzing power. The results of this test, and one to check the effect of bad residuals are discussed in App. E. The final acceptance cuts used are shown in Table 3-1.

B. Asymmetry Calculation

Once the procedures in section A have been completed, the polar and azimuthal scattering angles are computed. It is the asymmetry in the azimuthal angle that is related to the proton polarization. In addition, the distance of closest approach of the incident and scattered rays and the location of this point are calculated (X, Y, Z, and DCLOSE mentioned above).

Calculations of the polar (scattering) angle, θ , and the point of closest approach are unambiguous. Determination of the azimuthal angle, ϕ , is complicated by the fact that the origin (direction for ψ equal zero) is not uniquely determined. Indeed, the determination of ϕ depends on the physical system being measured. A review of the calculations needed is given in App. A.

The definitions of the triple scattering parameters lead to a natural definition of ϕ . Each parameter is defined as the transfer of polarization from a state in one of three initial orientations to a state in one of three final orientations. These orientations are defined relative to the laboratory momentum of the initial and final particles. The initial (subscript i) and final (subscript f) coordinate systems are defined as follows:

$$N_i = k_f \times k_i$$

$$N_f = N_i$$

$$L_i = k_i$$

$$L_f = k_f$$

$$S_i = N_i \times L_i$$

$$S_f = N_f \times L_f$$

All vectors are normalized to unity. The "k"s are in the same direction as the initial and final momenta. A diagram of these coordinate systems is shown in App. C.

It is easily seen that "N" is perpendicular to the scattering plane and both "S"s are in the scattering plane. If ψ is defined to be zero along S_f , then the $\psi = 0, \pi$ asymmetry will indicate the polarization in the N direction, and the $\psi = \pm\pi/2$ asymmetry will indicate the polarization in the S direction. These are exactly the polarizations desired (see Chap. 1). Any other choice of ψ will indicate a mixture of the two polarizations, unnecessarily complicating matters.

This definition of ψ has one complication; the definition of ψ when k_f equals k_i , such as when the polarimeter is placed directly in the proton beam. This is easily circumvented by defining N relative to the polarimeter axis, thus

$$N' = k_i \times X$$

where X is a horizontal vector in the polarimeter frame. L and S then have the same definitions as before. Since the polarimeter X-Z plane is the same as the laboratory frame, and the direct polarization is always oriented either along X or N, this provides the same convenience in determining the polarization (or analyzing power) as before. Calculations are simplified, in fact, if ψ is calculated in

this second coordinate system and the scattering ψ (when there is a target) is calculated separately. The final ψ is just $\phi_{\text{pol}} - \psi_{\text{scatt}}$.

Once the calculations of ϕ and θ are made, the asymmetry in ψ must be found. Several methods of doing this are available, each suited to different situations.

In the simplest system, such as the beam line polarimeter described in Chap. 2, the asymmetry is merely the difference in counts between left and right counters, divided by the sum. If the beam polarization alternates between two states of equal magnitude but opposite sign (a proper spin flip), the asymmetry can be defined as $(L-R)/(L+R)$, where $L=\sqrt{L_N R_R}$ and $R=\sqrt{L_R R_N}$, as stated in Chap. 2. This eliminates instrumental asymmetries to high order and is ideally suited to the case of a pencil beam and two small solid angle detectors at $\phi = 0^\circ$ and 180° . For the spin transfer experiments and calibrations this is not the case. The detectors have large solid angle wire chambers and, in the spin transfer experiment, the "beam" is the scattered flux, which illuminates the entire carbon analyzer (60 cm square). The simple method could still be used, but only by artificially limiting the sections of the analyzer and wire chambers used. A more efficient, and simpler, system can be used.

As described in Chap. 1, the nucleon-nucleon interaction obeys certain symmetry principles. These imply that the scattering of nucleons (whether nucleon-nucleon or nucleon-nucleus) will follow the probability distribution:

$$P(\theta, \phi) = (1. + A(\theta)(\sigma_y \cos(\phi) + \sigma_x \sin(\phi))) / 2\pi.$$

$A(\theta)$ is called the analyzing power, σ_y and σ_x are the polarizations in the $\phi=\pi/2$ and $\phi=0$ directions, and $P(\theta, \phi)$ is the probability density. The product $A\sigma$ is the asymmetry measured. The simple situation described earlier is just the case where only $\phi=\pi$ and 0 are measured.

Since the proper asymmetry (that is, the asymmetry due to scattering and not due to instrumental inefficiencies) contains only a cosine and sine term, the immediately obvious method of extracting their coefficients is to do a fourier analysis. This can be used, but will only give an accurate estimate of the asymmetry if the efficiency of detection is the same for all values of ϕ . For example, if only events entering along one side of the polarimeter are used, only those scattering inward will be detected. This will be reflected in a large calculated asymmetry. If two spin states with a proper spin flip between them are used, their average difference $((\epsilon_N - \epsilon_R)/2)$ can be used as the asymmetry. This is fine if instrumental asymmetries are small, since they cancel to first order. However, in cases like that just described, in which there is a large instrumental asymmetry, there will be a definite bias. Cases like this can be prevented by checking to see if all ϕ values for a given event are within the acceptance of the polarimeter. If they are not, the event is rejected. This test (the "cone" test) allows many more events to be used than in the simple situation of two small detectors described above, but it still severely restricts the use of events entering

along the edges of the polarimeter and of large angle scatters. Higher order terms in cosine and sine ($\cos(2\varphi)$, $\cos(3\varphi)$, etc.) can also be calculated for events passing the cone test. Since these should all be zero, any deviation is an indication of a varying efficiency of the chambers or scintillators (see App. E).

A second method of analysis was developed at SIN and reported by Besset². This method requires only that the $\varphi+\pi$ scatter be allowed, which is much less restrictive than the cone test. In fact, if two beam orientations with a proper spin flip between them are used, all events can be used. This method, and the fourier series method are discussed in App. B.

A third method, which allows use of all events, was described by Edgington³. This is more complicated than Besset's method and was not used.

Asymmetries extracted using the fourier series and the Besset method ($\varphi+\pi$ test and all events using spin flip) show good agreement, although in cases where events are near one edge, or for large scattering angles, so few events pass the cone test that a comparison of it with the others is not very significant.

C. Carbon Analyzing Power

After calibration of the polarimeter it is necessary to determine the carbon analyzing power, $A(\theta)$. This value is needed to determine the beam polarization from the measured asymmetry.

As described in Chap. 2, measurements of the analyzing power were made at two different times, using two slightly different

techniques. The analysis for the two cases is identical with the exception of the determination of the proton beam polarization.

In all cases cuts were placed on the front chambers to eliminate background. For the 800 MeV data, these were "boxes" about 1 cm square. Because of the increased multiple scattering in the lower energy measurements, the box sizes were increased to about 10 cm square. This insured that only the direct beam was used, and cosmic rays or small scatters before the carbon were eliminated. Since the lower energy beam was only polarized part of the time, it was necessary to test the polarized-quench flag on each event and eliminate those without the polarized flag. Other cuts, such as those on the distance of closest approach, are the same as given in Table 3-1.

Once the cuts are made, the sums discussed in App. B for the SIN method are accumulated. Since there is a proper spin flip between states and the beam is localized, there is no need to make any acceptance cut. Normalization between the two spin states is done by comparing events which scattered less than 8° in each of the two states.

The final problem is beam polarization determination. As mentioned in Chap. 2, beam intensities were too low to use the EPB polarimeter during the 800 MeV calibration. Because of this, the polarization was measured before the calibration and part way through with high beam intensity. During the calibration the line B polarimeter was monitored to insure there was no change in the

polarization. The values taken before the calibration started and about three quarters of the way through it show polarizations of 75% and 74.4%, respectively. A comparison of the EPB values at these times with the line B values gives the relative analyzing powers. The line B polarimeter showed variations in the polarization between 74% and 76% during the calibration. The value used to calculate the analyzing power for all runs was taken to be $(75 \pm 1)\%$.

Another uncertainty that may enter in, especially for the "S" orientation, is background. Putting cuts on the beam in the front chambers reduced the background to about 1-2%. It was found that the polarization of the background particles was high, essentially that of the beam. The dilution of the polarization from the pure beam was probably less than .2%. The "N" orientation at all energies had a much reduced background from the "S" orientation at 800 MeV and so the background's effect on the measurement was negligible.

The proton beam polarization during the lower energy calibrations could be obtained from the quench ratio, as described in Chap. 2. The polarization was also measured at high beam intensities by McNaughton⁴ before the polarimeter calibrations. Table 3-2 compares the average polarization value during the calibrations and those measured by McNaughton. The only large discrepancy was at 700 MeV. The analyzing power calculated with the lower beam polarization was much higher than the energy dependent fit (see Sec. F) was able to accommodate. The reason for the discrepancy is not known. Because of these problems, the 700 MeV data was not used. Because of problems

Table 3-2

Polarization During Lower Energy Calibrations

Energy	Calibration Polarization	McNaughton Value
550.	.830	.820
580.	.873	.852
650.	.839	.800
700.	.570	.851
750.	.860	.885
750.-2	.725	
750.-3	.834	

with the ion-source during the 750 MeV calibration, the data runs were divided into three groups, each of which had a different average polarization.

D. n-p Analyzing Power

As part of the n-p spin transfer experiment, the n-p analyzing power can be extracted. The method for this is quite simple. A polarized neutron beam impinges on a liquid hydrogen target. The beam polarization is reversed at fixed intervals and the difference in intensity between the two states for each θ bin is measured. The analyzing power is then given by:

$$A(\theta) = \frac{N - rR}{(N + rR) \langle \cos(\psi) \rangle P}$$

where N and R are the number of events in each spin state, r is a normalization factor, P the beam polarization, and $\langle \cos(\psi) \rangle$ the mean value of the azimuthal scattering angle relative to the beam polarization. Since the only thing that changes between spin states is the orientation of the spin (that is, there is no neutron beam movement or change in the detection system), the only critical matter is determining r. This parameter relates the total amount of beam incident on the target for the two spin states. Monitors for this purpose were described in Chap. 2, Sec. I-F. Each of these monitors was scaled twice, once with "Gross-Inhibit" and once with "Master-Inhibit". The difference between these is just the system

dead time (while an event is being read in). These monitors are in generally good agreement (see Table 3-3). There is a systematic difference between the beam line polarimeter and the neutron monitors, with the beam line polarimeter giving a ratio between states about 1% higher than the neutron monitors. The most likely causes for this are beam motion between spin states, uncertain subtraction of accidentals, and differences in detection efficiency between the up-down counters. Since the neutron monitors are at the end of a long collimator, they are not affected much by small proton beam motion. The beam line polarimeter is much more sensitive to proton beam motion just because of its geometry. Proton beam intensities are also much higher than neutron beam intensities, thus giving high accidental rates (at times being equal to the true coincidence rate, although more usually 10-20% of the true rates). Since accidentals are proportional to beam intensity squared, small differences in rates between states may lead to a less accurate relative normalization. Z-mon-MI was the monitor actually used for the normalizations.

One final cut must be placed on the data; the incident neutron energy extracted from the recoil proton momentum. Since only the quasi-elastic peak is polarized and only elastic n-p scatters are desired, protons which originated from pion-producing reactions in either the deuterium or hydrogen targets must be eliminated. This is easily done by calculating the energy of the incident neutron by measuring the angle and momentum of the recoil proton and assuming the reaction was elastic. The resultant spectrum is shown in Fig. 3-15.

Table 3-3

Polarization and Normalization of Neutron Beam

Orientation	N	S	S	L
Current	600 amp	600 amp	200 amp	600 amp
Polarization	.440±.026	.424±.025	.456±.027	.415±.025
Ratio N/R				
L+R-MI	.998	.998	1.009	1.109
Σ Pol	1.003	1.006	1.019	1.120
Z-MI	.999	.999	1.010	1.110
Z-GI	1.003	.999	1.014	1.120

Figure 3-15 Neutron spectrum deduced from spectrometer.

A cut can then be made on the high energy peak. A plot of neutron energy against the position across the magnet will show a curve in the peak, since the fields are weaker at the edges. A correction is applied to give a straight line for the highest energy peak. This enables one to make a narrower cut on the peak.

Once all cuts have been made, events are binned in 1° laboratory scattering angle bins (θ) and 18° ϕ bins. The analyzing power is calculated for each bin, then ϕ bins are summed for each θ bin. Results are given in Chap. 5.

E. n-p Spin Transfer

Measurement of the n-p spin transfer parameters was the goal of this experiment. Most of the techniques have been described. As in the analyzing power measurement, the high energy peak is isolated. The events are analyzed for their polarization using the same methods as described in the calibration section.

There is one major difference between the determination of the polarization in this experiment and the calibration experiment: the presence of a magnet, M2, between the LH_2 target and the polarimeter. This magnet both changes the direction of the proton's momentum and precesses its spin. Although the spin precession complicates the measurement, it also allows longitudinal spin components of the recoil protons to be measured. Two spin components, perpendicular to each other and the momentum, are measured. Each of these is a mixture of all three of the spin components present before the magnet. This gives

$$\sigma_{n2} = a\sigma_{n1} + b\sigma_{s1} + c\sigma_{\ell 1}$$

$$\sigma_{s2} = d\sigma_{n1} + e\sigma_{s1} + f\sigma_{\ell 1}.$$

The relation of these coefficients to current and scattering angles is discussed in App. C. Fig. C-1 shows the coordinate systems used. By combining data with different magnet currents, or different azimuthal angles, both of which change the coefficients, the three initial spins can be determined.

As can be seen from App. C, the coefficients are a function of the scattering angle (θ_{Hyd}), azimuthal angle (ϕ_{Hyd}), and energy (since spin precession and bend angle are functions of energy). Since the polarization can only be determined by summing over many particles, which will have different scattering angles, the coefficients must be averaged over many events. Thus, the coefficients are calculated for each event, binned, then averaged for each bin. Events are binned in 1° θ_{Hyd} bins and three ϕ_{Hyd} bins; $\pm 45^\circ$, greater than 45° and less than 45° . For the absolute value of ϕ greater than 90° , the bins are -135° to 135° , 90° to 135° , and -90° to -135° . Since the spectrometer acceptance becomes more limited for larger scattering angles, not all of these bins will be equally populated. When all three ϕ bins are allowed, there will be six measurements for each θ bin (3 ϕ bins times 2 polarization measurements per ϕ bin). Since there are only three independent parameters, the system is overdetermined and can, in principle, be

solved exactly. In practice, some of the coefficients are nearly zero and each measurement has an error associated with it. The practical method of solution is just to minimize the total χ^2 for all equations. Since the same parameters are present for both initial beam vertical and sideways, all equations for these initial spin states are combined (making a total of 18) before χ^2 minimization. All coefficients and measured asymmetries are given in App. D.

The search program used to find the coefficients was "CURFIT", by Bevington⁵. This program searches χ^2 space for each parameter until a relative minimum is found. It also computes an estimated error on the parameters, which is the error quoted on the final results.

The parameters originating from initially longitudinal beam (K_{LL} and K_{LS}) are also mixed. It would be desirable to use two magnet settings for longitudinal beam also. There was not, unfortunately, time for two magnet settings in the time allowed for the experiment. The parameters can be estimated, however, using a phase shift analysis and the following relation between the parameters:

$$\frac{K_{LS} + K_{SL}}{K_{SS} - K_{LL}} = \tan(\theta_{lab}).$$

This relation follows from time reversal invariance. When θ_{lab} is small, this essentially becomes $K_{LS} = -K_{SL}$. Thus, if the phase shift values for K_{SS} and K_{SL} are used, a relation can be found between K_{LL}

and K_{LS} . The actual method of solution was to do a phase shift analysis using the K_{NN} , K_{SS} , and K_{SL} data from this experiment, calculate K_{LS} from the phase shift analysis, and then solve for K_{LL} . Since K_{LL} and K_{SS} are roughly the same magnitude at larger angles, the above relation, $K_{LS} = -K_{SL}$, is very nearly true, and the estimate of K_{LL} should be fairly accurate.

F. Energy Dependent Fit to the Carbon Analyzing Power

As described earlier, the carbon analyzing power was measured at several energies. It would be useful to have an energy dependent parameterization of this analyzing power to use in future experiments, and in analyzing other data taken with this or similar polarimeters. Such a parameterization was done by Waters⁶ for data taken at TRIUMF. Since those measurements, analyzing powers have been measured at SIN⁷, and at LAMPF. The LAMPF measurements not only include the data described in this work, but analyzing powers measured in other experiments. The major additional LAMPF data comes from McNaughton⁸. McNaughton extracted the data from an experiment designed to measure the pp spin transfer parameters at 800 MeV. This involved a polarized proton beam scattering from an unpolarized target. If the two beam polarizations are averaged, the situation is identical to an unpolarized beam scattering from an unpolarized target. Since the pp analyzing power has been measured⁹, the polarization of the scattered beam is known and the carbon analyzing power can be determined. This method has the disadvantage of having a widely varying polarization (the pp analyzing power must be zero at 90° c.m. and reaches a

maximum of about .5). It does, however, allow the analyzing power to be measured over a wide range of energies without requiring a variable energy beam.

One other measurement was available from the HRS¹⁰ (High Resolution Spectrometer) at LAMPF, where a polarimeter similiar to the one described in this work is being used.

All of these measurements involved the inclusive analyzing power, that is, no attempt was made to see if the recoil particle was a proton and no time of flight cut was made.

Waters used the function

$$A = a(\text{psin}\theta)/(1 + b(\text{psin}\theta)^2 + c(\text{psin}\theta)^4)$$

to describe the angular dependence of the analyzing power, where p is the momentum of the proton at the carbon center, and θ is the laboratory scattering angle. The energy dependence of the parameters a , b , and c was given by a polynomial fit of the form

$$a = a_0 + a_1p + a_2p^2 + a_3p^3 + a_4p^4$$

$$b = b_0 + b_1p + b_2p^2 + b_3p^3$$

$$c = c_0 + c_1p + c_2p^2 + c_3p^3 + c_4p^4$$

The SIN group used the same form for their lower energy data, but found the need to add a fourth term, d , for their 561 and 487 MeV measurements.

$$A = a((p \sin \theta)/(1 + b(p \sin \theta)^2 + c(p \sin \theta)^4) + d)$$

They made no attempt to find an energy dependent fit.

Although a number of functions were tried, no simpler function was found for the lower energy data. The data above 450 MeV was described by the function

$$A = \frac{a(p \sin \theta)}{1 + b(p \sin \theta)^2 + c(p \sin \theta)^4} + d(\sin(5\theta))$$

where p and θ have the same meanings as before. This function fit the SIN data as well as their function, and gives a better fit at smaller angles, since the SIN function did not go to zero at 0° , which the analyzing power must do. A polynomial fit was again used to describe the energy dependence of the parameters. The $\sin(5\theta)$ term was chosen simply because it fit the data well, although it should be noted that this function has a peak at 18° and a zero at 36° , while the elastic p-p analyzing power peaks at 17° and has a zero at 40° (laboratory scattering angles). This close similarity may indicate that the larger angle analyzing power in p-C scattering is primarily quasi-free scattering.

Two fits were done, one for energies less than 500 MeV and one for energies greater than 400 MeV. An attempt was made to fit all

energies, but the polynomials needed to describe the entire range were unwieldy (over 20 coefficients were needed).

Bevington's CURFIT routine was used to fit the parameters. The method was as follows. First, single energy fits were done for each data set. The first parameter, a , was then fit with a polynomial. Single energy fits were again found, using this fitted value of a . A second parameter was fit, and these values substituted in for the next set, and so on, until all parameters were fit. The procedure was then repeated, allowing only one parameter at a time to vary until no significant improvement of the fit was obtained. This rather tedious procedure was needed because of the high correlation between coefficients (both at single energies and in the energy dependent coefficients). CURFIT relies on parameters being relatively independent, such that when one is varied until a χ^2 minimum is achieved, the observed minimum is near the true minimum for that parameter, regardless of what test values are used for the other parameters. This is not true for a polynomial fit of this sort.

Final fits were achieved using the following functions

100 to 500 MeV

$$a = a_0 + a_1 r + a_2 r^2 + a_3 r^3$$

$$b = b_0 + b_1 r + b_2 r^2 + b_3 r^3$$

$$c = c_0 + c_1 r + c_2 r^3 + c_3 r^3$$

400 to 800 MeV

$$a = a_0 + a_1 r + a_2 r^2 + a_3 r^3$$

$$b = b_0 + b_1 r + b_2 r^2 + b_3 r^3$$

$$c = c_0 + c_1 r + c_2 r^3 + c_3 r^3$$

$$d = d_0 + d_1 r + d_2 r^2 + d_3 r^3$$

For the lower energy fit $r = (p-0.7)$ in GeV/c, and for the higher energy fit $r = (p-1.2)$ in GeV/c. The offsets were used simply to keep the numbers to a reasonable size (that is, to keep from adding and subtracting very large numbers to get a small number). The values for the coefficients and a comparison with the TRIUMF fit are given in Chap. 4, and in Tables 4-3,7.

G. Systematic Uncertainties

Any experiment has both systematic and statistical uncertainties. The experiment is designed to keep systematic errors to a minimum, with the general guide of keeping the estimated systematic uncertainty less than the combined statistical uncertainty. Discussed below are sources of systematic uncertainty in this experiment and their estimated contribution to the total uncertainty. These are listed in Table 3-4.

1. Instrumental Asymmetries in the Polarimeter

Although the techniques described above for extracting asymmetries from the polarimeter should eliminate instrumental asymmetries, at least to first order, it is desirable to know at what level these exist. This can be checked by combining two spin states

Table 3-4

Experimental Uncertainties

Polarimeter	
A _c in Carbon	2.5%
Neutron Polarization	
Transfer	5.0%
Proton Pol.	3.0%
Solenoid Setting	2.0%
Total	6.1%
Deuteron Cont.	1.0%
Target Background	<1.0%
Precession Setting	<1.0%
Non-vert. H ₃ Field	<1.0%
Wire Spacing	<1.0%

Total relative uncertainty 6.7%

Error due to spin state normalization

±.02 (for transfer parameters

±.08 (for analyzing power

to give a net unpolarized beam and determining the coefficients for $\sin(\phi)$, $\cos(\phi)$ and higher order terms. This was done for both the zero degree data and for the spin transfer data. Results are presented in App. E. The only significant asymmetry is in $\cos\phi$ for the 5° bin in the spin transfer experiment. This was found to be caused by an inefficiency at one edge of the polarimeter due to TDCs for the delay line cutting off signals with very long times. Since alternating beam polarizations should cancel this, it is not felt to be a problem. Significant instrumental asymmetries exist for events with θ less than 4° due to the fast-clear. Since the analyzing power decreases rapidly in this region, events with θ less than 4° can be rejected without significantly increasing the statistical uncertainty of the measurement. Fig. 3-16 shows the θ distribution for events which would have been rejected by the fast clear.

One additional instrumental asymmetry may be present for the events which pass neither the cone test nor the $\phi + \pi$ test. This comes from the uncertainty in the normalization of the two spin states, which is needed to cancel instrumental asymmetries. It is only important for the angular bins near the edge of the polarimeter, where the events failing the cone and $\phi + \pi$ tests make up a significant percentage of the total. The normalization of the two spin states is believed to be accurate at the .5% level. This will lead to an uncertainty in the measured asymmetry of about .0025 for 1° and 5° bins (in the n-p spin transfer experiment), giving an uncertainty in the calculated transfer parameters of about $\pm .02$.

Figure 3-16 Theta spectrum of events rejected by the fast clear.

2. Spectrometer Instrumental Asymmetries

There may be instrumental asymmetries in the spectrometer which would affect the np analyzing power measurement. Fortunately, this can be checked by using different initial beam orientations. For example, longitudinal and sideways polarizations should show no left-right asymmetry. Within statistics, all asymmetries were found consistent with zero. Table 3-5 lists the analyzing powers calculated from the sideways and longitudinal orientations. The average of all ν bins does show a small ($-.007 \pm .003$) but definite bias which could be caused by a normalization error between the two spin states of about .5%.

3. Deuteron Contamination

It is possible to create deuterons through the reaction $np \rightarrow d\pi^0$ which have the same scattering angle and momentum as the protons in the high energy peak. These can usually be eliminated by time of flight cuts. However, an error in the experimental setup rendered the time of flight information taken useless. This error was not discovered until nearly the end of the experiment. Analysis of the last few runs in which the information was good indicate that deuteron contamination is about 1%. This contamination should dilute the measured polarization by that amount, which is negligible compared to the statistical errors of the experiment.

4. Precession Magnets

As stated in Chap. 2, the precession magnets orient the neutron polarization to within about 4° of the desired value. Since

Table 3-5

Instrumental Asymmetries in A_N Measurement

θ_H Bin	Analyzing Power
5.5	$-.003 \pm .010$
4.5	$-.003 \pm .008$
3.5	$-.002 \pm .007$
2.5	$-.013 \pm .007$
1.5	$-.010 \pm .006$
.65	$-.005 \pm .008$
Avg.	$-.007 \pm .003$

$\cos(4^\circ) = .997$, this is unimportant for the polarization in the desired direction. However, $\sin(4^\circ) = .070$, giving a significant polarization in a perpendicular direction. If the transfer for that direction is small, this will have no effect on the measured values. If it is large and the transfer in the direction being measured is small, it may be important. At larger angles all transfer coefficients are comparable, so this uncertainty should have no more than a few percent effect. However, at small angles K_{NN} and K_{SS} are small and K_{LL} is large. Since the spectrometer magnet precesses longitudinal beam into sideways, this uncertainty could have a several percent effect on the measurement of K_{SS} . For this reason, M2 was left on during the runs when the neutron polarization was sideways. Any residual longitudinal polarization would be transformed into vertical polarization. The transfer for vertical polarization is small, so there should be only a very small effect on the final values. This uncertainty should then be no more than a 1% effect in any angular bin.

5. Neutron Polarization

Several things contribute to the uncertainty in the neutron polarization. Among these are uncertainty in the $pd \rightarrow npp$ transfer, uncertainty in beam line polarimeter analyzing power, and uncertainties in the solenoid setting and proton polarization orientation. Most important of these are the analyzing power (about 1.5%) and the polarization transfer (about 5%). Since only 60% of the proton polarization is measured, the analyzing power uncertainty is

effectively 3%. The proton polarization is known to wander about the vertical direction to within about 4° . This and the uncertainty in the solenoid setting contribute another 2% to the uncertainty. Measurements were taken with the solenoid off to assure the proton polarization was within 4° of vertical, and measurements of the left-right asymmetry with the solenoid on determined the solenoid setting was within 4° of the proper value.

6. Spectrometer Magnet

One assumption made in the spin precession calculations of the recoil protons was that the magnetic field was only vertical. Bjork reported measurements of the magnetic field for this magnet. He found the horizontal field components in the fringe field had a maximum of 10% the intensity of the vertical field. Since the path length is no more than 10% of that through the vertical field section (the non-vertical fields are only at the edges), the total $\int B dl$ is only 1% or less of the main field. Also, these fields are in opposite directions at each end of the magnet, so they should tend to cancel out. Since the full field only precesses the protons 90° (69° net precession plus 21° bend), the precession due to these fringe fields is less than 1° , a negligible amount.

7. MWPC Wire Spacing

The front wire planes of the spectrometer are used to determine the ϕ value of the scatter. Since they have a 2 mm spacing, there is some uncertainty in ϕ . If ϕ were completely undetermined, for example, no asymmetry would be measured. The uncertainty is

largest near zero degrees. Monte Carlo simulations indicate the uncertainty is only important for events scattering less than about $.3^\circ$. Since the solid angle in this region is very small, these comprise only about 5% of the events in the $0-1^\circ$ bin, and would serve to dilute the measurement slightly. This is estimated to be no more than a 1% effect in the $0-2^\circ$ bin.

8. Carbon Analyzing Power.

The energy dependent fit described in the previous section was used to determine the analyzing power. This indicates the uncertainty in the analyzing power is about 2.5%. This includes a normalization uncertainty of about 1.5% and a statistical uncertainty of about 2.0%, for the 800 MeV measurements.

9. Background

One run was taken with no liquid hydrogen in the target. The rate for this situation was about 4% the target full rate. Calculations of the gas density and hydrogen in the target indicate about half this rate can be attributed to hydrogen, leaving a non-hydrogen background of 2%. Since this is primarily quasi-elastic scattering, the transfers are expected to be similar to the free transfers (the deuterium and beryllium quasi-elastic values are close to the measured elastic scattering values). The background is then estimated to change the final polarization less than 1%.

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CHAPTER FOUR-POLARIMETER CALIBRATION RESULTS

A. Carbon and Beryllium Analyzing Power

Results of the carbon analyzing power measurement are given in Table 4-1 and those of the beryllium analyzing power in Table 4-2. Only statistical uncertainties are given.

Measurements of the beryllium analyzing power were done because earlier work by Chamberlain¹ at 310 MeV indicated that beryllium might have a significantly higher analyzing power than that of carbon. The beryllium analyzing power at 780 MeV is shown in Fig. 4-1, along with the fit to the 750 MeV carbon data. Although the beryllium does seem to have a slightly higher analyzing power, it does not appear to be substantial enough to warrant the use of beryllium as an analyzer, considering the much greater cost and danger associated with it. The weighted average of the Be data is $.212 \pm .009$, compared with a value of $.197 \pm .004$ for the 750 MeV carbon data, only about a 7% difference.

Figs. 4-2,37 show all of the carbon analyzing power data reported in this work, the TRIUMF², SIN³, and other LAMPF⁴ data, along with the energy dependent fit to the data. Figs. 4-2,14 have the high energy (400-750 MeV) fit and Figs. 4-15,37 have the low energy (100-500 MeV) fit. Table 4-3 lists where each set was measured and Table 4-7 the coefficients for the fits.

At several energies two or three measurements were made within 50 MeV/c of each other. Figs. 4-38,45 show the data taken at comparable energies plotted on the same graph. Despite the fact that four different polarimeters were used and different methods were used to measure the analyzing power, all of the data agree within statistical uncertainties (generally of 1-4%).

Tables 4-4 and 4-5 give comparisons of the fits and data. The weighted average of the fit is obtained by replacing the measured value of each point with the fit value, and weighting with the statistical uncertainty of the data point. Table 4-6 lists the same values for the TRIUMF² fit to the data between 100 and 500 MeV. Table 4-8 lists the estimated error on the fit as a function of energy. The errors include a 1.5% normalization error for all energies, and a statistical error obtained by averaging data within a 100 MeV/c range. The percent error is the uncertainty at each energy divided by the average analyzing power at each energy.

Several features are apparent from these tables. First, the analyzing power appears to vary smoothly with energy. There is a gradual change in shape beginning around 450 MeV, with the analyzing power at larger angles becoming larger relative to the analyzing power at small angles. Because of this change in shape, two different functions were needed to fit the lower and high energy data. Only a few energies seemed to be inconsistent with a smooth fit, most notably the larger angle values for the TRIUMF 450 MeV (1024 MeV/c) data. In addition, the TRIUMF data at both 179 and 210 MeV (607 and 662 MeV/c)

have a data point at about .3 radian which is about 3 standard deviations away from the fit value. Other energies do not show any indication of a spike in this range, and it can probably be assumed the points are incorrect. Although they do not change the fit significantly, these points increase the total χ^2 substantially for these energies.

Although the TRIUMF fit does give a lower total χ^2 for their data than the fit reported here, it is substantially worse for the SIN data. For example, at 926 MeV/c, the TRIUMF fit to the data gives a total χ^2 of 102, while our fit gives only 35.8. For most energies, the differences in the two fits are not as dramatic, and in fact give essentially the same average analyzing power.

B. Polarimeter

Most of the results of tests on the recoil polarimeter are discussed in Chap. 3 and App. E. Those results are reviewed and some additional comments on the polarimeter efficiency are given here.

Instrumental asymmetries were found to be negligible, with the exception of a $\cos\phi$ term for events scattering near one edge (see Table E-1, -5° bin). This was determined to be due to use of TDCs whose range was marginally under that needed, making the wires toward one edge inefficient.

A system for resolving the inherent left-right ambiguity present in drift chambers was successfully used. The system has a failure rate of 1% or less per plane.

A hardware system was developed to reject small angle scatters in the carbon. This system allowed partial rejection of events scattering less than 4° lab, without affecting events with larger scattering angles. The system increased the percentage of good events with scatters greater than 4° written to tape from 20% to 33%. The percentage of events cleared varies with angle. Roughly 60% of the good events with scatters less than 2° are cleared, but only 20% of those scattering between 2° and 3° are cleared. The percentages given here are obtained by examining the theta distributions of all events, those that would have been cleared, and of those that would not have been cleared, after events with bad checksums and bad residuals were eliminated.

The total efficiency of the polarimeter (percentage of total events which are usable) is about 15% (depending on the energy). About 4% of the events are lost per plane. For 12 planes, the total loss is about 50% of the events. Of these, only ~30% scatter usefully (with the clear system in use). For the n-p spin transfer experiment, only about 30% of the events are in the high energy peak, giving a net efficiency of about 5%.

Figs. 4-46 and 4-47 show plots of A^2I , the quality factor, for the 750 MeV and 550 MeV data. Both peak at around 7° lab, with a very quick drop off for both larger and smaller angles.

C. Summary

The carbon analyzing power for protons between 530 and 750 has been measured between 3° and 30° laboratory angle. The values are in

good agreement with other measurements. The beryllium analyzing power was measured at 780 MeV and found to be within 20% of the carbon analyzing power.

A large solid angle polarimeter is described. The polarimeter was found to have negligible instrumental asymmetries and an efficiency of about 15% for 800 MeV protons. The polarimeter uses large (60 cm square) drift chambers. A system for resolving the left-right ambiguity of the drift chambers by use of induced pulses on cathode wires was successfully used.

Table 4-1

Carbon Analyzing Power A_c

T-Lab	800		750		650		580		550	
P	1404		1340		1209		1154		1117	
θ lab	A_c	err	A_c	err	A_c	err	A_c	err	A_c	err
2.9	.111	.010	.112	.013	.081	.014	.144	.018	.057	.030
5.0	.197	.011	.215	.015	.248	.018	.261	.019	.289	.035
7.0	.248	.012	.242	.016	.308	.020	.353	.020	.359	.037
9.0	.242	.015	.264	.019	.328	.023	.353	.022	.339	.042
11.0	.241	.017	.253	.023	.234	.026	.277	.027	.329	.047
13.5	.234	.015	.214	.020	.240	.024	.208	.024	.214	.044
16.5	.218	.016	.239	.020	.212	.025	.212	.025	.245	.045
19.5	.206	.017	.209	.021	.208	.027	.245	.026	.186	.050
22.5	.216	.019	.173	.023	.199	.029	.147	.028	.241	.053
25.7	.194	.021	.159	.025	.128	.031	.151	.030	.160	.060
29.6	.112	.030	.058	.038	.037	.045	.108	.044	.106	.080
33.5	.084	.041								

T is incident energy of proton beam in MeV

P is the momentum at the center of the carbon in MeV/c

Table 4-2

Beryllium Analyzing Power - 780 MeV (1440 MeV/c)

θ lab	A_{Be}	err
2.9	.143	.024
5.0	.199	.024
7.0	.204	.027
9.0	.289	.030
11.0	.244	.033
13.5	.292	.028
16.5	.202	.031
19.5	.233	.033
22.7	.154	.034
27.0	.159	.063

Table 4-3

Sources of Carbon Analyzing Powers Used in Energy Dependent Fit

T	P	Source	T	P	Source
750	1404	LZ	707	1352	LM
697	1340	LZ	676	1314	LM
620	1244	LM	592	1209	LZ
582	1196	LM	561	1170	S
549	1154	LZ	520	1117	LZ
511	1105	LM	483	1068	S
450	1024	T	440	1010	LM
387	937	T	380	926	S
374	918	LH	357	893	T
319	837	T	310	824	LM
299	807	S	279	776	T
242	716	T	234	703	LM
210	662	T	179	607	T
161	573	LM	157	565	T
145	542	T	133	517	T
119	487	T	113	474	T
107	461	LM			

T and P are energy and momentum at carbon center in MeV and MeV/c

Key - LZ - LAMPF data reported in this work
 LM - LAMPF McNaughton
 LH - LAMPF HRS McClelland
 T - TRIUMF
 S - SIN

Table 4-4

Comparison of A_c Fit to Data 400-750 MeV

P	Pts	χ^2	WAP	δ	WAF	Δ
1404	12	6.7	.197	.004	.201	.004
1352	12	13.5	.231	.005	.223	-.008
1340	11	10.6	.198	.006	.206	.008
1314	12	14.3	.232	.005	.230	-.002
1244	12	17.4	.259	.006	.240	-.019
1209	11	26.8	.202	.007	.216	.014
1197	12	16.3	.266	.008	.250	-.016
1170	30	35.1	.261	.002	.266	.005
1154	11	10.4	.237	.007	.230	-.007
1117	11	14.7	.231	.013	.235	.004
1105	12	20.0	.290	.010	.276	-.014
1068	30	21.8	.295	.004	.299	.004
1024	13	27.3	.286	.005	.272	-.014
937	13	8.4	.375	.005	.374	-.001

Key - WAP - weighted average of the data points
- δ - statistical uncertainty on weighted average
- WAF - weighted average of the fit
- Δ - WAF minus WAP

Table 4-5Comparison of A_c Fit to Data 100-500 MeV

P	Pts	χ^2	WAP	δ	WAF	Δ
1068	30	41.3	.295	.004	.301	.006
1024	13	25.8	.286	.005	.264	-.022
1010	12	14.7	.329	.019	.316	-.013
937	13	17.0	.375	.005	.360	-.015
926	30	35.8	.365	.003	.368	.003
918	12	32.7	.354	.004	.359	.005
893	13	27.5	.336	.005	.321	-.015
837	13	13.5	.368	.006	.374	.006
824	11	15.4	.371	.039	.432	.061
807	30	49.2	.450	.005	.470	.020
776	13	13.0	.448	.006	.446	-.002
716	13	13.5	.462	.006	.457	-.005
703	9	23.4	.468	.019	.506	.038
662	13	35.5	.489	.007	.470	-.019
607	11	23.0	.491	.010	.461	-.030
573	8	26.1	.455	.014	.437	-.018
565	11	5.58	.433	.013	.420	-.013
542	10	14.7	.409	.010	.406	-.003
517	11	1.91	.350	.106	.366	.016
487	10	28.1	.283	.010	.312	.029
474	9	10.6	.286	.020	.280	-.006
461	6	17.2	.199	.023	.261	.062

Table 4-6

Comparison of A_c Fit to Data 100-500 MeV
Triumf Fit

P	Pts	χ^2	WAP	δ	WAF	Δ
1068	30	123.6	.295	.004	.320	.025
1024	13	9.5	.286	.005	.287	.001
1010	12	14.5	.329	.019	.333	.004
937	13	32.9	.375	.005	.367	-.008
926	30	102.4	.365	.003	.378	.012
918	12	85.7	.354	.004	.368	.014
893	13	14.5	.336	.005	.330	-.006
837	13	11.8	.368	.006	.378	.010
824	11	15.5	.371	.039	.432	.061
807	30	53.8	.450	.005	.471	.021
776	13	12.5	.448	.006	.449	.001
716	13	12.3	.462	.006	.464	.002
703	9	26.8	.468	.019	.517	.049
662	13	29.7	.489	.007	.484	-.005
607	11	16.1	.491	.010	.478	-.013
573	8	27.8	.455	.014	.447	-.008
565	11	6.4	.433	.013	.431	-.002
542	10	13.1	.409	.010	.412	.003
517	11	2.7	.350	.016	.355	.005
487	10	20.2	.283	.010	.299	-.016
474	9	11.5	.286	.020	.262	-.024
461	6	12.0	.199	.023	.236	.037

Table 4-7

Coefficients for 400-750 MeV Fit

	0	1	2	3
a	1.5784	-1.9936	13.956	-106.95
b	-19.578	78.924	225.72	-2037.3
c	1105.9	-2674.0	-5704.3	48790.
d	.14397	-.076129	-.88023	7.8908

Coefficients for 100-500 MeV Fit

	0	1	2	3
a	5.4077	-3.0558	-23.434	68.809
b	-10.256	-67.242	598.35	-315.31
c	1025.5	618.73	-11421.	12747.

Table 4-8

Estimated Uncertainty in Analyzing Power Fit

P	%err	P	%err
1352.	1.9	1255.	2.0
1180.	1.7	1096.	1.9
1030.	1.8	920.	1.6
811.	1.7	690.	1.7
571.	2.0	484.	3.4

Figure 4-1 Beryllium analyzing power.

Figure 4-3

Figure 4-2

Figure 4-4

Figure 4-5

Figure 4-7

Figure 4-6

Figure 4-8

Figure 4-9

Figure 4-10

Figure 4-11

Figure 4-12

Figure 4-13

Figure 4-15

Figure 4-14

Figure 4-17

Figure 4-16

Figure 4-18

Figure 4-19

Figure 4-21

Figure 4-22

Figure 4-20

Figure 4-23

Figure 4-25

Figure 4-26

Figure 4-24

Figure 4-27

Figure 4-29

Figure 4-30

Figure 4-28

Figure 4-31

Figure 4-33

Figure 4-34

Figure 4-32

Figure 4-35

Figure 4-37

Figure 4-36

Figure 4-38

Figure 4-39

Figure 4-40

Figure 4-41

Figure 4-42

Figure 4-43

Figure 4-44

Figure 4-45

Figure 4-46 A^2I for p-C at 1403 MeV/c.

Figure 4-47 A^2I for p-C at 1154 MeV/c.

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CHAPTER FIVE-SPIN TRANSFER RESULTS AND CONCLUSIONS

A. n-p Analyzing Power

The measured np analyzing power is given in Table 5-1. Fig. 5-1 shows the data, along with the data from Newsom¹ at 780 MeV, and that of Hollas² at 790 MeV. The solid line is the Arndt³ phase shift prediction, which does include this set of data. The data are in substantial agreement with both the phase shift prediction and the trend of the previous data. A comparison of this data with the predictions of Chia are shown in Fig. 5-6, with the discussion in the next section.

B. Spin Transfer Parameters

1. Results

Results of the spin transfer measurements are given in Table 5-2, and shown in Figs. 5-2,5. Two of the parameters, K_{NN} and K_{SS} , were calculated in two ways. First, making no assumptions about K_{SL} and solving the coupled equations for all three parameters (see Chap. 3). Second, using the phase shift values for K_{SL} and solving the equations for the two remaining parameters. Both results, along with those for K_{SL} from the first method, are given in Table 5-2.

The 180° values for K_{NN} and K_{LL} are also given in Table 5-2. Since K_{NN} and K_{SS} are required to be equal at 180° by rotational invariance, the two parameters can be combined to estimate the 180° value. Since both parameters have slopes of nearly the same magnitude

Table 5-1

Free n-p Analyzing power

θ lab	θ c.m.	$-u$ (GeV/c) ²	A_N	err
5.5	166.9	.0194	-.040	.009
4.5	169.3	.0130	-.035	.009
3.5	171.7	.00790	-.031	.008
2.5	174.0	.00404	-.023	.007
1.5	176.4	.00146	-.010	.006
.66	178.4	.00027	-.010	.008

Table 5-2

Free np Spin Transfer Parameters - Without Phase Shift Input

θ c.m.	K_{NN}	K_{SS}	K_{SL}
168.3	$.645 \pm .094$	$-.558 \pm .232$	$.028 \pm .210$
173.1	$.358 \pm .083$	$-.471 \pm .130$	$.040 \pm .125$
177.1	$-.011 \pm .075$	$-.136 \pm .076$	$.046 \pm .077$
180.0	$-.074 \pm .053$		
(extrapolated values)			

Free np Spin Transfer Parameters - Phase Shift Input

θ c.m.	K_{NN}	K_{SS}	K_{LL}	K_{SL}	K_{LS}
168.3	$.653 \pm .091$	$-.610 \pm .123$	$-.452 \pm .195$	$.102$	$-.076$
173.1	$.356 \pm .076$	$-.535 \pm .088$	$-.579 \pm .145$	$.041$	$-.045$
177.1	$-.001 \pm .067$	$-.147 \pm .065$	$-.647 \pm .114$	$.009$	$-.020$
180.0	$-.074 \pm .046$		$-.696 \pm .090$		
(extrapolated values)					

K_{SL} and K_{LS} values are Arndt phase shift solution Si-81 values

θ_{lab}	θ c.m.	$-u$ GeV/c ²
4.9	168.3	.0155
2.9	173.1	.0543
1.2	177.1	.000931

Figure 5-1 n-p analyzing power, with phase shift prediction and larger angle data.

Figure 5-2 K_{NN} with Arndt phase shift solutions before (CK80) and after (SM81) inclusion of this data.

Figure 5-3 K_{SS} with Arndt phase shift solutions before and after inclusion of this data.

Figure 5-4 K_{SL} with Arndt phase shift solutions
before and after inclusion of this data.

Figure 5-5 K_{LL} with Arndt phase shift solutions
before and after inclusion of this data.

but with opposite sign near 180° , the two smallest angular bins were just averaged to get the 180° value. The 180° estimate for K_{LL} was obtained from a linear extrapolation of the last two data points.

Figs. 5-2,5 show the phase shift predictions of Arndt before this data was included (CK80) and after inclusion of this data (SM81). Although there is some disagreement, the general trend of the data is predicted fairly well. The major disagreement is near 180° , where the phase shifts predict K_{NN} to be about positive .1 (CK80) and .03 (CM81), while our data indicates a slightly (about $-.07$) negative value.

2. Comparison With Other Data

At this time, there is very little data in this region with which a comparison can be made. The only other free measurements at any energy in this angular region are those of Leung, Surko, and Woolverton (see Chap. 1). The Surko measurements (at 520 and 600 MeV) have such a large errors that a comparison is meaningless. The Leung measurements (also at 520 and 600 MeV) are of comparable statistical uncertainty and have both the same sign and magnitude as the present measurement. The overall accuracy of both the Leung and Surko measurements is poor. The 180° value is obtained by averaging over 10° range in the center of mass, in contrast to this experiment which averaged over only 4° center of mass. Although both measurements were taken using a dipole magnet between the LH_2 target and the polarimeter, no mention is made in either thesis of corrections for mixing of the parameters, as is discussed in App. C.

The true average angle of the measurement is not given, in contrast to this experiment. Finally, the Wolverton measurement of K_{NN} at 50 MeV also agrees with our measurement in both sign and approximate magnitude.

Measurements of K_{LL} and K_{NN} for the $pd+npp$ reaction were made at 800 Mev (see discussion of this in Chaps. 1 and 2). Although these can not be compared directly to the free parameters because of the final state interaction, there is again basic agreement with these measurements. A comparison relies on using the phase shifts for the free elastic scattering matrix to determine the quasi-elastic values. The phase shift predictions from Arndt's SM-81 solution can be used in conjunction with the formulas given in Chap. 1 to calculate the quasi-elastic values of K_{NN} and K_{LL} . This give values of $-.10$ for K_{NN} and $-.80$ for K_{LL} , compared to the measured values of $-.15$ and $-.64$, with uncertainties of $.03$. Since the phase shifts do not give predictions of the free values accurate at the $.03$ level, it is not too surprising that they do not give very good predictions of the quasi-elastic values. If more accurate phase shift solutions for the free case continue to give incorrect values for the quasi-elastic case, the assumption that the remaining protons are left in a 1S_0 final state a majority of the time must be questioned. If the amplitude analysis presented in Chap. 1 does accurately describe the quasi-elastic case, one thing is clear, that if the double spin-flip helicity amplitude M_2 dominates the scattering, both the free and quasi-elastic scattering will have K_{NN} values which are relatively

small and K_{LL} values which are both large (magnitude near 1) and negative. This is the case for the measured values. The possible significance of this is discussed in the next section.

3. Regge Analysis

Since various Regge analyses at energies greater than 2 GeV give a moderately good description of n-p CEX scattering cross sections and the shape of the cross section as a function of t persists into the medium energy range, it is worth considering the model predictions spin transfer observables.

Two models are considered here, Chia's pion-pomeron cut model, and Gotsman and Maor's modified "poor man's absorption" (PMA) model. Both models considered np CEX scattering at 10 GeV/c, with extensions to slightly higher and lower energies. Both models give essentially the same prediction. At $t=0$, the double flip helicity amplitude M_2 accounts for nearly 100% of the cross section. As t increases, the pion pole, which contributes equally to M_2 and M_4 , increases rapidly. Since both the cut and absorption models give contributions to M_2 which are 180° out of phase with the pion contribution, the magnitude of M_2 decreases rapidly. When t becomes roughly equal to the mass of the pion squared (about $.02 \text{ GeV}^2$), the pion contribution becomes roughly constant. The interference between the pion and background give the observed sharp peak in the cross section.

Both the cut and PMA models predict this interference behaviour, with M_2 and M_4 being the dominant amplitudes. As can be seen from Table 1-2, this behaviour will give rather dramatic changes

Figure 5-6 A_N with predictions by Arndt and Chia

Figure 5-7 K_{NN} and K_{SS} with predictions by Arndt and Chia

Figure 5-8 K_{SL} , K_{LS} predictions of Arndt and Chia
and K_{LL} with predictions of Arndt and Chia

Figure 5-9 Cross Section at 770 MeV with predictions of
Chia (normalized), and Arndt (unnormalized)

in the transfer parameters K_{NN} and K_{SS} , while K_{LL} will remain nearly constant (caution: as mentioned in Chap. 1, the amplitudes being used here are for the case in which the CEX region is considered to be small angle scattering. The formulas for K_{NN} , K_{SS} , etc., are then those listed in Table 1-2 as D_{NN} , D_{SS} , etc.).

Calculations of the spin parameters and differential cross section were made using Chia's model. Using the model exactly as given predicts a cross section at 800 MeV which is about a factor of two too large. To correct for this, all cut contributions were multiplied by a constant factor, such that the predicted and actual cross sections agree at $t = 0$. The other parameters were calculated using this normalization. No correction was made to the pion pole contribution. Use of this factor does not affect the shape of the cross section a significant amount, nor does it have much of an effect on the magnitudes or shapes of the spin transfer parameters.

Figs. 5-6,9 show the prediction's of Chia's model (with the modification given above) at 800 MeV for the various spin parameters and the cross section, along with the phase shift predictions of Arndt which include this data. Several features are immediately apparent. The model gives the correct sign and general shape for all parameters. The polarization is too low (a fault even at 10 GeV/c as noted by Chia), and K_{LL} is too negative (essentially -1 for the entire range shown). Since both of these involve M_1 , M_3 , and M_5 , to which the cut contributes little, the discrepancy is not surprising. If M_1 and M_3

were essentially constant and accounted for about 15% of the cross section, a much better fit to K_{LL} would result.

Gotsman and Maor's calculation give essentially the same results as Chia's. The energy dependence in their model is not as great as Chia's, so they come closer to the measured cross section at 800 MeV than does Chia. Their predictions for the spin transfer parameters give essentially the same results as Chia.

Since the same cross section shape as a function of t persists down to around 200 MeV, and the phase shift solution gives qualitatively good results even at 800 MeV, it is worth examining the helicity amplitude structure as a function of energy. Arndt's energy dependent solution SM-81 was used to calculate the helicity amplitudes between 200 and 800 MeV. Fig. 5-10 shows the behaviour of each helicity amplitude as a function of energy. The values plotted are the differences in magnitude between $t=0$ and $t=-.02 \text{ GeV}/c^2$, divided by the $t=0$ differential cross section. Fig. 5-11 shows the same data along with the 10 GeV/c Chia predictions. These plots demonstrate that the peak in the $t=0$ region is due to variations in the same amplitudes at all energies between 200 MeV and (at least) 10 GeV. M_4 , which should be dominated by the pion pole shows very little energy dependence, as predicted by the Regge description.

This energy independence appears to raise serious questions about both the cut and PMA models. In the PMA model, the background is explained physically as an absorption of low partial waves into inelastic channels. Since the inelastic cross section below 300 MeV

Figure 5-10 Helicity amplitude structure .2-.8 GeV.

Figure 5-11 Helicity amplitude structure .2-10 GeV.

is negligible, this explanation can not be used at lower energies. The cut model explains the background as a Pomeron-pion combination exchange. Since the Pomeron was originally devised to explain diffraction scattering, its properties below pion threshold are rather uncertain. The data and phase shift analysis do give a strong indication that whatever mechanism is responsible for the behavior in the CEX region, it extends from well below threshold to many GeV.

Although the nature of the background is still uncertain, the Regge models do give an explanation for the shape of the cross section and a reason why the double exponential form fits the cross section over such a large range. The pion contributes to M_2 and M_4 equally and is proportional to

$$M_2 = M_4 \propto \frac{t}{t - m_\pi^2}$$

while the background term is essentially constant. If the background value is set to $-K$, where K is positive, the cross section is proportional to $M_2^2 + M_4^2$, giving a cross section of the form

$$\frac{d\sigma}{dt} = K^2 - 2K\alpha \frac{t}{t - m_\pi^2} + 2\alpha^2 \frac{t^2}{(t - m_\pi^2)^2}$$

where α is a constant. When t is much less than $.02 (m_\pi^2)$, the cross section is dropping linearly with t . As t becomes greater than $.02$,

the drop still continues, but much more slowly. The double exponential form

$$\frac{d\sigma}{dt} = \alpha_1 \exp(\beta_1 t) + \alpha_2 \exp(\beta_2 t)$$

with α 's and β 's greater than 0 and t less than 0 has the same properties for a very large (compared to .02) value of β_1 and a somewhat smaller value of β_2 . The initial drop is given by the first exponential, which becomes negligible after $t=.02$, while the leveling off is given by the second exponential. The initial slope is given by $(\alpha_1 \beta_1 + \alpha_2 \beta_2)$ in the exponential form, and by $2K\alpha/m_\pi^2$ in the Regge pion model. If K is determined from the $t=0$ cross section at 770 MeV, the two values are 6263 and 6500, respectively. The value of α is determined from the known pion-nucleon coupling constant.

The energy dependence of the pion contribution is given by $(s/s_0)^{\alpha_\pi}$, where α_π is $(t-m_\pi^2)$. Since the exponent is near zero, there is very weak s dependence. s_0 is usually taken to be 1 GeV².

The weak energy dependence of the amplitudes indicates that the method for producing a polarized neutron beam used in this experiment (the $pd \rightarrow npp$) should work equally well for both lower energies (to 500 MeV or below) and higher energies (at least to 10 GeV, probably to 60 GeV or more), although decreasing cross sections at higher energies may give unacceptably low neutron beam intensities.

C. Summary and Conclusions

The analyzing power and the spin transfer parameters K_{NN} , K_{SS} , K_{LL} , and K_{SL} for n-p elastic scattering were measured. The values are in basic agreement with pre-existing phase shift solutions. Two Regge models describing data at 10 GeV/c were found to give substantially the same amplitude structure as that found at 800 MeV. Although both models give a good phenomenological description of the data, their physical interpretation is uncertain, since the same basic amplitude structure persists to energies below pion production threshold. The amplitude structure does support models in which the peak is given by the interference of one pion exchange with a roughly constant background. The nature of the background term is still unknown.

The free transfer parameters K_{NN} and K_{LL} were compared to quasi-elastic values. The two values are in good qualitative agreement, although the uncertainties on the free values are large compared to the quasi-elastic values. The phase shift solutions are not yet precise enough to allow accurate predictions of the quasi-elastic values from free values. The importance of the final state interaction in the quasi-elastic reaction is still uncertain.

The above remarks indicate that some questions still remain, in particular, the nature of the background in the Regge models and the importance of the final state interaction in the quasi-elastic reaction. What can be done experimentally to clarify either of these questions? Since Regge models already give a reasonable description of the data in np CEX scattering, it is not clear that more precise

data regarding this reaction will help. More theoretical work is needed to explain the persistence of the same amplitude structure over such a large energy range. In the case of the quasi-elastic reaction, a more accurate phase shift solution is needed. A complete understanding of the amplitude structure in this region will probably require some spin correlation experiments, such as A_{NN} and A_{LL} , to be done.

References - Chap. 5

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solutions are used in this work; CK80, SM81, and
C750. The first two are energy dependent solutions,
before and after inclusion of this data, C750 is
a single energy solution, which does include this
data. Solutions may be obtained through R. A. Arndt,
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Appendix A

Calculations of the scattering angle, distance of closest approach, and location of the point of closest approach are important in this sort of experiment. Although there is no great conceptual difficulty in calculating these quantities, there is enough tedious algebra to cause confusion. As an aid to others involved in this area, a review of the derivation of these quantities is given here.

The basic information available is the slope and intercept of the initial and final rays as projected onto the $x-z$ and $y-z$ planes, where the z axis is along the polarimeter, x is perpendicular to it and horizontal, and y is vertical (Fig. A-1). This gives four equations,

$$\begin{aligned} 1) \quad X_i &= A_{xi}Z + B_{xi} & X_f &= A_{xf}Z + B_{xf} \\ Y_i &= A_{yi}Z + B_{yi} & Y_f &= A_{yf}Z + B_{yf}, \end{aligned}$$

with the "A"s and "B"s being the slopes and intercepts. The rays may be written as vectors

$$\vec{i} = (A_{xi}, A_{yi}, 1) \quad \vec{f} = (A_{xf}, A_{yf}, 1).$$

The shortest segment connecting these rays will be one perpendicular to both and therefore parallel to their cross product. Call the end

points of this segment (x_i, y_i, z_i) and (x_f, y_f, z_f) . This gives the equation

$$\begin{aligned} 2) \quad (x_f - x_i, y_f - y_i, z_f - z_i) &= t(\vec{i} \times \vec{f}) \\ &= t((A_{y_i} - A_{y_f}), (A_{x_f} - A_{x_i}), (A_{x_i}A_{y_f} - A_{y_i}A_{x_f})) \end{aligned}$$

Using equations 1 and 2 then gives

$$\begin{aligned} x_f &= A_{x_i}z_i + B_{x_i} + t(A_{y_i} - A_{y_f}) \\ y_f &= A_{y_i}z_i + B_{y_i} + t(A_{x_f} - A_{x_i}) \end{aligned}$$

and

$$\begin{aligned} x_f &= A_{x_f}(z_i + t(A_{x_i}A_{y_f} - A_{y_i}A_{x_f})) + B_{x_f} \\ y_f &= A_{y_f}(z_i + t(A_{x_i}A_{y_f} - A_{y_i}A_{x_f})) + B_{y_f} \end{aligned}$$

Equating the two values of x_f and y_f leaves two equations and two unknowns, t and z_i . Solving for z_i gives

$$z_i = (CD - BE) / (C^2 - AB)$$

where

$$\begin{aligned} A &= \vec{i} \cdot \vec{i} = A_{x_i}^2 + A_{y_i}^2 + 1 \\ B &= \vec{f} \cdot \vec{f} = A_{x_f}^2 + A_{y_f}^2 + 1 \\ C &= \vec{i} \cdot \vec{f} = A_{x_i}A_{x_f} + A_{y_i}A_{y_f} + 1 \end{aligned}$$

$$D = A_{xf}(B_{xf} - B_{xi}) + A_{yf}(B_{yf} - B_{yi})$$

$$E = A_{xi}(B_{xf} - B_{xi}) + A_{yi}(B_{yf} - B_{yi})$$

Similiarly, $zf = (AD - CE)/(C^2 - AB)$. With zf and zi known, the location of the point of closest approach and the separation at that point can be found. Thus

$$x_{close} = (SA_{xi} + B_{xi} + TA_{xf} + B_{xf})/2$$

$$y_{close} = (SA_{yi} + B_{yi} + TA_{yf} + B_{yf})/2$$

$$z_{close} = (S + T)/2$$

$$d_{close} = (DX^2 + DY^2 + DZ^2)^{.5}$$

where

$$S = \frac{CD - BE}{C^2 - AB} = zi \quad T = \frac{AD - CE}{C^2 - AB} = zf$$

and

$$DX = B_{xi} - B_{xf} + SA_{xi} - TA_{xf}$$

$$DY = B_{yi} - B_{yf} + SA_{yi} - TA_{yf}$$

$$DZ = S - T.$$

The scattering angle is easily found from the relation

$$\vec{i} \cdot \vec{f} = |i| |f| \cos(\theta) \quad \theta = \arccos(C/(AB)^{.5})$$

-

The azimuthal angle is slightly more complicated. As described in Chap. 3, the direction in which φ equals zero is arbitrary. Described herein is the derivation for φ in which the "z" axis is along the incoming ray and $\varphi = 0$ when the final ray is in the x-z plane and pointing toward positive values of x.

First, the coordinate system must be defined. The primed system will be the one in which φ is defined, the unprimed system the polarimeter frame. As already stated, $\vec{z}' \parallel \vec{i}$. $\vec{x}'$ is perpendicular to $\vec{z}'$ and $\vec{y}$, thus $\vec{x}' \cdot \vec{y} = 0$ and $\vec{x}' \cdot \vec{z}' = 0$. $\vec{y}'$ is perpendicular to $\vec{z}'$ and $\vec{x}'$, thus $\vec{z}' \times \vec{x}' = \vec{y}'$. The projection of $\vec{f}$ onto the x'-y' plane determines φ :

$$\vec{x}' \cdot \vec{f} = \sin(\theta)\cos(\varphi) \text{ and } \vec{y}' \cdot \vec{f} = \sin(\theta)\sin(\varphi), \text{ implying}$$

$$\varphi = \arctan(\vec{y}' \cdot \vec{f} / \vec{x}' \cdot \vec{f}).$$

Given that

$$\vec{z}' = \left(\frac{A_{xi}}{\sqrt{A}}, \frac{A_{yi}}{\sqrt{A}}, \frac{1}{\sqrt{A}} \right) \text{ and}$$

$$\vec{f} = \left(\frac{A_{xf}}{\sqrt{B}}, \frac{A_{yf}}{\sqrt{B}}, \frac{1}{\sqrt{B}} \right),$$

the necessary dot products can be found, giving φ to be

$$\phi = \arctan\left(\frac{(A_{yf}(1 + A_{xi}^2) - A_{xi}A_{yi}A_{xf} - A_{yi})/\sqrt{A}}{A_{xf} - A_{xi}}\right)$$

One other calculation is needed for the $\phi + \pi$ test (see App. B), the slopes of a ray having the same scattering angle as f but with $\phi' = \phi + \pi$. This can be expressed by the two equations

$$\vec{A} \cdot \vec{i} = \vec{f} \cdot \vec{i} \quad \text{and} \quad \vec{A} \times \vec{i} = -(\vec{f} \times \vec{i})$$

where A is the alternate vector (A_x, A_y, A_z). The slopes needed are $A_{xa} = (A_x/A_z)$ and $A_{ya} = (A_y/A_z)$. Three equations may be derived from the above equalities:

$$A_{yi}A_z - A_y = A_{yf} - A_{yi}$$

$$A_x - A_{xi}A_z = A_{xi} - A_{xf}$$

$$A_{xf}A_x + A_{yi}A_y + A_z = A_{xi}A_{xf} + A_{yi}A_{yf} + 1$$

These may be solved simulataneously to give:

$$A_{xa} = (2A_{xi}(1 + A_{yfb}) + A_{xf}(A_{xsmys} - 1))/DEN$$

$$A_{ya} = (2A_{yi}(1 + A_{xfb}) + A_{yf}(A_{xsymys} + 1))/DEN$$

where

$$A_{yfb} = A_{yf}A_{yi}$$

$$A_{xfb} = A_{xf}A_{xi}$$

$$A_{xsmys} = A_{xi}^2 - A_{yi}^2$$

$$DEN = B - (A_{yi} - A_{yf})^2 - (A_{xi} - A_{xf})^2$$

The author would like to thank Steve Wood and Michael McNaughton who supplied these derivations.

Figure A-1 Polarimeter coordinate frame.

Appendix B

Extraction of the asymmetry from a set of events is the crucial operation for polarimeter experiments. The procedure for the case of two small counters 180° apart in ϕ is described in Chap. 3. Two other methods will be described in this appendix: fourier analysis, and the SIN "large acceptance" method.

Fourier series analysis is well known and has many applications. It is used only in its most straightforward form here. Events are scattered with a probability density given by

$$P(\phi) = g(\phi)(1 + \epsilon \cos(\phi) + \eta \sin(\phi))/2\pi$$

$g(\phi)$ is an efficiency function. In the simplest analysis $g(\phi)$ is a constant, G . Two integrals are needed to determine each coefficient. These are

$$I_1 = \frac{G\epsilon}{2\pi} = \frac{1}{\pi} \int P(\phi) \cos(\phi) d\phi$$

$$I_2 = \frac{G\eta}{2\pi} = \frac{1}{\pi} \int P(\phi) \sin(\phi) d\phi$$

$$I_3 = \frac{G}{2\pi} = \frac{1}{\pi} \int P(\phi) d\phi$$

thus

$$\epsilon = I_1/I_3 \quad \text{and} \quad \eta = I_2/I_3.$$

Coefficients of higher order terms ($\cos(2\phi)$, $\cos(3\phi)$, etc.) are found

by replacing $\cos(\phi)$ (or $\sin(\phi)$) with $\cos(n\phi)$ (or $\sin(n\phi)$), where n is the order. In the actual analysis the integrals are replaced by sums, thus

$$\epsilon = \frac{2\sum \cos(\phi)}{N} \qquad \eta = \frac{2\sum \sin(\phi)}{N}$$

where N is the number of events. The uncertainties on these estimators are given by

$$\sigma_{\epsilon} = ((2-\epsilon^2)/N)^{.5} \qquad \sigma_{\eta} = ((2-\eta^2)/N)^{.5}$$

If $g(\phi)$ is not constant, these estimators will be biased. If the deviation from constancy is small, as in the case of a slightly inefficient wire, for example, beam polarization can be reversed and the two states averaged. To first order, the bias will cancel. In a real experiment, however, we wish to use many events in which g varies greatly. For example, events scattering near the edge of the polarimeter will have $g(0) = 1$, while $g(\pi) = 0$. Depending on the location of the scatter and scattering angle, the events with $g = 0$ for part of their distribution will vary from none to almost all. Besset (see Chap. 3) has shown a method of using these events.

Besset's method assumes that $g(\phi) = g(\phi+\pi)$. It is easily shown that if this is true, the fourier integrals can be expressed in the following form

$$\int P(\phi) \cos(\phi) d\phi = \epsilon \int P(\phi) \cos^2(\phi) d\phi + \eta \int P(\phi) \sin(\phi) \cos(\phi) d\phi$$

$$\int P(\phi) \sin(\phi) d\phi = \eta \int P(\phi) \sin^2(\phi) d\phi + \epsilon \int P(\phi) \sin(\phi) \cos(\phi) d\phi$$

These integrals can be estimated with sums and expressed as two linear equations

$$\begin{pmatrix} \sum \cos \phi \\ \sum \sin \phi \end{pmatrix} = \begin{pmatrix} \sum \cos^2 \phi & \sum \sin \phi \cos \phi \\ \sum \sin \phi \cos \phi & \sum \sin^2 \phi \end{pmatrix} \begin{pmatrix} \epsilon \\ \eta \end{pmatrix}$$

which may be inverted to solve for ϵ and η . It is necessary to be sure that $g(\phi)$ has a symmetry period of 180° (that is, $g(\phi) = g(\phi + \pi)$). This can be done in two ways: require for each event scattering at angle ϕ that the angle $\phi + \pi$ is also within the spectrometer acceptance, or reverse the beam polarization with no acceptance requirement. The first method is straightforward. The $\phi + \pi$ test is made for each event by calculating the alternate slopes discussed in App. A, projecting to the back scintillator and rejecting the event if this projection falls outside the scintillator limits. If the test is passed, the appropriate values of $\cos(\phi)$, $\sin(\phi)$, etc. are summed. This is done for each spin state. After all events are analyzed the equations given above are solved for each spin state and the results averaged to get the final asymmetry. This method still rejects a fairly large percentage of events scattering near the edge of the analyzer.

If the spin states have a proper spin flip (polarization changes direction 180° but the magnitude remains constant) between them, it is possible to use all events. This is true regardless of the form of $g(\varphi)$. This is easily seen from the following equations. First, assume two spin states, N and K, have equal amounts of incident beam. The probability densities will be

$$P_N = g(\varphi)(1 + A\cos(\varphi) + B\sin(\varphi))/4\pi$$

$$P_R = g(\varphi)(1 - A\cos(\varphi) - B\sin(\varphi))/4\pi$$

There are no higher order terms than $\cos(\varphi)$ and $\sin(\varphi)$, since all instrumental asymmetries are accounted for with $g(\varphi)$. The normalization factor is 4π rather than 2π since each spin state is present only half the time. Now, if the φ value in the K state is shifted by π ($\varphi \rightarrow \varphi + \pi$), the probability density becomes

$$P_R = g(\varphi + \pi)(1 + A\cos\varphi + B\sin\varphi)/4\pi$$

since both cosine and sine reverse sign when the argument is changed by π . This is exactly the same as if all events were in the same initial state, but half had an efficiency function $g(\cdot)$ and the other $g'(\varphi) = g(\varphi + \pi)$. If these events are then combined, the total probability density is given by

$$G(\varphi)(1+A\cos(\varphi)+B\sin(\varphi))/2\pi$$

$$G(\varphi) = \frac{g(\varphi)+g'(\varphi)}{2}$$

Since G is symmetric in φ , the $\varphi+\pi$ condition is fulfilled. Of course, this will only be true if there is equal amount of beam incident on target from each state. This will usually be nearly true and if there is an independent monitor of beam intensity the two states can be normalized to correct for small differences.

Now consider the situation where there is not a proper spin flip between states. Although the incident beam is assumed to have a proper spin flip always, the scattered beam may not due to the analyzing power of the target. Polarization normal to the scattering plane is given by

$$P = \frac{A_N + K_{NN}\sigma_B \cos(\varphi)}{1 + A_N \sigma_B \cos(\varphi)}$$

where A_N is the analyzing power, σ_B the beam polarization, and φ the angle between the scattering plane and beam polarization. Clearly, changing the sign of σ_B will not change P to $-P$. If both A_N and σ_B are large, the difference may be quite large. Let us consider the case where the value of A_N is small, such that the product $P_N \sigma_B \cos \varphi$ is negligible compared to 1. The two probability distributions will then be

$$P_N = g(\varphi)(1 + A \cos \varphi + B \sin \varphi + A_N \cos \varphi) / 2\pi$$

$$P_R = g(\varphi)(1 - A \cos \varphi - B \sin \varphi + A_N \cos \varphi) / 2\pi$$

Performing the same trick as before of shifting φ by π and combining the two distributions gives

$$G(\varphi)(1 + A \cos \varphi + B \sin \varphi) / 2\pi + G'(\varphi)A_N \cos \varphi / 2\pi$$

where $G'(\varphi) = (g(\varphi) - g(\varphi + \pi)) / 2$. Since G' is antisymmetric in φ , the integrals of $G'(\varphi) \cos^2 \varphi$ and $G'(\varphi) \sin \varphi \cos \varphi$ will be zero, leaving the identical sums as for the proper spin flip case. The normalization in this case is slightly different than the previous case, since the amount of scattered beam is given by $I_s = I_o(1 + A_N \sigma_B \cos \varphi)$. Thus, even if the amount of incident beam is identical in each state, there will be different amounts of scattered beam. If the analyzing power is known corrections for this can be made.

In the n-p spin transfer experiment the above conditions were satisfied, since the maximum analyzing power is about .05 and the beam polarization is about .4. The product is at most .02, giving a 4% difference from a proper spin flip in A and A_N . This will average out for the cases where $g(\varphi) = g(\varphi + \pi)$, since one value will be high and the other low.

Appendix C

Since both neutrons and protons have a magnetic moment and this magnetic moment is on the same axis as the spin, it is possible to precess the spin in a magnetic field. A proton's momentum will also change direction in a magnetic field. These facts both make the spin transfer experiments possible and more complicated. Derivations of the equations needed to "untangle" spin precession effects will be given here.

Spin precession of relativistic particles is fully described by Bargmann¹ and Jackson². What follows is a summary of results.

First consider the neutron. This is the simpler case, since there is no change in the momentum as the particle traverses a magnetic field. The equation of motion for the spin in the rest frame of the neutron is given by

$$\frac{ds}{d\tau} = \frac{g\mu}{\hbar} \vec{s} \times \vec{B}$$

where g is the gyromagnetic ratio and μ is the nuclear magneton ($\mu = \hbar e/2m$). The angular change is given by $d\alpha = ds/s$. Substituting in the precession formula and using the relation between τ and t (lab time) of $\gamma\tau = t$ gives

$$\frac{d\alpha}{dt} = \frac{1}{\gamma s} \frac{ds}{d\tau}$$

The relation between distance travelled and time is $dx = c\beta dt$. Substituting into the above relation and integrating over the path length gives the total precession angle of

$$\alpha = \frac{g\mu}{\hbar c \beta} \int B dx \quad \text{with } B = \frac{|\vec{s} \times \vec{B}|}{s}$$

The proton bend angle can be derived in exactly the same fashion using the equations

$$F = q(\vec{v} \times \vec{B}) \Rightarrow \frac{d\vec{v}}{dt} = \frac{q(\vec{v} \times \vec{B})}{\gamma m}$$

to give the bend angle of

$$\theta_B = \frac{q}{\gamma \beta c m} \int B dx.$$

The spin precession of the proton is slightly more complicated than the neutron precession, since there is the additional effect due to the proton being in an accelerated frame. This effect is called Thomas precession. As shown by Bargmann, the total spin precession is given by

$$\theta_P = \frac{g\mu}{\beta c \hbar} \int B dx + \theta_B(1-\gamma)$$

and the net precession is thus

$$\theta_{\text{net}} = \frac{g\mu}{\beta c \hbar} \int B \, d\lambda - \theta_B \gamma.$$

$$= \theta_B \gamma (g/2 - 1)$$

For the case of the magnetic field aligned with the momentum, the proton spin precession formula is identical with that for the neutron (although the magnetic moments are different, giving a different total precession). Table C-1 gives the magnitude of various quantities mentioned here in MKS units and other units commonly used.

The neutron precession is used to align the neutron spin in the desired direction, as described in Chap. 2. Proton precession allows the measurement of the spin component which is initially aligned along the momentum. It has the undesired side effect of mixing all three initial spin components such that the two measured spin values are each some combination of the three initial components. The nature of this mixing will be discussed here.

Fig. C-1 shows the experimental situation. Basically, it is desired to rotate coordinate frame 1 into frame 2. For convenience in the experiment, θ_H is defined as positive in the counterclockwise direction, while θ_B is defined as positive in the clockwise direction. ϕ_H is defined as zero for a ray in the x-z plane and pointing toward positive x, and $\pi/2$ for a ray in the y-z plane and pointing toward positive y. Although shown in the x-z plane, the other coordinate frames actually rotate with ϕ_H . Frame 1 is defined in the following manner

$$n_1 = k_B \times k_1 = -\sin\phi_H \hat{x} + \cos\phi_H \hat{y}$$

$$k_1 = k_1 = \sin\theta_H \cos\phi_H \hat{x} + \sin\theta_H \sin\phi_H \hat{y} + \cos\theta_H \hat{z}$$

$$s_1 = n_1 \times k_1 = \cos\theta_H \cos\phi_H \hat{x} + \cos\theta_H \sin\phi_H \hat{y} - \sin\theta_H \hat{z}$$

Now, if the magnetic field, which is rotating frame 1 into frame 2, is assumed to have a field only in the y direction, only the components of momentum and spin which are in the x-z plane will be effected, and only by a rotation. Using the general relations for a vector v_1 rotated by an angle θ to vector v_2

$$v_{2x} = v_{1x} \cos\theta - v_{1z} \sin\theta$$

$$v_{2z} = v_{1z} \cos\theta + v_{1x} \sin\theta$$

frame 2 can be obtained in terms of the laboratory frame, thus

$$n_2 = (-\sin\phi_H \cos\theta_B) \hat{x} + \cos\phi_H \hat{y} + (-\sin\phi_H \sin\theta_B) \hat{z}$$

$$s_2 = (\cos\theta_H \cos\phi_H \cos\theta_B + \sin\theta_H \sin\theta_B) \hat{x} + (\cos\theta_H \sin\phi_H) \hat{y} \\ + (-\sin\theta_H \cos\theta_B + \cos\theta_H \cos\phi_H \sin\theta_B) \hat{z}$$

$$k_2 = (\sin\theta_H \cos\phi_H \cos\theta_B - \cos\theta_H \sin\theta_B) \hat{x} + (\sin\theta_H \sin\phi_H) \hat{y} \\ + (\cos\theta_H \cos\theta_B + \sin\theta_H \cos\phi_H \sin\theta_B) \hat{z}$$

σ_R is the spin vector of the recoil particle. In the recoil frame it

has components σ_n , σ_s , σ_k . These components are given in the lab frame by

$$\sigma_x = \sigma_n(-\sin\phi_H) + \sigma_s(\cos\theta_H \cos\phi_H) + \sigma_k(\sin\theta_H \cos\phi_H)$$

$$\sigma_y = \sigma_n \cos\phi_H + \sigma_s(\cos\theta_H \sin\phi_H) + \sigma_k(\sin\theta_H \sin\phi_H)$$

$$\sigma_z = \sigma_s(-\sin\theta_H) + \sigma_k \cos\theta_H$$

The spin precesses by an angle θ_p in the x-z plane such that the final spin components in the lab are

$$\sigma_{mx} = \sigma_x \cos\theta_p - \sigma_z \sin\theta_p$$

$$\sigma_{my} = \sigma_y$$

$$\sigma_{mz} = \sigma_z \cos\theta_p + \sigma_x \sin\theta_p$$

Replacing the lab components with frame 1 components gives

$$\begin{aligned} \sigma_{mx} = & \sigma_n(-\sin\phi_H \cos\theta_p) + \sigma_s(\cos\theta_H \cos\phi_H \cos\theta_p + \sin\theta_H \sin\theta_p) \\ & + \sigma_k(\sin\theta_H \cos\phi_H \cos\theta_p - \cos\theta_H \sin\theta_p) \end{aligned}$$

$$\sigma_{my} = \sigma_n \cos\phi_H + \sigma_s \cos\theta_H \sin\phi_H + \sigma_k \sin\theta_H \sin\phi_H$$

$$\begin{aligned} \sigma_{mz} = & \sigma_n(-\sin\phi_H \sin\theta_p) + \sigma_s(-\sin\theta_H \cos\theta_p + \cos\theta_H \cos\phi_H \sin\theta_p) \\ & + \sigma_k(\cos\theta_H \cos\theta_p + \sin\theta_H \cos\phi_H \sin\theta_p) \end{aligned}$$

The asymmetry detected in the polarimeter results only from the

components perpendicular to the momentum. These components are given by: $\sigma_m \cdot n_2$ (σ_{n2}) and $\sigma_m \cdot s_2$ (σ_{s2}). The final detected components are then

$$\begin{aligned}\sigma_{n2} &= \sigma_n(\cos^2\phi_H + \sin^2\phi_H \cos\alpha) \\ &\quad + \sigma_s(.5\cos\theta_H \sin 2\phi_H(1-\cos\alpha) - \sin\theta_H \sin\phi_H \sin\alpha) \\ &\quad + \sigma_k(\cos\theta_H \sin\phi_H \sin\alpha + .5\sin\theta_H \sin 2\phi_H(1-\cos\alpha)) \\ \sigma_{s2} &= \sigma_n(.5\cos\theta_H \sin 2\phi_H(1-\cos\alpha) + \sin\theta_H \sin\phi_H \sin\alpha) \\ &\quad + \sigma_s(\cos^2\theta_H(\sin^2\phi_H + \cos^2\phi_H \cos\alpha) + \sin^2\theta_H \cos\alpha) \\ &\quad + \sigma_k(-\cos\phi_H \sin\alpha + \cos\theta_H \sin\theta_H(\sin^2\phi_H + \cos^2\phi_H \cos\alpha - \cos\alpha))\end{aligned}$$

Where the identities

$$\sin A \sin B = .5(\cos(A-B) - \cos(A+B))$$

$$\cos A \cos B = .5(\cos(A-B) + \cos(A+B))$$

$$\sin A \cos B = .5(\sin(A+B) + \sin(A-B))$$

are used and $\theta_p - \theta_B$ is written as α . Note that if ϕ_H is either zero or π , the equations reduce to

$$\sigma_{n2} = \sigma_n$$

and

$$\sigma_{s2} = \sigma_s \cos\alpha - \sigma_k \sin\alpha.$$

This is the situation for most scattering angles, since the ψ_H acceptance of the spectrometer narrows rapidly away from zero degrees θ_H . It is only in the range $\pm 3^\circ$ where there is a significant amount of mixing between σ_n and σ_k , σ_s , the components in the scattering plane.

References - App. C

1. V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Lett.
2, 435 (1959)
 2. J. D. Jackson, "Classical Electrodynamics," 2nd Edition,
John Wiley and Sons, 558 (1975)
-

Figure C-1 Coordinate frames for spin precession calculations.

Table C-1

Useful Constants

	MKS	Other units
m_p	1.6725×10^{-27} kg	$938.26 \text{ MeV}/c^2$
m_n	1.6748×10^{-27} kg	$939.55 \text{ MeV}/c^2$
μ	5.0505×10^{-27} J-m ² /Wb	3.1524×10^{-18} MeV/gauss
$\hbar$	1.0545×10^{-34} J-sec	6.5820×10^{-22} MeV-sec
e	1.6021×10^{-19} C	1.0000×10^{-10} MeV-sec/m ² -gauss
c	2.9979×10^8 m/sec	2.9979×10^{23} F/sec
g_n	-3.8270	
g_p	5.5856	
$\mu/c\hbar$	$.15976$ m/Wb	1.5976×10^{-5} 1/gauss-m
$e/c\hbar$	$.31952$ m/Wb	3.1952×10^{-5} 1/gauss-m
$\hbar c$	3.1613×10^{-26} J-m	197.32 MeV-F

Appendix D

Listed below are the measured polarizations and spin precession coefficients for the n-p spin transfer experiment. The values are listed are a, b, c, σ , d, defined by the equation

$$a\sigma_n + b\sigma_s + c\sigma_l = \sigma_2 \pm d$$

The meaning of these coefficients is discussed in App. C. The label at the start of each line has the following meaning. The first letter, N, S, or L, indicates the direction of the neutron beam polarization, either normal, sideways or longitudinal. The following number, 2 or 6, indicates the spectrometer magnet current, either 200 or 600 amps. The final letter, n or s, indicates whether the polarization given is normal to the scattering plane or in the scattering plane (both transverse to the momentum). The σ are polarizations, not asymmetries. The beam polarizations have been included in the coefficients. Asymmetries and precession coefficients were calculated for 8 θ bins and 3 ϕ bins. The θ range for each set is given before the set. For θ less than zero the ϕ bins are: Bin 1 - between 135° and -135° , Bin 2 - between 90° and 135° , and Bin 3 - between -90° and -135° . For θ greater than zero, the ϕ bins are: Bin 1 - between -45° and 45° , Bin 2 - between 45° and 90° , and Bin 3 - between -45° and -90° . Bins 2 and 3 are not always present because of the limited acceptance of the spectrometer at larger angles.

Table D-1

Spin Precession Coefficients and Measured Polarizations

	σ_n	σ_s	σ_1	σ_2	$\Delta\sigma_2$
θ -5 to -6 Bin 1					
N6-n	-.942	-.035	.046	-.219	.058
N6-s	.029	.033	.058	.010	.058
S6-n	.062	.040	-.053	-.018	.075
S6-s	-.026	-.419	-.877	-.033	.075
S2-n	.065	.013	-.034	.034	.079
S2-s	-.006	-.812	-.535	-.134	.079
L6-n	.967	-.043	.058	-.016	.113
L6-s	-.032	.432	.893	-.073	.113
θ -4 to -5 Bin 1					
N6-n	-.916	-.048	.067	-.279	.048
N6-s	.032	.039	.063	-.033	.049
S6-n	.066	.042	-.059	.009	.063
S6-s	-.037	-.414	-.854	-.115	.063
S2-n	.079	.014	-.040	.024	.066
S2-s	-.009	-.803	-.521	-.235	.066
L6-n	.952	-.047	.066	.005	.094
L6-s	-.036	.434	.889	-.254	.094
θ -3 to -4 Bin 1					
N6-n	-.872	-.071	.106	-.187	.043
N6-s	.033	.043	.065	.085	.043
S6-n	.068	.041	-.062	.027	.055
S6-s	-.057	-.418	-.819	-.176	.055
S2-n	.080	.013	-.039	.022	.059
S2-s	-.014	-.790	-.499	-.277	.059
L6-n	.926	-.048	.073	.029	.083
L6-s	-.038	.452	.870	-.203	.083
θ -3 to -4 Bin 2					
N6-n	-.362	-.261	.577	-.429	.205
N6-s	.151	.618	.446	-.316	.205
S6-n	.471	.200	-.416	.526	.250
S6-s	-.193	-.446	-.350	-.405	.251
S2-n	.704	.065	-.258	.139	.287
S2-s	-.042	-.551	-.210	-.282	.287

0 -3 to -4 Bin 3

N6-n	-.390	-.259	.548	-.245	.588
N6-s	-.163	-.586	-.455	.576	.583
S6-n	-.475	-.213	.427	-.183	.912
S6-s	-.196	-.456	-.380	-.129	.847
S2-n	-.696	-.065	.259	-.646	.873
S2-s	-.043	-.559	-.219	.201	.896

0 -2 to -3 Bin 1

N6-n	-.836	-.087	.139	-.110	.041
N6-s	.022	.033	.044	-.047	.041
S6-n	.045	.026	-.042	-.017	.053
S6-s	-.075	-.423	-.789	-.055	.053
S2-n	.054	.008	-.026	-.018	.057
S2-s	-.019	-.779	-.481	-.117	.057
L6-n	.904	-.031	.051	.025	.079
L6-s	-.026	.469	.854	-.211	.078

0 -2 to -3 Bin 2

N6-n	-.241	-.220	.709	.101	.081
N6-s	.101	.758	.352	.027	.081
S6-n	.440	.130	-.329	.075	.103
S6-s	-.160	-.350	-.219	.033	.103
S2-n	.752	.041	-.203	.140	.113
S2-s	-.035	-.411	-.132	-.069	.113
L6-n	.514	-.260	.801	-.303	.157
L6-s	-.192	.865	.421	.011	.157

0 -2 to -3 Bin 3

N6-n	-.272	-.229	.677	.024	.140
N6-s	-.117	-.721	-.376	.197	.140
S6-n	-.447	-.147	.354	-.049	.191
S6-s	-.173	-.376	-.252	-.072	.191
S2-n	-.737	-.047	.222	-.259	.202
S2-s	-.041	-.457	-.156	-.087	.202
L6-n	.534	.276	-.783	.354	.276
L6-s	.212	.834	.459	-.055	.276

0 -1 to -2 Bin 1

N6-n	-.812	-.096	.161	.002	.045
N6-s	.006	.010	.012	.066	.045
S6-n	.012	.007	-.011	-.036	.058
S6-s	-.087	-.427	-.767	-.048	.058
S2-n	.022	.003	-.011	.181	.062
S2-s	-.023	-.772	-.470	-.070	.062
L6-n	.889	-.008	.014	-.018	.086
L6-s	-.007	.482	.842	-.302	.086

0 -1 to -2 Bin 2

N6-n	-.208	-.195	.746	.087	.067
N6-s	.090	.796	.315	-.108	.067
S6-n	.432	.106	-.300	.028	.087
S6-s	-.156	-.318	-.181	-.093	.087
S2-n	.764	.033	-.185	.097	.093
S2-s	-.037	-.370	-.110	-.039	.093
L6-n	.492	-.227	.825	-.117	.129
L6-s	-.183	.880	.370	-.067	.129

0 -1 to -2 Bin 3

N6-n	-.219	-.200	.735	-.101	.083
N6-s	-.097	-.782	-.325	-.049	.083
S6-n	-.433	-.113	.311	-.023	.108
S6-s	-.162	-.329	-.194	.028	.108
S2-n	-.759	-.034	.193	.033	.118
S2-s	-.040	-.386	-.119	-.165	.118
L6-n	.498	.234	-.819	.197	.158
L6-s	.192	.872	.385	.039	.158

0 0 to -1 Bin 1

N6-n	-.805	-.097	.168	-.048	.073
N6-s	.002	.004	.004	.061	.073
S6-n	.004	.002	-.004	-.024	.093
S6-s	-.093	-.429	-.760	.082	.093
S2-n	-.015	-.002	.008	.028	.102
S2-s	-.024	-.771	-.467	.054	.102
L6-n	.885	-.003	.005	.028	.139
L6-s	-.002	.486	.837	-.308	.139

0 0 to -1 Bin 2

N6-n	-.199	-.181	.758	.080	.105
N6-s	.090	.807	.300	-.166	.105
S6-n	.430	.097	-.294	.035	.136
S6-s	-.163	-.311	-.170	-.038	.136
S2-n	.766	.029	-.182	.237	.145
S2-s	-.043	-.362	-.107	-.104	.145
L6-n	.486	-.209	.834	-.334	.200
L6-s	-.190	.887	.351	.191	.200

0 0 to -1 Bin 3

N6-n	-.201	-.182	.756	-.026	.106
N6-s	-.092	-.804	-.303	.127	.106
S6-n	-.429	-.099	.296	.259	.138
S6-s	-.165	-.313	-.172	-.030	.138
S2-n	-.766	-.289	.181	-.032	.151
S2-s	-.043	-.359	-.105	-.051	.150
L6-n	.486	.211	-.833	.342	.198
L6-s	.192	.885	.354	-.308	.198

0 0 to +1 Bin 1

N6-n	.805	.093	.171	-.003	.079
N6-s	-.001	.000	.001	.142	.079
S6-n	-.001	-.001	-.001	.054	.103
S6-s	.096	.433	-.755	-.097	.103
S2-n	-.013	-.002	-.007	.136	.119
S2-s	.028	.768	-.459	-.154	.119
L6-n	.886	-.001	-.001	-.157	.152
L6-s	-.001	.491	-.832	.180	.152

0 0 to +1 Bin 2

N6-n	.200	.162	.762	-.064	.106
N6-s	.096	.808	-.288	-.014	.106
S6-n	.431	.090	.295	-.031	.139
S6-s	.179	.310	-.165	-.086	.139
S2-n	.772	.231	.176	.009	.154
S2-s	.053	.346	-.097	-.024	.154
L6-n	.487	.188	.838	-.265	.201
L6-s	.207	.887	-.338	.021	.201

0 0 to +1 Bin 3

N6-n	-.198	.162	.764	-.053	.109
N6-s	-.096	-.809	.287	.250	.109
S6-n	-.428	-.089	-.294	.006	.143
S6-s	.180	-.308	-.163	.252	.143
S2-n	-.770	-.024	-.176	-.071	.154
S2-s	.053	.347	-.099	.049	.154
L6-n	.484	-.108	-.839	.119	.209
L6-s	-.208	.888	-.336	.311	.209

0 +1 to +2 Bin 1

N6-n	.789	.096	.186	-.057	.062
N6-s	.001	.006	-.004	.003	.062
S6-n	.004	.001	.004	.121	.079
S6-s	.106	.440	-.738	.125	.079
S2-n	-.013	-.002	.008	.046	.100
S2-s	.033	.760	-.448	-.073	.100
L6-n	.877	.002	.006	.137	.115
L6-s	.002	.504	-.820	.141	.115

0 +1 to +2 Bin 2

N6-n	.202	.151	.763	.064	.072
N6-s	.101	.807	-.283	-.006	.072
S6-n	.432	.085	.297	-.179	.093
S6-s	.191	.312	-.163	-.063	.093
S2-n	.773	.020	.174	.079	.106
S2-s	.059	.341	-.095	-.142	.106
L6-n	.490	.176	.840	-.158	.136
L6-s	.220	.887	-.332	.051	.136

0 +1 to +2 Bin 3

N6-n	.201	.157	.754	-.028	.087
N6-s	-.106	-.796	.293	.186	.087
S6-n	-.433	-.091	-.307	.184	.114
S6-s	.195	.321	-.173	.093	.114
S2-n	-.767	-.023	-.187	.158	.132
S2-s	.061	.367	-.107	.155	.132
L6-n	.493	-.184	-.835	.482	.166
L6-s	-.227	.880	-.346	-.292	.167

Appendix E

Several checks for instrumental asymmetries were made on the recoil polarimeter. Additional tests were made to check the effect of using the residual cut and DCLOSE cuts.

Results of the instrumental asymmetry checks are presented in Table E-1. Averaging over the two spin states gives a net unpolarized beam and all parameters should be zero, with the exception of the asymmetry normal to the scattering plane due to the np analyzing power. For checks done with the polarimeter directly in a polarized beam, all coefficients should be zero. Table E-1 also indicates the asymmetry measured using the cone test and $\phi + \pi$ test.

DCLOSE, the distance of closest approach of the incident and final rays in the polarimeter, is used to eliminate events with double scatters or those in which the two rays are so far apart as to make the determination of the scattering angle uncertain. Tests were made on the zero degree 800 MeV runs to see the effect of the DCLOSE cut on the analyzing power. Table E-2 lists the results. As can be seen, the computed analyzing power does drop for larger values of DCLOSE, but not so dramatically as to make the maximum limit of the cut a critical parameter. The upper limit was set at 5 mm for the measurements described in this work.

During the 800 MeV calibrations, the polarimeter was moved to different positions (see Chap. 2). No significant difference was

found in the average analyzing power for the different positions or polarizations. Results are shown in Table E-2.

The value (or harm) of using all six chambers in the polarimeter can also be examined. Again using the 800 MeV calibration measurement, the analyzing power was measured using only the first, third, fourth, and sixth chambers. Although the number of events does increase, the analyzing power drops slightly. The tests indicate that there is no significant loss in using all six chambers, since the quality factor, A^2I , only decreases by about 5% in going from four chambers to six. Results are presented in Table E-2.

Table E-1

Instrumental Asymmetries in the Recoil Polarimeter

All n-p data combined

θ Bin	error	$\cos 2\phi$	$\cos 3\phi$	$\cos 4\phi$	$\sin 2\phi$	$\sin 3\phi$	$\sin 4\phi$
-5. $^{\circ}$	.007	-.013	.005	-.003	.002	-.005	.018
-3. $^{\circ}$	.004	-.009	-.006	.009	.006	-.001	-.005
-1. $^{\circ}$	.004	-.003	-.002	.001	-.002	.004	-.002
1. $^{\circ}$	.010	.009	.015	.010	.005	-.008	.021

θ Bin	cone test			$\phi + \pi$ test			
	error	$\cos \phi$	$\sin \phi$	error	$\cos \phi$	$\sin \phi$	ϵ due to A_n
-5. $^{\circ}$	.007	.037	.007	.006	.037	.011	.007
-3. $^{\circ}$	.004	.007	.004	.004	.008	.002	.004
-1. $^{\circ}$	.004	.004	-.001	.004	.001	-.002	.002
1. $^{\circ}$	.010	.009	.004	.008	.005	.009	.002

Errors given above are common to all values on that line.

All 800 MeV calibrations combined (cone test)

	error	ϕ	2ϕ	3ϕ	4ϕ	5ϕ
cos	.007	.011	.009	-.005	.000	-.002
sin	.007	.002	-.001	.004	.005	-.010

800 MeV calibration (all events used)

Average $\sin \phi$ asymmetry for vertical polarization $-.001 \pm .004$
 Average $\cos \phi$ asymmetry for horizontal polarization $-.001 \pm .007$

Table E-2

Effects of Various Cuts on Analyzing Power

All results from 800 MeV calibrations

Average analyzing power for different DCLOSE cuts
(average θ from 2° to 30°)

DCLOSE	Av A_N
0.0 to 4.0 mm	$.182 \pm .005$
2.5 to 6.0 mm	$.136 \pm .014$
4.0 to 10. mm	$.132 \pm .017$

Average analyzing power for different polarimeter positions
(average $\theta = 4^\circ$ to 30° DCLOSE of 5 mm)

Pol. Orientation	Pos.	Av. A_N
Horiz	Center	$.193 \pm .010$
Vert	Center	$.194 \pm .010$
Vert	+15 cm	$.206 \pm .008$
Vert	-15 cm	$.195 \pm .009$

Average analyzing power using different chambers
(average θ from 2° to 30° , DCLOSE of 4 mm)

Chmbrs. 1,3,4,6	$.177 \pm .005$
All Chambers	$.182 \pm .005$

Intensity ratio 1:1.1