Measurement of the $pp\pi d$ Spin Correlation Parameters A_{SL} and A_{LL} at Energies Between 500 and 800 MeV

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MEASUREMENT OF THE $pp \rightarrow \pi d$ SPIN CORRELATION PARAMETERS
 A_{SL} AND A_{LL} AT ENERGIES BETWEEN 500 AND 800 MeV

by

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ABSTRACT

Angular distributions of the spin correlation parameters A_{SL} and A_{LL} for the inelastic reaction $pp \rightarrow \pi d$ have been measured at pion center-of-mass angles between 40° and 130° , at energies of 500, 650, and 800 MeV. Additional measurements of $A_{LL}(\theta)$ were made at 600, 700, and 750 MeV. The reaction was studied using an incident beam of either longitudinally or transversely polarized protons and a target of longitudinally polarized protons. Both the final state pion and deuteron were detected in a two-armed detector system. The momenta of particles detected in the deuteron arm were analyzed with a magnetic spectrometer which allowed the deuterons to be distinguished from particles produced by quasi-free, three-body, or other background reactions.

A_{SL} was found to be negative (≈ -0.5) at 500 MeV. It became increasingly more negative as energy increased, going down to as low as -0.88 at forward angles at 800 MeV. A_{SL} showed only a slight angular dependence in the entire energy range. The angular distribution of A_{LL} was found to be almost flat at 500 (≈ -0.5) and 600 MeV (≈ -0.4). As energy increased A_{LL} became less negative and began to peak at $\theta_{cm} = 90^\circ$. At 800 MeV A_{LL} was positive at almost all measured angles and had a well defined peak at $\theta_{cm} = 90^\circ$ which reached a maximum of about $+0.4$.

The data were compared to several partial wave analyses and to theoretical calculations based on unified theories of $NN \rightarrow NN$, $\pi d \rightarrow \pi d$, and $NN \rightarrow \pi d$ reactions. In general these later calculations were found to be unsuccessful in fitting our data. Partial wave analyses, which included the present data, fitted the data reasonably well and did not indicate the need for any unusual (dibaryon like) structures in any of the partial waves.

CHAPTER I

INTRODUCTION

Introduction

The role of pions in nucleon-nucleon (NN) interactions has been of interest to physicists since their discovery by Powell¹ in 1947. The reaction $pp \rightarrow \pi d$, being the simplest example of pion production, has been the center of many experimental and theoretical investigations concerning the mechanism of pion production and nuclear forces. Until recently experiments on this reaction had been limited to a few differential cross-section and polarization measurements. These measurements were capable of revealing much about the general form of the reaction, but were insensitive to many of the finer details.

Recent advances in the theoretical understanding of the NN interaction and pion production have made it interesting to perform additional measurements. In the past, theories treated elastic and inelastic NN scattering as two separate reactions. However the two channels are obviously coupled and the theory must consider the two together. Since the πd reaction is the first inelastic pp channel to open (at 288 MeV) it provides a critical test for such theories. Study of the $pp \rightarrow \pi d$ reaction may also shed light on the question of the existence of dibaryon resonances. Theoretical discussions of dibaryons date back to 1963² and 1968³. The modern interest started with measurements of the spin dependent total pp cross-section differences $\Delta\sigma_T$ and $\Delta\sigma_L$ made by an Argonne-Northwestern group⁴ and a Rice-Houston group⁵ at the Argonne ZGS. Phase shift analysis (PSA) of these and other NN data

were made by several authors^{6,7,8} and the dibaryon resonance hypothesis was advanced. The various PSA differed in details but all agreed that dibaryon resonances, if they exist, must be mostly inelastic. It follows that the best place to look for them is in single pion production, e.g. $pp \rightarrow pn\pi$, or $pp \rightarrow \pi d$. Although the cross-sections for the two channels are approximately the same at 500 MeV, the $pp \rightarrow pn\pi$ channel rapidly begins to dominate the inelastic single pion production cross-section as energy increases, accounting for about 95% of the cross-section at 800 MeV. In spite of this the $pp \rightarrow \pi d$ channel is still an important channel to study because its two-body final state is much simpler to study theoretically as well as experimentally. In addition, because of the strong coupling which exists between the two channels, the $pp \rightarrow \pi d$ channel should contain most of the same effects of the phenomena found in the dominant $pp \rightarrow pn\pi$ channel.

Coincidentally the recent development of both polarized beams and targets has revolutionized the technology of spin dependent measurements. Measurements which formerly were impossible or required double or triple scattering can now be made by a single scattering experiment. As a consequence there has been a resurgence on the part of experimentalist to use this technology to expand the volume of spin dependent data in all NN channels including the inelastic channels.

In this dissertation we will describe the measurement of the $pp \rightarrow \pi d$ spin correlation parameters $A_{SL}(\theta)$ and $A_{LL}(\theta)$ at six different energies between 500 and 800 MeV. The measurements not only contribute to our understanding of inelasticity in nucleon-nucleon collisions, but shed light on the dibaryon conjecture.

CHAPTER II

THEORY AND FORMALISM

Theory

Several historical reviews on the development of the theory of pion production from NN interactions have been published to date. Lazard et al.⁹ gives a summary of the theoretical work done on pion absorption by deuterium (the inverse of pion production) up to 1969. More recent reports by Thomas and Landau¹⁰ on πd and π -nucleus scattering, and by Betz et al.¹¹ on pion production in nucleon-nucleon collisions, extend the reviews of the theoretical developments up to 1981.

The first theories of pion production emerged only a few years after the discovery of the pion in 1947. This first generation of theories was started in 1951 when Chew et al.¹² calculated the matrix element for pion production using a simple impulse approximation. A few years later, after the Chew-Wick^{13,14} field theory description of πN dynamics had been developed, more sophisticated theories began to emerge which used this approach to include the effect of pion rescattering through the recently discovered $\Delta(3,3)$ resonance. Although the results of these early theories, by such authors as Lichtenberg¹⁵, Aitken et al.¹⁶, and Durney¹⁷, were in reasonable agreement with the existing experimental data, they were limited to energies near the pion production threshold. This low energy limitation was the result of using non-relativistic kinematics, considering only the pion s and p waves, and not including the effect of pion multiple rescattering.

The next advance in the theory came in 1960 in a paper by Woodruff.¹⁸ Woodruff used Chew-Wick field theory and nuclear wave functions calculated from the Gammel-Thaler potential, to derive a formally correct expression to second order in the πN interaction. Further refinements were added to this theory over the next decade by Koltun and Reitan¹⁹ and Lazard et al.⁹ Although these authors were able to include the effects of pion scattering to first order they neglected the higher order multiple scattering terms which were later found to have a significant effect at higher energies. The second generation theories represented definite improvements over the earlier ones, but they were still valid only at lower energies because, only the pion was treated relativistically, only the pion s and p waves were considered, and multiple rescattering was only calculated to first order.

The present phase of the theoretical work began in the mid 1970's when the need to extend to higher energies forced theorists to seriously consider the higher order effects of multiple pion rescattering through the $\Delta(3,3)$ resonance. The first step towards this goal was the development of the coupled channels model (CCM).²⁰ Theories in the past had always used a conventional potential model where NN scattering was the result of a potential acting between the two nucleons. The CCM is a generalization of this whereby the potential between the internal Δ and N^* excitations and the nucleons are included. These isobar states are coupled to the NN state by coupling potentials derivable from meson exchanges between the two baryons. Green and Niskanen²⁰ were some of the first to use the CCM in their theory for the $pp \rightarrow nd$ re-

action and its inverse. Their work led to a set of coupled differential equations involving the NN , $N\Delta$, and $\Delta\Delta$ channels. Moreover their model allowed a complete summation of the multiple rescattering terms for pion production and could include the effects of heavy meson as well as pion exchanges. These higher order terms were found to have as much as a 20% effect on some amplitudes. However this model had several drawbacks; the coupling constants were static, the theory was essentially non-relativistic and three-body unitarity was only approximately conserved. The attempt to rectify the unitarity problem led theorists to the development of the unified theories which could simultaneously describe all three NN , $NN\pi$, and πd channels. Through the work of such authors as Afnan and Thomas²¹, Mitzutani and Koltun²², Thomas and Rinat²³, Blankleider and Afnan²⁴, Rinat and Starkand²⁵, and Fayard et al.²⁶, emerged a consistent set of exactly unitary coupled integral equations which had the form of the Faddeev equations. These unified theories enabled exact summation over all pion multiple rescattering terms (however with the restriction that no more than one pion at a time be involved in the intermediate state). Although the effects of heavy meson exchanges did not appear readily in these theories, they could be included along with relativistic corrections. Detailed predictions from several authors are now available. These predictions of the spin correlation parameters are presented along with the experimental data in Chapter V.

Formalism

Ever since the dichotomy arose in the 19th century between theoretical and experimental physics there has been a need for a formalism common to both. Such a formalism enables comparisons to be made between theory and experiment by parameterizing the data in a physically meaningful way. Over the years a number of similar formalisms based on the S-matrix have been developed which relate the spin observables of the reaction to the scattering amplitudes.^{27,28,29,30} In this section the notation of Foroughi³¹ will be used to derive the formalism for the specific reaction $pp \rightarrow nd$, where no final state spins are observed. A more general discussion of the formalism for binary reactions involving particles of arbitrary spins is given in Bourrely et al.³²

Foroughi's formalism (as well as many others) refers to a particle's spin component by the relativistically invariant quantity known as the helicity λ . Instead of labeling particle spin states by their component along some fixed axis the helicity description labels particle states along their direction of motion. Since the formalism is relativistic the natural coordinate system to use is the center-of-mass (CM) coordinate system illustrated in Figure 2-1a. Since measurements of spin observables are made in the laboratory (LAB) the coordinate system illustrated in Figure 2-1b is often used. The discussion in this chapter will use the CM x-y-z system while latter chapters will refer to the LAB L-N-S (for longitudinal, normal, and sideways) coordinate system. In both cases the sign of $\hat{y}$ or $\hat{N}$ is chosen to form a

Figure 2-1a. CM x-y-z coordinate system.

Figure 2-1b. LAB L-N-S coordinate system.

right-handed coordinate system. The transformation from one system to another is trivial if the spin of the deuteron is not observed.

The S-matrix formalism describes scattering processes by a scattering amplitude which depends on the kinematical variables and quantum numbers of the particles involved in the scattering. The scattering amplitude has the form of a matrix in spin and charge space. Since the two spaces are independent (except for the exclusion principle) they can be discussed separately. In the following section we will construct the most general form of the scattering matrix which describes the reaction $pp \rightarrow \pi d$ in spin space. The elements of this matrix, known as the helicity matrix H , can be defined as the elements of the transition matrix taken between final and initial helicity states,

$$H_{\lambda_{\pi}\lambda_d; \lambda_b\lambda_t}(\theta, \phi) = \langle \theta\phi; \lambda_{\pi}\lambda_d | T | 00; \lambda_b\lambda_t \rangle \quad (2-1)$$

where $iT = 1 - S$, subscripts b and t refer to the beam and target protons, λ are the helicities, and θ and ϕ are the pion's polar and azimuthal cm scattering angles. Since $\lambda_{\pi} = 0$ the notation can be simplified somewhat,

$$H_{\mu; \lambda_b\lambda_t}(\theta, \phi) = \langle \theta\phi; \mu | T | 00; \lambda_b\lambda_t \rangle \quad (2-2)$$

where $\mu = \lambda_d$. Partial wave decomposition can be used to write the elements in terms of the d-functions and partial wave amplitudes $\alpha_{\lambda-\mu}^S(J)$:

$$H_{\mu; \lambda_b \lambda_t}(\theta, \phi) = -ie^{-i\lambda\phi} \sum_J (2J+1) H_{\mu; \lambda_b \lambda_t}^J d_{\lambda, -\mu}^J(\theta) \quad (2-3)$$

where $\lambda = \lambda_b - \lambda_t$, and

$$H_{\mu; \lambda_b \lambda_t}^J = \sum_{L_p L_\pi s} \frac{[(2L_p+1)(2L_\pi+1)]^{1/2}}{(2J+1)} \times$$

$$\langle 1/2 \lambda_b, 1/2 -\lambda_t | s \mu \rangle \langle L_p 0, s \mu | J \mu \rangle \langle L_\pi 0, 1-\mu | J -\mu \rangle \alpha_{L_p L_\pi}^s(J) \quad (2-4)$$

$s=0,1$ for singlet and triplet pp states.

Since $\mu = \pm 1, 0$ and $\lambda_b, \lambda_t = \pm 1/2$ the elements of the helicity matrix

$H_{\mu; \lambda_b \lambda_t}$ will form a 3 by 4 matrix:

$$H = \begin{pmatrix} H_{+1,++} & H_{+1,+} & H_{+1,-} & H_{+1,--} \\ H_{0,++} & H_{0,+} & H_{0,-} & H_{0,--} \\ H_{-1,++} & H_{-1,+} & H_{-1,-} & H_{-1,--} \end{pmatrix} \quad (2-5)$$

The helicity matrix must obey certain known symmetry requirements.

Parity: Since both the deuteron and pion have integer spin but the pion has odd parity, while the deuteron has even, the matrix must transform under space inversion like a pseudo-scalar. This will require the elements of H to have the following property,

$$H_{-\mu; -\lambda_b -\lambda_t}(\theta, \phi) = -(-1)^{\lambda-\mu} H_{\mu; \lambda_b \lambda_t}(\theta, \pi-\phi) \quad (2-6)$$

This leaves only 6 independent helicity amplitudes which can be used to rewrite H as,

$$H = \begin{pmatrix} M_1 & T_2 e^{i\phi} & T_3 e^{-i\phi} & M_4 \\ S & T_6 e^{i\phi} & T_5 e^{-i\phi} & S \\ M_4 & -T_3 e^{i\phi} & -T_2 e^{-i\phi} & M_1 \end{pmatrix} \quad (2-7)$$

The letters S, T, and M are used to represent respectively, pure singlet, pure triplet, and mixed singlet-triplet amplitudes.

Exclusion Principle: Since there are two identical particles in the initial state its wave function must be anti-symmetric with respect to change in particle labels. This will require the helicity amplitudes to have the following property.

$$H_{\mu; \lambda_b \lambda_t}(\theta, \phi) = (-1)^{\mu} H_{\mu; \lambda_t \lambda_b}(\pi - \theta, \phi) \quad (2-8)$$

Thus S and T_6 must be symmetric about $\theta = \pi/2$ and M_1 and M_4 must be anti-symmetric about $\pi/2$, while $T_2(\theta) = -T_3(\pi - \theta)$.

Knowing H, the differential cross-section (σ) for an interaction where no final state spins are observed will be,

$$\sigma = \text{Tr}(\rho_{in} H^{\dagger} H) \quad (2-9)$$

where ρ_{in} is the initial spin density matrix of the two protons,

$$\rho_{in} = \frac{1}{4} (1 + \vec{P}^b \cdot \vec{\sigma}^b) (1 + \vec{P}^t \cdot \vec{\sigma}^t) \quad (2-10)$$

where $\vec{P}$ is the average polarization for the ensemble of particles,

$\bar{\sigma}$ are the Pauli spin matrix, and superscripts b and t refer to the beam and target. This definition of ρ_{in} can be used to write the differential cross-section as,

$$\sigma = \frac{1}{4} \text{Tr } W + \frac{1}{4} \sum_i P_i^b \text{Tr}(\sigma_i^b W) + \frac{1}{4} \sum_j P_j^t \text{Tr}(\sigma_j^t W) + \frac{1}{4} \sum_i P_i^b P_j^t \text{Tr}(\sigma_i^b \sigma_j^t W) \quad (2-11)$$

where $W = H^\dagger H$, and $i, j = x, y, z$. The traces represent the unpolarized and polarized differential cross-sections:

$$\sigma_{\alpha\beta} = \frac{1}{4} \text{Tr}(\sigma_\alpha^b \sigma_\beta^t W) \quad (2-12)$$

where $\alpha, \beta = 0, x, y, z$. The spin correlation parameters $A_{\alpha\beta}$ can be defined in terms of the differential cross-sections:

$$A_{\alpha\beta} = \frac{\sigma_{\alpha\beta}}{\sigma_{00}} = \frac{1}{4\sigma_{00}} \text{Tr}(\sigma_\alpha^b \sigma_\beta^t W) \quad (2-13)$$

where A_{00} has been normalized to 1. A list of all the non zero parameters is given in Table 2-1.

From the symmetry requirements of the helicity amplitudes one finds that the spin correlation parameters must have the following symmetry relations,

$$A_{y0}(\theta) = A_{0y}(\pi-\theta) \quad (2-14a)$$

$$A_{xz}(\theta) = A_{zx}(\pi-\theta) \quad (2-14b)$$

$$A_{xx}(\theta) = A_{xx}(\pi - \theta) \quad (2-14c)$$

$$A_{yy}(\theta) = A_{yy}(\pi - \theta) \quad (2-14d)$$

$$A_{zz}(\theta) = A_{zz}(\pi - \theta) \quad (2-14e)$$

The orthogonality relations of the helicity amplitudes can be used to find expressions for the four non-zero helicity amplitudes at $\theta = 90^\circ$ in terms of the spin correlation parameters,

$$|S|^2 = \sigma_{oo} (1 + A_{zz}) \quad (2-15)$$

$$|T_2|^2 = |T_3|^2 = \frac{\sigma_{oo}}{2} (1 - A_{yy}) \quad (2-16)$$

$$|T_6|^2 = \sigma_{oo} (A_{yy} - A_{zz}) \quad (2-17)$$

Table 2-1. Spin correlation parameters in terms of the helicity amplitudes.

CM LAB

$$A_{oo} = A_{00} = (1/(2\sigma_{oo})) (|M_1|^2 + |T_2|^2 + |T_3|^2 + |M_4|^2 + |S|^2 + |T_6|^2) \quad (2-18a)$$

$$A_{yo} = A_{N0} = (1/\sigma_{oo}) \operatorname{Im}(-M_4 T_2^* + M_1 T_3^* + S T_6^*) \quad (2-18b)$$

$$A_{oy} = -A_{ON} = (1/\sigma_{oo}) \operatorname{Im}(-M_4 T_3^* + M_1 T_2^* + S T_6^*) \quad (2-18c)$$

$$A_{xz} = -A_{SL} = (1/\sigma_{oo}) \operatorname{Re}(-M_4 T_2^* + M_1 T_3^* + S T_6^*) \quad (2-18d)$$

$$A_{zx} = A_{LS} = (1/\sigma_{oo}) \operatorname{Re}(-M_4 T_3^* + M_1 T_2^* + S T_6^*) \quad (2-18e)$$

$$A_{xx} = A_{SS} = (1/\sigma_{oo}) (\operatorname{Re}(M_1 M_4^* + T_2 T_3^*) - 1/2 |S|^2 + 1/2 |T_6|^2) \quad (2-18f)$$

$$A_{yy} = -A_{NN} = (1/\sigma_{oo}) (\operatorname{Re}(T_2 T_3^* - M_1 M_4^*) + 1/2 |S|^2 + 1/2 |T_6|^2) \quad (2-18g)$$

$$A_{zz} = -A_{LL} = (1/(2\sigma_{oo})) (|M_1|^2 - |T_2|^2 - |T_3|^2 + |M_4|^2 + |S|^2 - |T_6|^2) \quad (2-18h)$$

In addition δ , the relative phase between S and T_6 , can be found at $\theta = 90^\circ$ from the ratio of A_{y0} over A_{xz} ,

$$\delta = \tan^{-1}(A_{y0} / A_{xz}) \quad (2-19)$$

Thus model independent measurements of the singlet and triplet amplitudes and phase δ can be made at $\theta = 90^\circ$.

Two other model independent measurements, that can be made at all angles, are $\sigma^T \equiv \sigma_{00}(1-A_{zz})$ which is the sum of the squares of the triplet amplitudes, and $\sigma^{SM} \equiv \sigma_{00}(1+A_{zz})$ which is the sum of the squares of the singlet and mixed amplitudes.

To determine all six helicity amplitudes and their phases requires a minimum of 11 independent measurements over the angular range from 0 to 90° . Eight of these use polarized beam and/or target but do not include measurements of the deuteron's spin (e.g. σ_{00} , A_{y0} , A_{0y} , A_{xx} , A_{yy} , A_{zz} , A_{xz} , and A_{zx}). The remaining three measurements with polarized beam and target require that the spin of the final state deuteron be measured, (three of the observables t_{11} , t_{21} , and t_{20} or t_{22}).

By writing the general expression for the differential cross-section out in terms of the spin correlation parameters one can see how these quantities can be measured.

$$\begin{aligned} \sigma = \sigma_{00} \big(& 1 + (\vec{P}^b \cdot \hat{y})A_{y0} + (\vec{P}^t \cdot \hat{y})A_{0y} + (\vec{P}^b \cdot \hat{x})(\vec{P}^t \cdot \hat{z})A_{xz} + (\vec{P}^b \cdot \hat{z})(\vec{P}^t \cdot \hat{x})A_{zx} \\ & + (\vec{P}^b \cdot \hat{x})(\vec{P}^t \cdot \hat{x})A_{xx} + (\vec{P}^b \cdot \hat{y})(\vec{P}^t \cdot \hat{y})A_{yy} + (\vec{P}^b \cdot \hat{z})(\vec{P}^t \cdot \hat{z})A_{zz} \big) \end{aligned} \quad (2-20)$$

For example if both the beam and target are polarized along the z axis then equation 2-20 reduces to,

$$\sigma = \sigma_{00} (1 + (\vec{P}^b \cdot \hat{z})(\vec{P}^t \cdot \hat{z})A_{zz}) \quad (2-21)$$

By reversing the polarization of either the beam or target and measuring the differential cross-section for each polarization state the scattering asymmetry ϵ can be defined as,

$$\epsilon = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} \quad (2-22)$$

where $\uparrow$ indicates polarization along the $+z$ axis and $\downarrow$ along the $-z$ axis. Dividing ϵ by the beam and target polarizations gives the spin correlation parameter A_{zz} :

$$A_{zz} = \frac{\epsilon}{|\vec{P}^b| |\vec{P}^t|} \quad (2-23)$$

Thus measuring the spin correlation parameters is simply a matter of measuring the beam and target polarizations and the scattering asymmetry with the beam and target oriented along the various axis.

CHAPTER III

THE EXPERIMENT

Introduction

The experiments which constitute the subject of this dissertation were performed at the BR experimental area of the Los Alamos Meson Physics Facility (LAMPF). The purpose of the experiments was to measure the spin correlation parameters A_{SL} and A_{LL} of the reaction $pp \rightarrow \pi d$, within the energy range of 500 to 800 MeV. The reaction was studied using an incident beam of either longitudinally or transversely polarized protons and a target of longitudinally polarized protons. The scattered pions and deuterons were detected in a two-armed detector system which had a magnetic spectrometer for the deuterons and either a wire chamber telescope or a scintillation counter for the pions. The experimental set-up consisted of the following principal components; polarized proton beam, beam monitoring and control system, polarized proton target, deuteron spectrometer, pion detectors, and the data acquisition and on-line analysis system. Each of these components will be described in detail in the following sections.

The Beam

The beam of protons used in the present experiments was provided by the LAMPF linear proton accelerator.³³ The LAMPF accelerator consists of a 750 KeV Cockcroft-Walton injector, followed by a 100 MeV Alvarez-type drift tube linac, and finally a 805 MHz side-coupled cavity linac. The RF nature of the accelerator allows it to be

operated in an AC mode where both a high intensity H^+ beam and a low intensity H^- beam may be accelerated simultaneously. The beam current has a time structure characterized by 500 μs long macro-pulses which occur at a rate of 120 Hz. Each macro-pulse is further divided into 0.25 ns micro-pulses which occur every 5 ns.

The beam of polarized H^- ions used in the experiments was produced by a Lamb-shift ion source³⁴ which was capable of orienting the polarization vector in any desired direction. Since the several experimental areas which shared the polarized beam were all at different locations with respect to the main beam line the beam polarization vector was not the same at each area. This condition often resulted in a spin orientation which was chosen as a compromise between the requirements of the various experiments sharing the beam.

To reduce systematic effects in asymmetry measurements the beam polarization direction was reversed by the source every 2 to 3 minutes. The source also provided a means to measure the polarization by the "quench ratio" technique.³⁴ By detuning the source the polarized part of the beam can be quenched leaving only the unpolarized beam. The beam polarization is then given by the ratio of the two beam intensities. In practice the quenched beam intensity was measured for only a few seconds before each spin change. Because of the short duration of the quenched beam any anomaly in the beam intensity, unconnected with the quench, which might occur during this time could effect the measurement. This effect could be reduced by averaging the data from numerous quench ratio measurements. Because of the intensity fluctuations the quench ratio technique was a better measure of the

beam polarization over a long period (several hours), then over a short period (less than an hour).

The beam for this experiment had a polarization between 70 and 80% and an intensity from 0.1 to 1 pa. Data were taken over the summer of 1982 during two beam production cycles at a variety of beam energies and spin orientations which are listed in Table 3-1.

Table 3-1. Beam Energy and Spin Orientations.

<u>ENERGY (MeV)</u>	<u>ORIENTATION</u>	<u>CYCLE</u>	<u>DATES</u>
500	Mixed longitudinal and transverse	33	July 7-July 16
600	Longitudinal	34	Sep. 15-Sep. 18
650	Mixed longitudinal and transverse	33	July 18-July 26
700	Longitudinal	34	Sep. 11-Sep. 14
750	Longitudinal	34	Sep. 7-Sep. 10
800	Mixed longitudinal and transverse	34	Aug. 16-Sep. 2

The BR Beam Line

The BR beam line provided the means to control and monitor the incident proton beam. The beam to BR was diverted from the H^- beam by using a thin foil to strip the electrons off some of the H^- atoms in the beam to produce the H^+ beam which was then deflected by a dipole magnet. The intensity of the H^+ beam could be adjusted by varying the amount of foil which intercepted the beam. Once the H^+ beam had been diverted it was fine tuned to give a 1 cm diameter beam spot centered on the target by passing it through a series of bending, focusing, and

steering magnets. The beam also passed through a solenoid magnet which was capable of rotating the transverse spin component of the beam by as much as $\pm 26^\circ$. Figure 3-1 shows the components of the beam line in the experimental area.

The location and spot size of the beam could be monitored at various points along the beam line by profile monitors or by polaroid film burns. A continuous monitor of the beam quality was provided by the beam-location-counter (BLC). BLC was 5 cm square by 0.6 cm thick plastic scintillator with a 1.5 cm diameter hole in the center. The hole was centered on the beam axis so that any shift in the beam location would cause a change in the counting rate of BLC.

The integrated beam current was measured by an ion chamber (ICH) located about 1 m upstream of the target. The ion chamber measured the beam current by collecting the electrons ionized from gas molecules by the passage of charged particles through the chamber. The current output signal was amplified and converted to a frequency by a current to frequency converter. The frequency output was then shaped into NIM pulses which could be counted by the data acquisition hardware.

The Polarimeter

A second measure of the beam's polarization was made by the beam line polarimeter which was located 2 m upstream from the target. A schematic diagram of the polarimeter is shown in Figure 3-2. The polarimeter determined the average of the normal and reverse beam polarization by measuring the asymmetry of protons which scatter elastically from a hydrogen target, ($1/8$ " thick CH_2).³⁵ Four pairs of

Figure 3-1. The BR Beam Line.

Figure 3-2. The Polarimeter.

plastic scintillator detectors were located above and below and to the left and right of the beam axis at angles which would detect the scattered and recoil protons at angles near 30° c.m. An elastic event was defined as a coincidence between two conjugate detectors. Since an up scattered event for a normal beam is equivalent to a down scattered event for a reverse beam the asymmetry can be defined as,

$$\epsilon_{ud} = \frac{\sqrt{U_n D_r} - \sqrt{D_n U_r}}{\sqrt{U_n D_r} + \sqrt{D_n U_r}} \quad (3-1)$$

where, U_n , D_n , U_r , and D_r are the up and down yields for normal and

reverse beams. By defining the asymmetry in this way it has been shown that instrumental uncertainties will cancel out to high order.³⁶ The left-right asymmetry, ϵ_{lr} , can be defined similarly in terms of L_n , R_n , L_r , and R_r . As a result of parity conservation the asymmetry is related only to the spin component perpendicular to the scattering plane of the polarimeter. Thus the up-down asymmetry measures the polarization along the sideways $\hat{S}$ axis and the left-right asymmetry measures the polarization along the normal $\hat{N}$ axis. Since the $\hat{L}$ vector will always lie in the scattering plane no measure of the beam polarization along this direction could be made by the polarimeter. The up-down and left-right asymmetries could be used to calculate the $\hat{S}$ and $\hat{N}$ components of the beam polarization by dividing the measured asymmetries by their respective analyzing powers, A_{ud} and A_{lr} . The analyzing powers were found at each energy by dividing the polarimeter asymmetries by the polarization determined by the quench ratio, using the average of all the available data. Since the quench ratio was used to calibrate the polarimeter, the polarimeter was only a secondary measure of the beam polarization. However in the short run the polarimeter was expected to give a better measure of the polarization because it is not effected by the beam intensity fluctuations which limit the accuracy of measurements made using the quench ratio technique.

Although the polarimeter's primary function was to measure the incident beam polarization it also served as a backup beam current monitor. The integrated beam intensity was proportional to the sum of counts in all the polarimeter counters.

The Polarized Proton Target (PPT)

The target of polarized protons for this experiment was provided by the polarized proton target system (PPT). Polarization of the target protons was achieved by an optical pumping technique. A brief and somewhat over simplified description of this technique is given below. A much more detailed and quantitative discussion can be found in the thesis of Tippens.³⁷ Propanediol ($C_3H_8O_2$) doped with Cr^{V} was used as the target material. Free electrons from the Cr^{V} radical could combine with the protons bound in the propanediol molecule to form atomic hydrogen. By placing the material in a region of high magnetic field the energy levels of the hydrogen atom could be split into four states in proportion to the strength of the field and according to the spin orientation of the proton and electron. The relative population P of each state is determined by the Boltzmann distribution,

$$P \propto \exp\{-(\mu_e - \mu_p)B/kT\} \quad (3-2)$$

where μ_e and μ_p are the electron and proton electronmagnetic moments respectively, B is the magnetic field, k is the Boltzmann constant, and T is the temperature of the target material. To get high polarization one needs a high field B , and a low temperature T . For this target $B = 25$ kG, and $T = 0.5$ K which yielded a net polarization of only $1/2\%$. To generate much higher polarizations in the 70 to 80% range optical pumping was used. Figure 3-3 is helpful in seeing how this process works. By selecting the proper microwave frequency ν_- , such that $h\nu_- = \mu_e B - \mu_p B$, (≈ 71 GHz), transitions between $|-, +\rangle$ and $|+, -\rangle$ states

Figure 3-3. Energy level diagram for the electron-proton system. Populations are shown before and after induced transitions. $|+, +\rangle$ denotes electron and proton spins respectively, parallel to the magnetic field.

will be induced in an effort to equalize the populations of the two states. The notation for the states is that the first sign refers to the electron spin and the second to the proton spin parallel (+) or antiparallel (-) to the magnetic field. The induced transitions will cause the electron and proton spins to flip simultaneously. After the electron and proton flip one another they can realign themselves with the magnetic field. Since the proton relaxation time is typically an hour or more it will remain oriented. On the other hand the electron relaxation time is only about 40 ms so it quickly realigns itself and is ready to flip another proton. Thus only a small number of electrons can service a large number of protons. According to the Boltzmann distribution, when there are no microwaves to induce transitions and the

target is at its operating temperature of 0.5 K and field of 25 kG, the relative populations of the - and + electron states is expected to be 800 to 1. If microwaves are used to equalize the populations P_{+-} and P_{-+} of the $|+-\rangle$ and $| -+\rangle$ states at 800 for each state then according to the Boltzmann distribution, when equilibrium is reached, the population P_{++} of the $|++\rangle$ state will be $\frac{1}{800} \times P_{-+}$ or 1 while the population P_{--} of the $|--\rangle$ state will be $800 \times P_{+-}$ or 640,000. Thus there will be 640,800 - protons for every 801 + protons yielding a net polarization of nearly 99.8%. By selecting a slightly higher frequency ν_+ , such that $h\nu_+ = \mu_e B + \mu_p B$, transition between the $|+,+\rangle$ and $|-, -\rangle$ states will be induced and the polarization of the target will be reversed. In practice such high target polarizations are never seen. The polarization can be reduced considerably if B or T vary over the target volume, or if B, T, or ν were not at their optimum values. Even if none of the above were true one would still not see such high polarizations because the atomic energy levels are broad enough that they overlap slightly allowing microwaves of one frequency to induce transitions between the other two states.

To reduce systematic effects in the asymmetry measurements the spin of the target was reversed every other data acquisition run. Data at a given angle setting were acquired in groups or cycles of four runs with two target reversals per cycle. Data for each run were accumulated for a predetermined integrated beam current, which was estimated would yield a statistically sufficient number of signal events. Runs typically lasted about an hour while target reversals took 30 minutes.

The polarized proton target system (PPT) consisted of five major components; the magnet, cryostat, target material, microwave source, and the polarization monitoring system. Each of these components will be discussed below.

The PPT Magnet (HERA)

The PPT magnet (HERA) consisted of a pair of super conducting Helmholtz coils which produced a 25 kG field at the target.³⁸ The coils of the superconducting magnet were cooled by a bath of liquid ^4He which was maintained at a temperature of 4 K by allowing it to boil off at atmospheric pressure. The field was uniform to within $\pm 0.01\%$ over the target volume and was oriented parallel to the incident beam axis. The coils of the magnet gave an unobstructed open cone angle of $\pm 45^\circ$ with respect to the beam axis. This limited the angular range of the pions detected outside the magnet to angles less than 75° c.m.

The magnetic fringe field was quite strong, up to 600 Gauss at distances over a meter away. The fringe field affected nearby electronics, altered the trajectory of scattered particles, and precessed the spin of the incident beam. The effect on nearby electronics was minimized by keeping all photomultiplier tubes as far away as possible and adding extra shielding to those nearby. The fringe fields altered the trajectory of scattered particles by rotating their trajectories counter-clockwise, (looking down stream), about the beam axis by an angle ϕ . Figure 3-4 shows a plot of ϕ at a distance of one meter from the target center versus momentum for several different θ_{lab} angles. The trajectories of scattered particles were also bent slightly towards

the beam axis by an angle $\Delta\theta$. Figure 3-5 shows a plot of $\Delta\theta$ at one meter versus momentum for several different θ_{lab} angles. Knowing the bend angles allowed the location of the pion and deuteron detectors to be adjusted to accommodate these deflections. The trajectory of the incident beam was not effected by the fringe field since the incident beam traveled down the axis of the magnetic field where its momentum was always parallel to the field lines. However the fringe field did act like a solenoid to precess the transverse spin component of the incident beam clockwise about the beam axis by an angle between 30 and 40° depending on the beam momentum. This rotation was partially compensated by the field of the spin precession solenoid located about 3 m upstream of the target.

The Cryostat

The target was cooled by a ^3He - ^4He refrigeration system. Since ^3He is such an expensive material it was circulated in a closed loop and was cooled by thermal contact with the ^4He which supplied the cooling power for the entire cryostat. Liquid ^4He , stored in a 1000 l dewar, entered the system at atmospheric pressure and temperature of 4 K, where it was cooled down to 2 K by allowing it to boil off at a pressure of 10 torr. At the same time ^3He gas entered the system at a pressure slightly below one half of an atmosphere. The ^3He gas was first cooled and liquified at 2 K by thermal contact with the ^4He gas and liquid. Then it was cooled to its final temperature of 1/2 K by thermal contact with the ^3He gas boiled from the target and by passing it through an expansion valve. The target was submersed in a bath of

Figure 3-4. Φ vs P. Figure 3-5. $\Delta\theta$ vs P.

^3He which flowed through the expansion valve. ^3He gas which boiled off the target was pumped out at a high rate at a pressure of 0.1 torr to be cleaned and recycled.

The Target Material

propanediol, $\text{C}_3\text{H}_8\text{O}_2$, was used as the target material for the PPT.³⁹ The propanediol was doped with about 2% Cr^{V} by weight to provide the free electrons which are needed to polarize the protons. The propanediol which is a liquid at room temperature was formed into 1 mm diameter beads by dripping it into liquid nitrogen. Beads were used to improve the thermal contact with the liquid ^3He bath and allow the energy of the absorbed microwaves to be dissipated more readily. The beads were contained in a perforated 10 mil thick teflon cylinder 5.5 cm long and 2 cm in diameter. The packing fraction of the beads was about $2/3$ which yielded an effective hydrogen density of about 0.073 gm/cm^3 . A carbon target was also available to give an indication of the background contamination caused by the non-hydrogenic target nuclei. The carbon target consisted of a teflon cylinder identical to the propanediol container filled with hollow graphite beads which yielded approximately the same net quasi-free proton density as the oxygen and carbon in the propanediol target.

The Microwaves

The microwaves were provided by a 400 mw, 71 GHz klystron, and fed to the target by a wave guide. The frequency could be adjusted to the optimum frequency for + and - polarization by changing the klystron's

cathode voltage. The microwave power could be varied by adjusting an attenuator. Too much power would cause the propanediol beads to heat up and too little power would not saturate the desired transitions.

The Nuclear Magnetic Resonance System

The NMR system was used to measure the relative polarization of the target. The energy difference between protons in the + and - target polarization states will be $2\mu_p B$. Transitions between the two states can be induced by irradiating the target material with an RF field of frequency ν such that $h\nu = 2\mu_p B$, (106.4 MHz). If the populations of the two states are unequal then transitions will be induced from one state to another in an attempt to equalize the two populations, (and depolarize the target). This will either release or absorb energy from the RF field causing the amplitude of the signal to be modulated in proportion to the target polarization. To minimize target depolarization the frequency of the RF field was only swept through resonance once during each measurement.

The system was calibrated by measuring the NMR signal of a target of known polarization. By turning the microwaves off and allowing the target to come to thermal equilibrium the polarization could be determined from Boltzmann statistics knowing B and T . The magnetic field B was known to better than $\pm 0.01\%$ and the temperature T was measured indirectly to within $\pm 0.1\%$ using a capacitance manometer to measure the ^3He gas pressure at the target and converting the pressure to temperature. During the course of the experiment a number of such thermal equilibrium calibration measurements were made. Using the cal-

ibration the absolute polarization of the enhanced target could be determined to within $\pm 4\%$.

The Deuteron Spectrometer

The deuteron spectrometer measured the momenta, scattering angle, and time-of-flight of particles scattered into it. A sketch of the deuteron and pion detectors is shown in Figure 3-6. The momenta and scattering angles were determined using four multi wire proportional counters (MWPC) to measure the particles trajectories before and after being bent by the spectrometer magnet. A brief description of the MWPC's is given in Appendix A. Each of the chambers gives the horizontal and vertical location of the particles to within ± 0.6 mm, which in combination with multiple scattering determined the momentum and angles to $\pm 2\%$ and $\pm 0.5^\circ$ respectively. The solid angle of the spectrometer was limited by the second wire chamber to be 12 msr. Scintillators S1, S2, and S3 were used to measure the time-of-flight over the spectrometer's 3.6 meter flight path and as part of the deuteron event trigger. The entire spectrometer assembly was mounted on air pads which allowed it to be rotated about a pivot point beneath the target center from 0 to 42° . Angle settings were indicated to within $\pm 0.1^\circ$ by a marker fixed to the spectrometer which pointed to angle markings painted on the floor. To compensate for the unevenness of the floor upon which the spectrometer rested, the spectrometer's height and level could be adjusted using a set of jacks which supported it when it was not being moved on the air pads.

Figure 3-6. The deuteron and pion detector system.

The Pion Telescope

The pion telescope, shown in Figure 3-7, used two MWPC's to measure the angle of particles scattered into it. Each MWPC had an X and a Y plane capable of measuring the coordinates of hits to within ± 0.6 mm. The front chamber, W5, defined the solid angle of the telescope to be 65 msr. A set of four scintillators, located behind W6, provided part of the pion event trigger as well as timing information. The entire pion telescope assembly was mounted on a set of wheels which allowed it to be rotated about the pivot point from 0 to -44° . Like the deuteron spectrometer the angle settings could be measured to within $\pm 0.1^\circ$ by a marker fixed to the telescope which pointed to angle markings painted on the floor, and the height and level could be adjusted by a set of jacks.

The pion telescope was also designed to accommodate the bending of the scattered particles trajectories caused by the fringe field of the PPT magnet. Since the deuterons were detected in a plane parallel to the floor the bending of the trajectories by the PPT fringe field required that pions be detected out of the horizontal plane. To accommodate this vertical bending the pion telescope's wire chambers were mounted on a platform which could be raised a distance H above the beam axis and tilted an angle α about a point beneath the front wire chamber. H could be adjusted anywhere from 0 to 180 mm, and α could be adjusted in 1° steps from 0 to 15° . The rear scintillators could also be raised to the height necessary to detect all the pions which passed through the wire chambers.

Figure 3-7. The Pion Telescope.

The Inside Counter

The coils of the PPT magnet limited the angular range of pions detected outside the magnet bore to lab angles less than $\pm 45^\circ$ or pion c.m. angles less than 75° . To detect pions with c.m. angles of 75° or greater the inside counter shown in Figure 3-8 was used. The inside counter consisted of a scintillator, (S4), and a small wire chamber, (W7), mounted inside the bore of the magnet. W7 had an X and a Y plane both capable of determining the location of hits to within ± 0.6 mm over an active area of 6.4 cm square, while S4 had an active area of 9 by 10 cm. The location of the inside counter could be adjusted to whatever position the recoiling pions were predicted to intercept it. Because W7 was mounted so close to the target it had very poor angular resolution and subtended a large solid angle. W7's large solid angle resulted in a high counting rate and a low efficiency. Because of its low efficiency a good hit in W7 was not required as part of the inside counter event trigger. This requirement could be added in the software during later data analysis.

Detection of pions using the inside counter gave a poor quality signal compared to the pion telescope. However the deuteron spectrometer provided enough information to allow the signal to background ratio to be kept at a reasonable level.

Data Acquisition and On-Line Analysis

Data were acquired using a CAMAC system interfaced to a PDP 11/60 computer through a microprogrammable branch driver (MBD). The data acquisition hardware was located in the BR counting house some 40 m

Figure 3-8. The Inside Counter. (Looking up stream.)

N.W. of the experimental area. Software for the MBD and the PDP computer was written using the LAMPF RSX-11D general data acquisition and analysis system, "Q".⁴⁰ A special CAMAC unit called the LAMPF trigger module (LTM) was used to alert the MBD that a certain type of event had occurred. Each event caused the MBD to read in a specific set of CAMAC registers and transfer the data to the computer through buffers shared by the MBD and PDP. As requested the computer could either write the raw data to tape or process it using the analyzer. A description of the event trigger logic followed by a discussion of the analyzer is given below.

The Event Trigger Logic

The event trigger logic was used to define and trigger LTM EVENTS 4, 5, and 8, which caused data to be read in and passed to the computer. EVENT 4 dumped the MBD data buffer and was triggered at the end of every beam macro-pulse or at the end of a run. Dumping the buffer between macro-pulses insured that the time between macro-pulses was put to good use processing events and that the buffer would be cleared and ready to accept data from the next macro-pulse. EVENT 5 was triggered every spin change or at the end of a run and caused the CAMAC scalars to be read in and cleared. EVENT 8 indicated that a good two body event had occurred in the deuteron and pion detectors. EVENT 8 caused the ADC, TDC, and wire chamber information to be read in.

The event trigger logic was separated into two parts, the run control logic and the main event logic. The run control logic, which monitored the status of the beam and run, was used to trigger EVENTS 4

and 5 as well as to define a number of CAMAC scaler inhibits. The appropriate signals were provided by a pair of LAMPF gate generators, LGG1 and LGG2. A schematic diagram of the run control logic is shown in Figure 3-9. The logical expression for each of the inverted AND (NAND) gates is given in the schematic. Note a bar above an expression indicates the complement. The following notes concerning some of the inputs and outputs should enable the reader to interpret the logic. The beam gate BG, sent from the central control room, was held true throughout the duration of each macro-pulse. The polarized beam signal P, from the ion source, was true for polarized beam and false for quenched. Beam intensity BI was a signal generated in the counting house from signals sent from the polarimeter. It remained true as long as beam was entering the experimental area. The LGG1 run gate RUN was set by the computer to be true at the start of a run and false at the end. NN and RR were two signals which originated at the ion source. A true NN or RR signal indicated normal and reverse beam respectively, while both NN and RR false indicated a spin change was in progress. Since there tended to be some noise in these signals when they dropped a 10 s monostable pulse was added to prevent the noise from causing multiple EVENT 5 triggers. The NN and RR signals were connected to the LGG2 start and stop inputs respectively. This caused the LGG2 run gate to be true when NN was true and false when RR was true. Thus the LGG2 run gate and its complement were used to indicate the beam polarization state. Using the LGG2 run gate signals to set bits in the coincidence buffer allowed the beam polarization state to be recorded for each event. The two signals were also AND'ed together with a 10 KHz clock

Figure 3-9. The run control logic.

to generate the normal and reverse clock signals. The B, C, P, and Q scaler inhibit signals were used to inhibit various CAMAC scalers. The B inhibit signal was also used by the main trigger logic which will be discussed next.

The Main Trigger Logic

The main trigger logic was used to trigger an EVENT 8 whenever a good two body event had occurred. A good two body event was defined as the simultaneous detection of a charged particle by the deuteron and pion detector scintillators as well as sufficient wire chamber information to determine the trajectories of the particles. A schematic diagram of the main trigger logic is shown in Figure 3-10.

To minimize event processing time the main trigger logic was divided into two stages, the PP fast gate PPFG, and the PP master gate PPMG. Output signals from the PPFG and PPMG were gated through the fast trigger or FTOR, and the master trigger or MTOR. This allowed the main trigger logic to be easily modified to handle a neutral particle event. Since such events were not part of this experiment these gates will not be discussed. The PPFG was triggered by a coincidence between the spectrometer scintillator gate SSG and the recoil or gate ROR. If the inside counter was used then the PPFG was triggered by a coincidence between SSG and S4. The PPFG could also be inhibited by a veto signal from the master inhibit. SSG was formed by a coincidence between the front spectrometer scintillator, S1, and either of the two rear scintillators, S2 or S3, while ROR was formed by a hit in any of the four recoil counter scintillators, S8, S9, S10, or S20. A pulse

Figure 3-10. The main trigger logic.

from PPFG would start the TDC's and pulse the ADC's gates to avoid the need for more delays in the TDC and ADC inputs. The PPFG signal also formed part of the PPMG logic. The PPMG was triggered by a three fold coincidence between the PPFG, the spectrometer wire chamber gate SWCG and the recoil wire chamber gate RWCG. If the inside counter was being used then only a two fold coincidence between PPFG and SWCG was required. In order to reconstruct a spectrometer event only 3 out of the 4 spectrometer X and Y planes need be hit. Hence the spectrometer wire chamber fast discriminator outputs were used to define SWCG as $SWCG = {}^{3/4}(W_x) \cdot {}^{3/4}(W_y)$, where ${}^{3/4}$ indicates that only 3 out of the 4 need be hit. Similarly recoil counter events could be reconstructed using only the X and Y hits of either of the two wire chambers W5 or W6. Thus $RWCG = (W5_x \cdot W5_y) + (W6_x \cdot W6_y)$. Triggering PPMG caused the event to be accepted and read in as a good EVENT 8. If PPMG was not triggered a PP fast clear (PPFC) pulse would be generated by the PPFG and would clear the TDC and ADC inputs. Reading in an EVENT 8 required about 300 μ s, during which time the main trigger logic was inhibited by a busy signal from the LAMPF trigger module. If PPFG was triggered but PPMG was not then the event was rejected. Rejecting an event at this point required that the TDC's and ADC's be reset and the coincidence buffer be cleared. Since the process required about 2 μ s to complete, a 4 μ s monostable pulse was triggered which inhibited the electronics during this time. A measure of the live time of the system could be obtained using the master inhibit to gate the BR polarimeter scalers. The live time was given by the ratio of the number of counts with

(master inhibit)*(inhibit B) over the number of counts with just inhibit B.

The Analyzer

On-line data analysis was done with a variety of programs written using the standard LAMPF "Q" system software. These programs were designed to give sufficient information on-line to indicate the performance of the experiment and quality of the data. Data from EVENT 8's were processed using the event analysis program EX518A. Other programs included an NMR program and two CAMAC scaler routines. Since data taking was inhibited while an event was being processed EVENT 8's were handled using the "may process mode". In this mode data was first written to tape and then, if time permitted, analyzed on-line. EX518A used the raw data to calculate a number of physical quantities such as deuteron and pion time-of-flight, lab and c.m. scattering angles, momenta, and target projections. Each of these quantities could be displayed in the form of a histogram on which gates or cuts could be placed to reject non-signal events. Since all events were first recorded on tape before being processed the cuts had no effect on data stored on tape. By using cuts the on-line analyzer was able to give a very good picture of what the signal data was like.

The NMR program was automatically started at the beginning of each run for which data was being recorded on tape. The program communicated with the NMR system through the MBD and CAMAC. The target polarization was sampled every two to three minutes and the NMR signal was recorded and saved in a disk file. Each NMR signal area and an

estimate of the target's polarization were output on a Decwriter as they were read in giving a continuous monitor of the target's performance.

CAMAC scalars were handled using two programs, SLR and POL. SLR printed out a table listing the current value of all the normal and reverse scalars. These scalars were then used to calculate a number of ratios and asymmetries which were printed out following the scalars. By examining the output it was easy to spot malfunctioning hardware or anomalous experimental conditions. POL was simply a program which used the polarimeter and quench ratio scalars to calculate the beam polarization as well as the beam alignment on the polarimeter target.

CHAPTER IV

OFF-LINE ANALYSIS AND SYSTEMATIC UNCERTAINTY

Introduction

Although the data were analyzed on-line during data acquisition, a more careful and more thorough analysis is required to extract the final spin correlation parameters. In this chapter we present the details of this analysis as well as a discussion of the systematic errors in the final results.

Summary Taping

The off-line event analysis of the raw data written to tape during data acquisition was done in two steps, summary taping using a PDP 11/70 computer, and replay using a VAX 11/780 computer. The summary tape analyzer corrected the raw data for the spectrometer time-of-flight (TOF) and for missing wire chamber hits before separating out the πd events and writing them to a second tape. Missing hits in the deuteron spectrometer and pion telescope wire chambers were corrected using information from hits in the other chambers to estimate where the missing hit should have occurred. Since the inside counter had only a single wire chamber no correction for missing hits in it was possible. The spectrometer event trigger requirement that 3 out of the 4 X and Y planes be hit made it possible to correct missing hits using the assumption that the projection of the incident and exiting trajectories of particles which pass through the spectrome-

ter intersect at the symmetry plane of the spectrometer magnet. This assumption was verified using perfect events to show that the intersection of the trajectories did indeed lie on a plane which coincided with the spectrometer magnet's symmetry plane. The two good hits on one side of the magnet were used to determine the point of intersection with the symmetry plane. A line drawn through this point and the good hit on the other side passed through the missing plane at the point where the missing hit should have occurred. The pion telescope event trigger requirement that there be a good X and Y hit in one of the two chambers was chosen to allow missing hits to be corrected using perfect events to determine the correlation between hits in the two wire chamber X and Y planes. Once the correlation function was found it was used to calculate the location of missing hits. Since the correlation function varied with the pion telescope setting a new function was determined for each setting. Multiple hits for both detectors were corrected like missing hits except that the location of the missing hit was used to choose the closest of the multiple hits as the correct hit. Events with more than one multiple hit in a set of planes were rejected.

Corrections to the spectrometer time-of-flight were also made to improve the time resolution of the two rear scintillators S2 and S3. Since both these 65 cm long scintillators were viewed from only one end, the time resolution was limited by the propagation time for light to travel the length of the scintillator. A correction of up to 10% was made using the location of the X hit in the wire chamber W4 to determine where the particle passed through the scintillator and estimate

the time delay for light to reach the end viewed by the photomultiplier tube.

After the corrections had been made the summary tape analyzer separated out the possible πd events from the many pp events using a crude cut on the deuteron peak in the corrected spectrometer TOF histogram. Typically this would reject 60 to 80% of events recorded on the raw data tape. This meant that data stored on many raw data tapes could be reorganized and condensed on to just a few summary tapes which allowed the subsequent replay of these tapes to proceed more easily and to require much less computer time.

Replay

The second step of the off-line event analysis was to analyze, or replay, the summary tapes using the analyzer ANA518. Like the on-line event analysis program, ANA518 used the MWPC and time-of-flight data to calculate a number of physical quantities which were displayed as histograms which could be cut to reject non-signal events. A list of some of these histograms along with their function is given in Table 4-1. The momentum and angles of all events were corrected for the incident and exiting energy loss in the target and for the bending caused by the fringe field of HERA. Events whose kinematics proved impossible to calculate were rejected.

Two-body reactions such as $pp \rightarrow \pi d$ have the advantage that the vector momentum of both final particles can be uniquely determined by a measure of the vector momentum of just one particle. That is, the kinematics of the reaction are completely determined by the spectrometer's

Table 4-1. Replay histograms and their functions.

<u>HISTOGRAM</u>	<u>DESCRIPTION</u>	<u>FUNCTION</u>
PMOM	Deuteron momentum	Signal cuts
PMASS	Measured deuteron mass	Signal cuts
TOF	Spectrometer time-of-flight	Signal cuts
TIR	Time between spectrometer scintillator S1 and pion telescope scintillators	Signal cuts
MM	Missing mass, where $MM = 2M_p + T_p$ $- M_d - T_d - M_\pi - T_\pi$	Signal cuts, or background fits
TGTSX	Spectrometer X target projection	Signal cuts
TGTSY	Spectrometer Y target projection	Signal cuts
TGTRX	Pion telescope X target projection	Signal cuts
TGTRY	Pion telescope Y target projection	Signal cuts
DPHI	Coplanarity. Measured - expected pion azimuthal angles	Signal cuts
DTHR	Measured - expected pion polar c.m. angle	Background fits
THRCM	Pion polar c.m. angle	Angle bin cuts
THSCM	Deuteron polar c.m. angle	Angle bin cuts

measurement of the deuteron momentum and lab scattering angle. The additional information provided by the pion detectors could be used to compare measured pion polar and azimuthal c.m. angles with the angles predicted knowing the deuteron vector momentum. These two angle differences could be displayed as histograms DTHR and DPHI respectively.

Histograms DTHR and DPHI were useful in distinguishing background from signal events since events with measured angles which differ significantly from the expected were probably not from the desired reaction. Such background events were most likely the result of quasi-free scattering from the non-hydrogenic target nuclei.

ANA518 sorted events into three angle bins according to their c.m. scattering angles by placing special cuts on either the deuteron or pion c.m. angle histograms THSCM or THRCM. Since the pion c.m. angles are more spread out in the lab frame than the deuteron, THRCM was chosen as the angle bin histogram for the pion telescope data. For data taken with the pion telescope DTHR was chosen as the histogram that best displayed a sharp signal peak that sat upon a broad background. No cuts were placed on DTHR during replay to preserve the full extent of the background for fitting during later data analysis. Using the angle bin and beam spin state the signal histogram DTHR was displayed as a two parameter histogram $Z(x,y)$, where $x = \text{DTHR}$, $y = \text{beam spin} \times \text{angle bin}$, and $Z = \text{number of counts}$. This allowed each of the six possible angle bin and beam spin combinations to be displayed as separate histograms. Figures 4-1, and 4-2 show typical THRCM and DTHR histograms from a run taken with the pion telescope. The same cuts were used to replay each run at a given beam energy and angle setting. At the conclusion of the replay of each run the histograms and CAMAC scalars were saved in a disk file.

Replay of data taken with the inside counter was done similar to that from the pion telescope. However it was found that the efficiency of the inside wire chamber was so low that its inclusion introduced

Figure 4-1. THRCM angle bin histogram for pion telescope data.

Figure 4-2. DTHR signal histogram for pion telescope data.

large systematic errors to the data which could not be corrected. Therefore W7 was not used. With only the inside scintillator left to detect pions, such histograms as TGTRX, TGTRY, TlR, DPHI, DTHR, and THRCM were meaningless and could not be cut to reject non-signal events. For inside counter data MM was chosen as the signal histogram and was replayed without cuts and displayed as a two parameter histogram. THSCM was also chosen as the angle bin histogram for inside counter data. Figures 4-3 and 4-4 show typical THSCM and MM histograms from a run taken with the inside counter. Since there was no measure of the pion's kinematics the quasi-free background contamination of the signal increased considerably. In addition THSCM gave a poorer measure of the c.m. angle due to the compression of the deuterons kinematics in the lab frame.

Background

Although histogram cuts were used to reject non-signal events there were always a small fraction of these background events which managed to pass all the cuts and contaminated the signal. A program CALBGD was used to estimate the ratio of background to signal events. To run CALBGD the position of four markers, 2, 3 and 1, 4 were input to define the location and extent of the signal and background peaks respectively in the signal histogram. CALBGD called the subroutine PEKFIT⁴¹ which used the four markers to fit the signal histogram with a gaussian signal peak superimposed upon a quadratic background. The fitted background area was then used to calculate the ratio of back-

Figure 4-3. THSCM angle bin histogram for inside counter data.

Figure 4-4. MM signal histogram for inside counter data.

ground events over the total number of events in the signal peak region defined by markers 2 and 3.

In order to improve statistics and reduce the amount of fitting required, all runs for a given incident beam energy, angle setting, and target polarization state were summed together and fit by CALBGD. Since the background ratios varied with beam spin and angle bin CALBGD fit each of the six combinations separately and calculated a ratio for each one. After fitting, CALBGD saved the results for later use by writing the marker locations and background ratios to a disk file.

Background ratios were typically 3 to 8% for pion telescope data, and 10 to 30% for inside counter data. The accuracy of these ratios could be verified by comparing the fitted background to the signal seen using the carbon target. Since the carbon target contained approximately the same volume and density of quasi-free protons as the propanediol target the carbon target signal should give a very good estimate of the size and shape of the quasi-free background contamination of the polarized target data. Figures 4-5 and 4-6 show typical DTHR and MM histograms, background fits, and corresponding carbon target signals. The backgrounds calculated by CALBGD were found to agree to within a few percent of the carbon target signal areas.

NMR Calibration

The NMR system was calibrated using the thermal equilibrium (microwaves off) data to measure the NMR signal of a target with polarization that could be found from Boltzman statistics knowing B and T. The magnet shunt voltage, target ^3He vapor pressure, and NMR signal

Figure 4-5. DTHR signal histogram with background fit and carbon target data.

Figure 4-6. MM signal histogram with background fit and carbon target data.

area were recorded for each thermal equilibrium measurement. The magnetic field B was given by the shunt voltage and the temperature T could be found from the ^3He vapor pressure using the empirical formula⁴²,

$$T = .7086 + .0435 \times P - .0010 \times P^2 \quad (.71 \text{ K} < T < 1.14 \text{ K}) \quad (4-1)$$

where $T = ^3\text{He}$ temperature in K, and $P = ^3\text{He}$ pressure in torr.

Thermal equilibrium target polarizations were typically only 0.25%. For this reason the size of the NMR signal had to be increased by a gain factor and by multiple sweeps of the NMR frequency through the resonance. The area of each sweep was added to form an accumulated area. Knowing the net area and the polarization the NMR calibration constant POLCAL was given by,

$$\text{POLCAL} = \frac{(\text{thermal equilb. pol.}) \times (\# \text{ of sweeps}) \times (\text{gain})}{(\text{net NMR signal area})} \quad (4-2)$$

A set of thermal equilibrium measurements was taken about once a week during data taking. Each set consisted of about 20 to 40 measurements taken over a period of about an hour. An average value of POLCAL and its standard deviation was found for each set of measurements. Figure 4-7 shows a plot of POLCAL vs. time. The calibration was assumed to remain constant with time and so a weighted average value of POLCAL was used as the calibration constant. Data for the experiment was taken over two time periods, Cycles 33 and 34, separated by some 22 days. Since the target material was removed and the target system mod-

Figure 4-7. POLCAL vs time.

ified between cycles a separate weighted average was calculated for each cycle. Since the enhanced (polarized) target NMR signal was measured with just one sweep and a gain of one, the enhanced target polarization was given by the product of POLCAL times the NMR signal area.

NMR

NMR data files created during data acquisition were analyzed by the program NMRPOL. NMRPOL determined the signal area of each NMR measurement by calling the subroutine PEKFIT to fit the background with a quadratic function and then subtract it from the total area. The average area and its standard deviation were calculated for each run and saved in a disk file for later use.

Polarimeter Calibration

In order to use the polarimeter to measure the beam polarization its analyzing power must be determined at each energy. To obtain these analyzing powers the weighted average of the up-down and left-right polarimeter asymmetries $\langle \epsilon_{ud} \rangle$ and $\langle \epsilon_{lr} \rangle$ for all runs at a given energy were divided by the weighted average polarization given by the quench ratio $\langle P_{qr} \rangle$. These two quantities were then divided by the $\hat{S}$ or $\hat{N}$ spin components of the beam at the polarimeter target ($|\hat{P} \cdot \hat{S}|$ or $|\hat{P} \cdot \hat{N}|$) to give the up-down and left-right analyzing powers A_{ud} and A_{lr} ,

$$A_{ud} = \frac{\langle \epsilon_{ud} \rangle}{\langle P_{qr} \rangle \times |\hat{P} \cdot \hat{S}|} \quad (4-3a)$$

$$A_{lr} = \frac{\langle \epsilon_{lr} \rangle}{\langle P_{qr} \rangle \times |\hat{P} \cdot \hat{N}|} \quad (4-3b)$$

The spin orientation of the beam could be determined to within $\pm 3^\circ$ at any point along the BR beam by knowledge of its orientation at the source and its precession through the beam transport system, the bend angles along the beam line, and the field of the spin precession and PPT magnets. A plot of the two analyzing powers vs. incident beam energy is shown in Figure 4-8. The average of the normal and reverse $\hat{S}$ and $\hat{N}$ spin components of the beam measured by the polarimeter ($P_{pol}(S)$ or $P_{pol}(N)$) will be given by,

$$P_{\text{pol}}(\text{S}) = \epsilon_{\text{ud}} / A_{\text{ud}} \quad (4-4a)$$

$$P_{\text{pol}}(\text{N}) = \epsilon_{\text{lr}} / A_{\text{lr}} \quad (4-4b)$$

Asymmetry Analysis

Once the runs had been summary taped and replayed, background ratios calculated, NMR areas averaged, and polarimeter and NMR system had been calibrated the asymmetry analysis program EASY could be run. A schematic diagram of EASY is shown in Figure 4-9. EASY used data stored in various data and histogram files to calculate the beam and target polarizations and the relative yields for each run. Once these quantities had been found EASY calculated the spin correlation param-

Figure 4-8. Up-down and left-right polarimeter analyzing power vs. incident beam energy.

Figure 4-9. A schematic of the asymmetry analysis program EASY.

eters using equation 4-5 which was derived from equation 2-20 for a longitudinally polarized target.

$$I = I_0 (1 + P^b |\hat{P}^b \cdot \hat{N}| A_{NO} + P^b P^t (|\hat{P}^b \cdot \hat{S}| A_{SL} + |\hat{P}^b \cdot \hat{L}| A_{LL})) \quad (4-5)$$

Combining a pair of runs with the same incident beam energy and angle setting, the two different target polarization states and the two different beam polarization states gave four equations, one for each combination of beam and target polarization state. These four equations were then used to solve for the four unknowns, I_0 , A_{NO} , A_{SL} , and A_{LL} . Since A_{SL} and A_{LL} are always summed together with the same $|\hat{P}^b \cdot \hat{S}|$ and $|\hat{P}^b \cdot \hat{L}|$ coefficients they could not be determined independently at this point. The three unknowns that could be determined at this point were I_0 , A_{NO} , and A' , where $A' = |\hat{P}^b \cdot \hat{S}| A_{SL} + |\hat{P}^b \cdot \hat{L}| A_{LL}$. Since the four measurements overdetermine the three unknowns, χ^2 minimization could be used to reduce the four equations to three. The problem then becomes a matter of inverting a symmetric 3×3 matrix to solve for the three unknowns. Details of the χ^2 minimization as well as the yield and polarization calculations are given in Appendix B. EASY also calculated the random error of the spin correlation parameters from the statistical errors of the yields and uncertainties of the beam and target polarizations measurements. The pion c.m. angle for each angle bin was also calculated by EASY to be the average c.m. angle of counts in each angle bin.

Separating A_{SL} and A_{LL} from A' sometimes required further calculations. If the beam was pure longitudinal then $A' = A_{LL}$ and no further

calculations were necessary. Otherwise data from two different beam spin orientations were used to give two equations for A' to solve for the two unknowns A_{SL} and A_{LL} . Further details are given in Appendix B.

Systematic Uncertainty

The errors computed by EASY and quoted in Tables 5-1 and 5-2 of Chapter V reflect the statistical uncertainties in the yield and polarization measurements. In addition to the statistical uncertainties there are a number of systematic errors in these quantities which should be considered. A discussion of the various sources of systematic error is presented below and a summary of these errors is given in Table 4-2.

Target Polarization

Systematic error in determining the absolute target polarization was the result of systematic uncertainty in the calibration coefficient POLCAL. A secondary measure of the calibration, by comparing the measured $pp+pp$ target asymmetry A_{ON} to the beam asymmetry A_{NO} , was not possible with a longitudinal target. However a previous experiment at LAMPF³⁷, which used a target polarized along the $\hat{N}$ axis and a similar NMR system, was able to use this technique to show that the calibration was good to within $\pm 2\%$. A second source of systematic error came from the assumption that the calibration remains constant with time. A plot of POLCAL vs. time shows the systematic error from this drift to be less than $\pm 2\%$.

Beam Polarization

The systematic error of the beam polarization varied depending on the method used to calculate it. If the polarimeter was used the systematic error in the beam polarization was determined by the uncertainty of the polarimeter's analyzing power to be $\pm 1/2\%$. If the beam's transverse spin component was too small to use the polarimeter, the quench ratio was used. The systematic error of quench ratio measurements was estimated to be $\pm 2\%$ for data taken during Cycle 33 and $\pm 1\%$ for Cycle 34.

In addition, the error in determining the spin orientation at the polarized proton target PPT must be considered. The spin orientation of the beam entering the experimental area was known to within $\pm 2^\circ$. If the beam had any transverse component, the $\pm 1^\circ$ uncertainty of its rotation through the spin precession and PPT magnets must be added to this.

Yield

For asymmetry experiments it is not necessary to determine the absolute yields, only the relative yields of the four beam and target states need be measured, and only systematic errors in these yields will effect the measurement of the spin correlation parameters. Since the data for each angle setting were taken in a cycle of four runs with two target reversals per cycle, while every thing else was kept the same, many such errors were eliminated. One source of systematic error came from the error of the integrated beam current measured by the ion chamber. An estimate of this error was made from measurements of the

relative beam current made by the polarimeter compared to that of the ion chamber. From this comparison it was found that for data taken during Cycle 33 (500 and 650 MeV), the two measurements agreed to within $\pm 3\%$ and $\pm 2\%$ respectively. For data taken during Cycle 34 the two measurements agree to better than $\pm 1\%$. The systematic error in the relative yield due to the uncertainty of the integrated beam current is expected to be about half this difference.

A second source of error was caused by variations in the beam tune. The yield would be reduced if the location and diameter of the beam spot changed to the extent that part of the beam no longer hit the target. The tune of the beam was checked periodically using the profile monitors and film burns. A continuous monitor of the beam quality was also provided by the beam-location-counter BLC. In general if the number of counts in BLC were to change by a factor of two or more the beam was checked with a film burn and retuned if necessary. Plots of yield vs. BLC showed no correlation as BLC varied by a factor of two or more. The systematic error due to bad beam tunes should be small ($< 1\%$).

A third source of systematic error came from the fact that events with more than one multiple hit per set of wire chamber planes were rejected by the analyzer. Multiple hits were most likely the result of a random background event occurring in coincidence with a true event. If the ratio of true to random events were to vary between beam and target spin states the number of rejected true events would also vary. This would introduce a false asymmetry into the final results. Since the analyzer is capable of correcting events with only one multiple hit

per set of planes this effect is removed to second order. One way the ratio of true to random events could be effected was by variations in the beam intensity. This happens because true events are proportional to the beam intensity while random events are proportional to the beam intensity squared. Care was taken during data taking to insure that the beam intensity remained constant to within 20% during each data taking cycle. Plots of yield vs. beam intensity for cycles of runs with beam intensity fluctuations showed no correlation between the two. The systematic error in the relative yield from beam intensity effects is estimated to be small ($<1\%$).

A second way in which the ratio of true to random events could vary is if the random events themselves possessed asymmetry. Most of the random events came from quasi-free pp scattering which should not show any asymmetry for a beam with no $\hat{N}$ spin component. However some of the random events are the result of elastic pp scattering. These events will have an asymmetry due to the non zero pp+pp spin correlation parameters A_{SL} and A_{LL} . Calculations of the asymmetry between the normal and reverse ratios of rejected multiple hit events to good events showed no such effect. The error in yield due to random event asymmetry should therefore be small ($<1\%$).

Background Subtraction

One final contribution to the systematic error came from the background subtraction. These background subtraction errors can be used to estimate an upper bound on the systematic error in the determination the relative yields. For data taken with the pion telescope the signal

peak was sharp and well defined and the background was quite broad and small, 5% or less. This shape allowed these backgrounds to be fit with precision. For data taken using the inside counter the signal peak tended to be much broader and sat upon a large 10 to 30% background. This condition made the fits much less precise. The accuracy of the fitted backgrounds could be checked by comparing the fitted background ratio to the ratio calculated using the carbon target data. For telescope data the two background ratios agreed to within $\pm 2\%$ absolute. The systematic error should be about half this value or $\pm 1\%$ absolute. For inside data the two ratios agreed to within only $\pm 8\%$ giving an error of about $\pm 4\%$ absolute. Since the background is subtracted by multiplying the yield by one minus the background ratio, an absolute percent error in the ratio is equivalent to a relative percent error in the yield.

In situations with small signals and large backgrounds, namely the 500 and 800 MeV inside counter data, the signal peak was too broad and the background too large to allow the background to be fit as a quadratic function beneath a gaussian shaped signal peak. For these two cases the background was fit without specifying a signal peak. The resulting over estimate of the background fit added an extra 5% to the systematic error of the background ratio.

Pion θ_{cm}

The pion polar center-of-mass angle θ_{cm} was determined two different ways depending on which pion detector was used. For data taken with the inside counter only the deuteron kinematics measured by the

spectrometer were used to determine θ_{cm} . Since the deuteron kinematics were highly compressed in the lab frame this gave a poor measure of θ_{cm} . For this case the systematic error of θ_{cm} was about $\pm 3^\circ$. When data was taken with the pion telescope information from both arms was used to calculate θ_{cm} . This gave a much better measure of θ_{cm} . The systematic error for this case was about $\pm 0.5^\circ$.

Table 4-2. Systematic uncertainties.

Target Polarization:	$\pm 4\%$	
Beam Polarization:	$\pm 0.5\%$	(Polarimeter)
	$\leq \pm 2\%$	(Quench Ratio)
Beam Spin Orientation:	$\leq \pm 3^\circ$	
Relative Yield:	$\pm 1.5\%$	(Cycle 33, 500 MeV data)
	$\pm 1\%$	(Cycle 33, 650 MeV data)
	$\pm 0.5\%$	(Cycle 34 data)
Background Subtraction:	$\pm 1\%$	(Pion telescope data)
	$\pm 4\%$	(Inside counter data)
	$\pm 9\%$	(Inside data w/o sig. peak fit)
θ_{cm} :	$\pm 0.5^\circ$	(Pion telescope data)
	$\pm 3^\circ$	(Inside data)

CHAPTER V

RESULTS AND CONCLUSIONS

Experimental Results

Numerical results of the two spin correlation parameters, A_{LL} and A_{SL} are given in Tables 5-1 and 5-2. These data are also plotted along with several partial wave analysis and theoretical predictions in figures to be discussed later. Since A_{LL} is symmetric about $\theta_{cm} = 90^\circ$, data taken at $\theta_{cm} > 90^\circ$ have been folded over to produce plots which range from 0 to 90° . Errors indicated on the plots and given in the tables are purely statistical. Systematic errors are estimated in Chapter IV to be less than 7%. The angle bin width of each point is approximately $\pm 5^\circ$.

The actual kinetic energy of the incident proton beam delivered to the experiment was often a few MeV less than the quoted value. In addition the energy of the incident beam was reduced further by energy loss as it passed through the target material and surrounding cryostat. Table 5-3 lists the true incident kinetic energy after the expected energy loss for each of the six nominal energies. The uncertainty of the value of the true incident energy minus the expected energy loss is estimated to be ± 4 MeV.

Comparison of the data at 500 MeV with that of Aprile et al.⁴³ of SIN is shown in Figure 5-1. Considerable differences exist between the LAMPF and the SIN A_{LL} results near 90° . The disagreement with the SIN result is not presently understood. However one major difference between the two experiments was that this experiment used a magnetic

Table 5-1. A_{LL} vs θ_{cm}

500 MeV			600 MeV			650 MeV		
A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}
-0.635	.037	41.3	-0.457	.020	39.7	-0.267	.028	37.2
-0.597	.040	49.9	-0.399	.022	48.3	-0.291	.029	40.9
-0.598	.035	50.7	-0.376	.020	49.6	-0.188	.027	46.4
-0.568	.035	54.9	-0.361	.022	57.1	-0.222	.040	50.0
-0.526	.041	59.2	-0.336	.027	57.3	-0.126	.029	50.5
-0.618	.036	60.2	-0.341	.020	60.5	-0.225	.027	55.5
-0.578	.033	61.5	-0.359	.028	63.7	-0.188	.050	59.0
-0.628	.042	68.2	-0.317	.030	63.9	-0.145	.039	59.3
-0.572	.034	69.3	-0.317	.022	67.4	-0.112	.029	59.9
-0.446	.034	92.4	-0.354	.031	68.3	-0.129	.056	63.4
-0.532	.040	92.6	-0.332	.028	71.0	-0.080	.052	65.9
-0.518	.031	93.8	-0.305	.036	73.6	-0.110	.060	68.6
-0.548	.033	105.9	-0.369	.033	73.9	-0.102	.040	68.8
-0.494	.031	106.9	-0.376	.034	89.5	-0.079	.053	73.2
-0.527	.028	108.8	-0.290	.033	103.2	-0.045	.060	74.6
-0.532	.034	116.1	-0.346	.032	105.5	-0.030	.028	82.0
-0.476	.036	117.8	-0.297	.030	117.9	-0.006	.027	97.6
-0.495	.031	119.4	-0.329	.027	127.8	-0.090	.027	110.3

700 MeV			750 MeV			800 MeV		
A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}
-0.290	.022	39.7	-0.330	.025	36.3	-0.080	.022	49.6
-0.151	.022	48.8	-0.248	.030	39.8	0.031	.028	58.2
-0.141	.022	49.6	-0.187	.024	45.9	0.082	.023	58.4
-0.095	.023	57.6	-0.136	.023	48.7	0.139	.027	64.5
-0.066	.025	57.9	-0.105	.029	49.6	0.152	.036	67.2
-0.027	.021	60.3	-0.033	.023	55.9	0.242	.022	68.3
-0.044	.032	63.8	0.008	.023	57.9	0.243	.037	71.4
0.001	.025	64.6	0.009	.026	58.2	0.277	.026	72.3
0.029	.022	67.9	0.019	.029	60.4	0.304	.039	76.7
0.031	.032	68.5	0.045	.032	64.1	0.401	.043	83.4
0.052	.026	72.5	0.092	.027	64.9	0.413	.049	96.4
0.080	.031	74.1	0.135	.024	68.1	0.354	.042	103.1
0.155	.040	86.3	0.157	.034	68.9	0.336	.045	107.8
0.132	.037	94.1	0.205	.027	72.4	0.241	.037	114.7
0.122	.039	100.2	0.217	.033	74.5	0.062	.033	123.9
0.137	.032	103.6	0.243	.026	83.4			
0.100	.033	108.3	0.359	.039	87.3			
-0.002	.038	111.1	0.321	.026	97.8			
0.094	.029	111.9	0.257	.037	102.1			
0.034	.031	115.2	0.222	.046	109.8			
-0.053	.033	118.6	0.185	.026	110.6			
-0.075	.028	122.6	0.111	.038	114.2			
-0.031	.028	123.5	0.065	.037	119.9			
-0.139	.024	130.9	-0.022	.033	127.4			

Table 5-2. A_{SL} vs θ_{cm}

500 MeV			650 MeV			800 MeV		
A_{SL}	ERROR	θ_{cm}	A_{SL}	ERROR	θ_{cm}	A_{SL}	ERROR	θ_{cm}
-0.475	.031	41.3	-0.623	.064	37.2	-0.836	.026	49.6
-0.556	.050	49.9	-0.670	.049	40.9	-0.877	.030	58.2
-0.475	.030	50.7	-0.673	.062	46.4	-0.844	.028	58.4
-0.493	.033	54.9	-0.742	.050	50.0	-0.762	.029	64.5
-0.530	.052	59.2	-0.711	.045	50.5	-0.806	.039	67.2
-0.570	.030	60.2	-0.717	.056	55.5	-0.812	.027	68.3
-0.577	.033	61.5	-0.668	.070	59.0	-0.759	.040	71.4
-0.570	.054	68.2	-0.728	.046	59.3	-0.774	.028	72.3
-0.566	.034	69.3	-0.750	.043	59.9	-0.765	.043	76.7
-0.481	.032	92.4	-0.793	.064	63.4	-0.697	.046	83.4
-0.367	.033	92.6	-0.787	.077	65.9	-0.739	.046	96.4
-0.420	.033	93.8	-0.841	.069	68.6	-0.740	.048	103.1
-0.382	.029	105.9	-0.836	.044	68.8	-0.689	.042	107.8
-0.400	.028	106.9	-0.746	.075	73.2	-0.640	.046	114.7
-0.416	.027	108.8	-0.809	.064	74.6	-0.580	.041	123.9
-0.351	.033	116.1	-0.790	.028	82.0			
-0.395	.032	117.8	-0.730	.026	97.6			
-0.419	.030	119.4	-0.654	.026	110.3			

Table 5-3. Nominal vs True incident proton energies.

Nominal kinetic energy	True kinetic energy - energy loss
500 MeV	488 MeV
600 MeV	589 MeV
650 MeV	640 MeV
700 MeV	692 MeV
750 MeV	743 MeV
800 MeV	793 MeV

Figure 5-1. LAMPF vs SIN A_{LL} and A_{SL} measurements at 500 MeV.
 Dots: LAMPF (this experiment), Crosses: SIN (Aprile et al.)

spectrometer to momentum analyze the scattered deuterons while the SIN experiment of Aprile et al. did not. Analysis of the deuteron momentum was found to be important in reducing the background contamination of the signal events in this region which were about 20% for this

experiment. In addition the discrepancy may be the result of using different background subtraction techniques. The SIN experiment subtracted backgrounds empirically using carbon target data while we subtracted backgrounds analytically by fitting peak shapes.

Three Levels of Analysis

The experimental results can be analyzed at three different levels: purely phenomenological analysis, partial wave analysis, and comparison with theory. Phenomenological, or model independent analysis, interprets basic properties of the experimental observables, such as symmetries, without the use of any detailed theoretical input. Although the amount of information that can be learned from this approach is limited its conclusions are completely reliable. Partial wave analysis (PWA) is not a theory. It is a parameterization of the experimental observables in terms of the partial wave amplitudes in one particular reaction channel. It correlates different types of data in that channel and is capable of revealing inconsistencies in the data, making predictions of unmeasured observables, and revealing structure in the partial wave amplitudes. Finally there is "theory" which predicts the partial wave amplitudes and experimental observables, in one or more of the reaction channels, by describing the reaction in terms of the interactions involved. As described in Chap. II a number of theories have been developed which have varying degrees of sophistication and success. We present below a discussion of our results in terms of each of these levels of analysis.

Phenomenological Analysis

As described in Chapter II we can derive the amplitudes $|T_6|$ and $|S|$ and the relative phase δ at $\theta_{cm} = 90^\circ$, in a completely model independent manner. These are plotted as a function of the incident beam energy in Figures 5-2 and 5-3. Similarly we can obtain in a purely phenomenological manner the spin dependent cross-sections σ^T and σ^{SM} , which are respectively the sum of the squared triplet amplitudes, and the sum of the squared singlet and mixed amplitudes. These are plotted as a function of energy at $\theta_{cm} = 50, 70$, and 90° in Figures 5-4 and 5-5. Errors shown in these plots are statistical errors only. Values of A_{NN} , and A_{NO} used to calculate $|T_6|$, and δ were taken from Tippens et al.⁴⁴, and Saha et al.⁴⁵ respectively. The unpolarized cross-sections σ_{00} were calculated from coefficients of fits to the world data by Saha et al.⁴⁵ These figures include the measurements of Aprile et al.⁴³ along with several theoretical and partial wave analysis predictions to be discussed later.

From early cross-section measurements it is well known that the $pp \rightarrow \pi d$ reaction within the 500 to 800 MeV energy range is dominated by the effects of the NA intermediate state. Within this energy range partial waves up to $L_\pi = 2$ are the most important while higher partial waves are suppressed by the centrifugal barrier. A list of the partial wave amplitudes up to $L_\pi = 5$, as defined by Mandl and Regge²⁷ and extended by Blankleider and Afnan²⁴, in terms of the initial pp and final pion states, is given in Table 5-4. Also listed are the L_Δ , the relative angular momentum between the nucleon and the Δ if the reaction proceeds through the NA intermediate state. $L_\Delta = *$ indicates that no

Figure 5-2. $|T_6|$, $|S|$, and δ vs T_p , (Experiment and Partial Wave Analysis). Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Hiroshige et al. D type solution (Ref. 46), Dashed curve: Watari et al. (Ref. 47).

Figure 5-3. $|T_6|$, $|S|$, and δ vs T_p , (Experiment and Theory).
Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43),
Solid curve: Lyon (Ref. 48), Dot Dash curve: Blankleider and Afnan
(Ref. 24), Dashed curve: Popping and Sauer (Ref. 49).

Figure 5-4. σ^{SM} and σ^T vs T_p at $\theta_{cm} = 50, 70$, and 90° , (Experiment and Partial Wave Analysis). Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Hiroshige et al. D type solution (Ref. 46), Dashed curve: Watari et al. (Ref. 47).

Figure 5-5. σ^{SM} and σ^{T} vs T_p at $\theta_{\text{cm}} = 50, 70, \text{ and } 90^\circ$, (Experiment and Theory). Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Lyon (Ref. 47), Dot Dash curve: Blankleider and Afnan (Ref. 24), Dashed curve: Popping and Sauer (Ref. 49).

Table 5-4. Notation for the partial wave amplitudes.

Amplitude	$2^{S+1}L_{PJ}$	L_π	L_Δ	Amplitude	$2^{S+1}L_{PJ}$	L_π	L_Δ
a_0	1S_0	1	*	a_8	1G_4	3	2
a_1	3P_1	0	1	a_9	3F_3	4	1
a_2	1D_2	1	0	a_{10}	3F_4	4	3
a_3	3P_1	2	1	a_{11}	3H_4	4	3
a_4	3P_2	2	1	a_{12}	3H_5	4	3
a_5	3F_2	2	1	a_{13}	1G_4	5	2
a_6	3F_3	2	1	a_{14}	1I_6	5	4
a_7	1D_2	3	0				

$\text{N}\Delta$ intermediate state is possible. If the partial wave amplitudes are in fact being dominated by the $\text{N}\Delta$ resonance this should show up as a peak in the energy dependence of the amplitudes at an energy corresponding to the formation of an $\text{N}\Delta$ intermediate state. If the deuteron had no binding energy, and hence no fermi motion, one would expect $L_\Delta=0$ intermediate $\text{N}\Delta$ states to be formed at a pion lab energy of 175 MeV which corresponds to an incident proton lab energy of 637 MeV. However as explained by Bugg⁵⁰, this energy will be shifted down by approximately 67 MeV due to the 70 MeV/c spectator momentum of the nucleons and the kinematics which favor the formation of $L_\Delta=0$ $\text{N}\Delta$ states through a head-on collision between the proton and the pion. For intermediate $\text{N}\Delta$ states with relative angular momentum $L_\Delta=1$ or greater, the centrifugal barrier will cause the peaks to occur at progressively higher energies. Thus the singlet amplitude $^1D_2(1)$ which has an

intermediate $L_{\Delta}=0$ NA state should peak near 570 MeV, while the $L_{\Delta}=1$ amplitudes ${}^3P_1(2)$, ${}^3P_2(2)$, ${}^3F_2(2)$, and ${}^3F_3(2)$ should peak near 660 MeV.

From the angular distributions of A_{SL} and A_{LL} it is difficult to tell which of the amplitudes are the more important. However from equation 2-18h we can see that if the reaction is dominated by the triplet amplitudes the value of A_{LL} should be near +1. Conversely if the reaction is dominated by the singlets A_{LL} should be near -1. As the values of A_{LL} indicate neither the singlet or triplet amplitudes are dominant at all energies. The general trend appears to be that the singlet amplitudes are stronger at lower energies while the triplets are stronger at higher energies. Plots of σ^T , σ^{SM} and amplitudes $|T_6|$, $|S|$ (Figures 5-2 through 5-5) also confirm this trend. These plots also show that σ^{SM} , which is dominated by the 1D_2 amplitude, peaks near 570 MeV. Similarly the triplet cross-section, which are fed by the 3P_1 , 3P_2 , 3F_2 , and 3F_3 initial states, peak near 660 MeV. This is precisely what we expected if the reaction is dominated by the NA initial state.

Although the phase δ cannot reveal anything about the relative strengths of the amplitudes S and T_6 it is sensitive to the presence of any resonance like phenomena. Since δ is observed to vary by less than 35° over the measured energy range this is a good indication that there are no resonance effects in the amplitudes S and T_6 which determine δ .

Partial Wave Analysis

In Chapter II it was described how the spin observables are formed from bilinear combinations of the six complex helicity amplitudes M_1 ,

T_2 , T_3 , M_4 , S , and T_6 , which in turn can be expressed as sums over the partial wave amplitudes $\alpha_{L_p L_\pi}^S(J)$. It is the purpose of partial wave analysis (PWA) to determine the partial wave amplitudes which will give the best fit to the experimental data over the given energy range. In principle, given a complete set of data over some energy range, different PWA should arrive at the same set of partial wave amplitudes. In practice this is never the case. One never has a complete set of data. In addition only a finite number of amplitudes can be determined requiring the series of partial waves to be terminated at some value of L_π or L_p where the amplitudes are expected to be small. Higher partial waves can be set to zero or taken from theory. Furthermore restrictions on permissible energy variations of the parameters as well as the choice of starting points for the parameter search can also influence the outcome of the PWA. To date a number of energy dependent partial wave analysis of the $pp \rightarrow \pi d$ channel have been completed. One such analysis is that of Strakovsky et al.⁵¹ at Leningrad. These authors used over 1000 data points from the global data available as of 1982 to make an analysis of the partial wave amplitudes with $L_\pi \leq 4$ in the energy range from 440 to 1240 MeV. Higher partial waves, which should be small, were set to zero. The global data set as of 1982 consisted primarily of differential cross-section and asymmetry measurements. The only spin correlation data that were available were that of Aprile et al.⁴³ and of Hoftiezer et al.⁵² from SIN which were all at energies below 580 MeV. By omitting some of the older less reliable data to minimize the χ^2 of the resulting solution, and by requiring a

resonance like energy dependence of the amplitudes, these authors arrived at a single energy dependent solution.

Several partial wave analysis of the $pp \rightarrow \pi d$ channel have also been made by the group of Watari et al. at Osaka.^{46,47} Their initial analysis (Hiroshige et al.⁴⁶) was similar to that of Strakovsky et al.⁵¹ in that they also used the global data available as of 1982 to find solutions to the partial wave amplitudes with $L_\pi \leq 4$ while higher partial waves were set to zero. However their energy range was from near threshold (≈ 288 MeV) to 810 MeV. This analysis resulted in two sets of solutions referred to as the S and the D type solutions. The D solutions, which have large $^1D_2(1)$ and $^3F_3(2)$ amplitudes, were preferred over the S solutions, which had large $^1S_0(1)$ amplitudes, because the S solutions violated the two channel unitarity condition. The Osaka group have recently completed a second analysis (Watari et al.⁴⁷) in the same energy range. This analysis uses the same data set as before plus the additional spin correlation data of this experiment as well as that of Tippens et al.⁴⁴ to calculate the amplitudes a_0 to a_8 ($L_\pi \leq 3$) from threshold up to 810 MeV. Higher partial wave amplitudes are either taken from the theory of Lyon group⁴⁸ or set to zero. Given only nine amplitudes to determine with an extended data set as well as some restrictions on the higher partial wave amplitudes, this second analysis arrives at just one solution.

Finally a partial wave analysis has recently been completed by Bugg.⁵⁰ Bugg's analysis uses essentially the same data set as the Osaka group's latest analysis to determine the partial wave amplitudes up to a_6 ($L_\pi \leq 2$) from 450 to 800 MeV. Amplitudes a_7 to a_{14} are taken

from the theory of Blankleider and Afnan²⁴ while still higher partial waves are set to zero. In addition Bugg finds that the value of a_3 is small and that the χ^2 of the solution is improved by setting it to zero. Given only six amplitudes to determine, Bugg's analysis finds just one solution. However the choice of $a_3=0$ and the reliance on theory to predict more of the higher partial wave amplitudes leaves Bugg's analysis considerably more model dependent than the analysis of Watari et al. Both Watari et al. and Bugg determine the energy dependence of the amplitudes by finding a number of energy independent solutions within the energy range and requiring these solutions to have a smoothly varying energy dependence which can be interpolated to find the amplitudes at any energy within the energy range.

Results of the different PWA calculations are plotted along with the data in Figure 5-6. Due to the lack of spin correlation data above 600 MeV the initial PWA predictions of Hiroshige et al.⁴⁶ and Strakovsky et al.⁵¹ do a poor job of fitting the data above this energy. The difference between the Osaka group's two results show how much the analysis have been improved by the inclusion of the new data. Comparison of Bugg's⁵⁰ and Watari et al.'s⁴⁷ latest PWA predictions to the data shows that these analysis are now able to fit the data reasonably well. As shown in Figure 5-7 both these analysis predict large a_2 and a_6 amplitudes which peak near energies of 570 and 660 MeV respectively, indicating that the interaction is dominated by the NA intermediate state through the 1D_2 and 3F_3 initial pp states. The energy dependence and phases of the amplitudes predicted by these analysis also fail to show any evidence of dibaryon resonances.

Figure 5-6. A_{LL} and A_{SL} vs θ_{cm} , (Experiment and Partial Wave Analysis).
Dots: This experiment, Dot Dash curve: Strakovsky et al. (Ref. 51),
Solid curve: Hiroshige et al. D type solution (Ref. 46), Dashed curve:
Watari et al. (Ref. 47), Dotted curve: Bugg (Ref. 50).

Figure 5-7. The Energy dependence of the partial wave amplitudes a_2 and a_6 . Dotted curve: Bugg (Ref. 50), Dashed curve: Watari et al. (Ref. 47).

Theoretical Analysis

Results of the unified theory calculations of the Lyon group⁴⁸, Blankleider and Afnan²⁴, and Popping and Sauer⁴⁹ are compared to the data of this experiment in Figure 5-8. Despite the fact that these authors agree on the basic ingredients there are still large differences among them as to how pion absorption should be taken into account

Figure 5-8. A_{LL} and A_{SL} vs θ_{cm} , (Experiment and Theory).
Dots: This experiment, Solid curve: Lyon (Ref. 48), Dot Dash curve: Blankleider and Afnan (Ref. 24), Dashed curve: Popping and Sauer (Ref. 49).

and what the πN and NN scattering potentials should be. Heavy vector meson exchange was not included in either calculation. None of the theories are able to predict more than the general trend of the data. Plots of σ^{SM} and σ^{T} (Figure 5-5) show the underlying reason for this. All of these calculations do reasonably well in predicting the 1D_2 dominated singlet contribution but both the Lyon group and Blankleider and Afnan significantly underestimate the triplet contribution. Popping and Sauer do somewhat better, especially above 650 MeV, but have a peculiar oscillation in the triplet contribution, σ^{T} , around 575 MeV. It is not clear at this stage what ingredient has been left out in all these theories and what accounts for the often substantial differences between them. With such divergence between the results of these theories it would hardly be prudent to try to improve the agreement between any one of them and the data by adding artificial constructs such as dibaryons or other six-quark constructs.

Concluding Remarks

New and precise measurements of the $pp \rightarrow \pi d$ spin correlation parameters A_{SL} and A_{LL} have been obtained in the 500 to 800 MeV energy range. With the exception of the 500 MeV A_{LL} measurement near 90° there seems to be no disagreement with previous data when they exist (< 600 MeV). The partial wave analysis of the Osaka group and Bugg have been much improved by the inclusion of this new data. The results do not demonstrate the existence any structures other than those expected from the dominance of this reaction by the $N\Delta$ intermediate state with $L_\Delta = 0$ and 1. Results of the theoretical predictions based on different

variants of unified model look promising but are not yet at the point at which new constructs such as dibaryons may be built upon them. Hopefully the present experiment will contribute towards improving the theories and lead to a definitive conclusion about possible dibaryon resonances with masses less than 2241 MeV.

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Measurement of the $pp \rightarrow \pi d$ Spin Correlation Parameters A_{SL} and A_{LL} at Energies Between 500 and 800 MeV

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MEASUREMENT OF THE $pp \rightarrow \pi d$ SPIN CORRELATION PARAMETERS
 A_{SL} AND A_{LL} AT ENERGIES BETWEEN 500 AND 800 MeV

by

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ABSTRACT

Angular distributions of the spin correlation parameters A_{SL} and A_{LL} for the inelastic reaction $pp \rightarrow \pi d$ have been measured at pion center-of-mass angles between 40° and 130° , at energies of 500, 650, and 800 MeV. Additional measurements of $A_{LL}(\theta)$ were made at 600, 700, and 750 MeV. The reaction was studied using an incident beam of either longitudinally or transversely polarized protons and a target of longitudinally polarized protons. Both the final state pion and deuteron were detected in a two-armed detector system. The momenta of particles detected in the deuteron arm were analyzed with a magnetic spectrometer which allowed the deuterons to be distinguished from particles produced by quasi-free, three-body, or other background reactions.

A_{SL} was found to be negative (≈ -0.5) at 500 MeV. It became increasingly more negative as energy increased, going down to as low as -0.88 at forward angles at 800 MeV. A_{SL} showed only a slight angular dependence in the entire energy range. The angular distribution of A_{LL} was found to be almost flat at 500 (≈ -0.5) and 600 MeV (≈ -0.4). As energy increased A_{LL} became less negative and began to peak at $\theta_{cm} = 90^\circ$. At 800 MeV A_{LL} was positive at almost all measured angles and had a well defined peak at $\theta_{cm} = 90^\circ$ which reached a maximum of about $+0.4$.

The data were compared to several partial wave analyses and to theoretical calculations based on unified theories of $NN \rightarrow NN$, $\pi d \rightarrow \pi d$, and $NN \rightarrow \pi d$ reactions. In general these later calculations were found to be unsuccessful in fitting our data. Partial wave analyses, which included the present data, fitted the data reasonably well and did not indicate the need for any unusual (dibaryon like) structures in any of the partial waves.

CHAPTER I

INTRODUCTION

Introduction

The role of pions in nucleon-nucleon (NN) interactions has been of interest to physicists since their discovery by Powell¹ in 1947. The reaction $pp \rightarrow \pi d$, being the simplest example of pion production, has been the center of many experimental and theoretical investigations concerning the mechanism of pion production and nuclear forces. Until recently experiments on this reaction had been limited to a few differential cross-section and polarization measurements. These measurements were capable of revealing much about the general form of the reaction, but were insensitive to many of the finer details.

Recent advances in the theoretical understanding of the NN interaction and pion production have made it interesting to perform additional measurements. In the past, theories treated elastic and inelastic NN scattering as two separate reactions. However the two channels are obviously coupled and the theory must consider the two together. Since the πd reaction is the first inelastic pp channel to open (at 268 MeV) it provides a critical test for such theories. Study of the $pp \rightarrow \pi d$ reaction may also shed light on the question of the existence of dibaryon resonances. Theoretical discussions of dibaryons date back to 1963² and 1968³. The modern interest started with measurements of the spin dependent total pp cross-section differences $\Delta\sigma_T$ and $\Delta\sigma_L$ made by an Argonne-Northwestern group⁴ and a Rice-Houston group⁵ at the Argonne ZGS. Phase shift analysis (PSA) of these and other NN data

were made by several authors^{6,7,8} and the dibaryon resonance hypothesis was advanced. The various PSA differed in details but all agreed that dibaryon resonances, if they exist, must be mostly inelastic. It follows that the best place to look for them is in single pion production, e.g. $pp \rightarrow pn\pi$, or $pp \rightarrow \pi d$. Although the cross-sections for the two channels are approximately the same at 500 MeV, the $pp \rightarrow pn\pi$ channel rapidly begins to dominate the inelastic single pion production cross-section as energy increases, accounting for about 95% of the cross-section at 800 MeV. In spite of this the $pp \rightarrow \pi d$ channel is still an important channel to study because its two-body final state is much simpler to study theoretically as well as experimentally. In addition, because of the strong coupling which exists between the two channels, the $pp \rightarrow \pi d$ channel should contain most of the same effects of the phenomena found in the dominant $pp \rightarrow pn\pi$ channel.

Coincidentally the recent development of both polarized beams and targets has revolutionized the technology of spin dependent measurements. Measurements which formerly were impossible or required double or triple scattering can now be made by a single scattering experiment. As a consequence there has been a resurgence on the part of experimentalist to use this technology to expand the volume of spin dependent data in all NN channels including the inelastic channels.

In this dissertation we will describe the measurement of the $pp \rightarrow \pi d$ spin correlation parameters $A_{SL}(\theta)$ and $A_{LL}(\theta)$ at six different energies between 500 and 800 MeV. The measurements not only contribute to our understanding of inelasticity in nucleon-nucleon collisions, but shed light on the dibaryon conjecture.

CHAPTER II

THEORY AND FORMALISM

Theory

Several historical reviews on the development of the theory of pion production from NN interactions have been published to date. Lazard et al.⁹ gives a summary of the theoretical work done on pion absorption by deuterium (the inverse of pion production) up to 1969. More recent reports by Thomas and Landau¹⁰ on πd and π -nucleus scattering, and by Betz et al.¹¹ on pion production in nucleon-nucleon collisions, extend the reviews of the theoretical developments up to 1981.

The first theories of pion production emerged only a few years after the discovery of the pion in 1947. This first generation of theories was started in 1951 when Chew et al.¹² calculated the matrix element for pion production using a simple impulse approximation. A few years later, after the Chew-Wick^{13,14} field theory description of πN dynamics had been developed, more sophisticated theories began to emerge which used this approach to include the effect of pion rescattering through the recently discovered $\Delta(3,3)$ resonance. Although the results of these early theories, by such authors as Lichtenberg¹⁵, Aitken et al.¹⁶, and Durney¹⁷, were in reasonable agreement with the existing experimental data, they were limited to energies near the pion production threshold. This low energy limitation was the result of using non-relativistic kinematics, considering only the pion s and p waves, and not including the effect of pion multiple rescattering.

The next advance in the theory came in 1960 in a paper by Woodruff.¹⁸ Woodruff used Chew-Wick field theory and nuclear wave functions calculated from the Gammel-Thaler potential, to derive a formally correct expression to second order in the πN interaction. Further refinements were added to this theory over the next decade by Koltun and Reitan¹⁹ and Lazard et al.⁹ Although these authors were able to include the effects of pion scattering to first order they neglected the higher order multiple scattering terms which were later found to have a significant effect at higher energies. The second generation theories represented definite improvements over the earlier ones, but they were still valid only at lower energies because, only the pion was treated relativistically, only the pion s and p waves were considered, and multiple rescattering was only calculated to first order.

The present phase of the theoretical work began in the mid 1970's when the need to extend to higher energies forced theorists to seriously consider the higher order effects of multiple pion rescattering through the $\Delta(3,3)$ resonance. The first step towards this goal was the development of the coupled channels model (CCM).²⁰ Theories in the past had always used a conventional potential model where NN scattering was the result of a potential acting between the two nucleons. The CCM is a generalization of this whereby the potential between the internal Δ and N^* excitations and the nucleons are included. These isobar states are coupled to the NN state by coupling potentials derivable from meson exchanges between the two baryons. Green and Niskanen²⁰ were some of the first to use the CCM in their theory for the $pp \rightarrow nd$ re-

action and its inverse. Their work led to a set of coupled differential equations involving the NN , $N\Delta$, and $\Delta\Delta$ channels. Moreover their model allowed a complete summation of the multiple rescattering terms for pion production and could include the effects of heavy meson as well as pion exchanges. These higher order terms were found to have as much as a 20% effect on some amplitudes. However this model had several drawbacks; the coupling constants were static, the theory was essentially non-relativistic and three-body unitarity was only approximately conserved. The attempt to rectify the unitarity problem led theorists to the development of the unified theories which could simultaneously describe all three NN , $NN\pi$, and πd channels. Through the work of such authors as Afnan and Thomas²¹, Mitzutani and Koltun²², Thomas and Rinat²³, Blankleider and Afnan²⁴, Rinat and Starkand²⁵, and Fayard et al.²⁶, emerged a consistent set of exactly unitary coupled integral equations which had the form of the Faddeev equations. These unified theories enabled exact summation over all pion multiple rescattering terms (however with the restriction that no more than one pion at a time be involved in the intermediate state). Although the effects of heavy meson exchanges did not appear readily in these theories, they could be included along with relativistic corrections. Detailed predictions from several authors are now available. These predictions of the spin correlation parameters are presented along with the experimental data in Chapter V.

Formalism

Ever since the dichotomy arose in the 19th century between theoretical and experimental physics there has been a need for a formalism common to both. Such a formalism enables comparisons to be made between theory and experiment by parameterizing the data in a physically meaningful way. Over the years a number of similar formalisms based on the S-matrix have been developed which relate the spin observables of the reaction to the scattering amplitudes.^{27,28,29,30} In this section the notation of Foroughi³¹ will be used to derive the formalism for the specific reaction $pp \rightarrow \pi d$, where no final state spins are observed. A more general discussion of the formalism for binary reactions involving particles of arbitrary spins is given in Bourrely et al.³²

Foroughi's formalism (as well as many others) refers to a particle's spin component by the relativistically invariant quantity known as the helicity λ . Instead of labeling particle spin states by their component along some fixed axis the helicity description labels particle states along their direction of motion. Since the formalism is relativistic the natural coordinate system to use is the center-of-mass (CM) coordinate system illustrated in Figure 2-1a. Since measurements of spin observables are made in the laboratory (LAB) the coordinate system illustrated in Figure 2-1b is often used. The discussion in this chapter will use the CM x-y-z system while latter chapters will refer to the LAB L-N-S (for longitudinal, normal, and sideways) coordinate system. In both cases the sign of $\hat{y}$ or $\hat{N}$ is chosen to form a

Figure 2-1a. CM x-y-z coordinate system.

Figure 2-1b. LAB L-N-S coordinate system.

right-handed coordinate system. The transformation from one system to another is trivial if the spin of the deuteron is not observed.

The S-matrix formalism describes scattering processes by a scattering amplitude which depends on the kinematical variables and quantum numbers of the particles involved in the scattering. The scattering amplitude has the form of a matrix in spin and charge space. Since the two spaces are independent (except for the exclusion principle) they can be discussed separately. In the following section we will construct the most general form of the scattering matrix which describes the reaction $pp \rightarrow \pi d$ in spin space. The elements of this matrix, known as the helicity matrix H , can be defined as the elements of the transition matrix taken between final and initial helicity states,

$$H_{\lambda_{\pi}\lambda_d; \lambda_b\lambda_t}(\theta, \phi) = \langle \theta\phi; \lambda_{\pi}\lambda_d | T | 00; \lambda_b\lambda_t \rangle \quad (2-1)$$

where $iT = 1 - S$, subscripts b and t refer to the beam and target protons, λ are the helicities, and θ and ϕ are the pion's polar and azimuthal cm scattering angles. Since $\lambda_{\pi} = 0$ the notation can be simplified somewhat,

$$H_{\mu; \lambda_b\lambda_t}(\theta, \phi) = \langle \theta\phi; \mu | T | 00; \lambda_b\lambda_t \rangle \quad (2-2)$$

where $\mu = \lambda_d$. Partial wave decomposition can be used to write the elements in terms of the d-functions and partial wave amplitudes $\alpha_{\lambda-\mu}^s(J)$:

$$H_{\mu; \lambda_b \lambda_t}(\theta, \phi) = -ie^{-i\lambda\phi} \sum_J (2J+1) H_{\mu; \lambda_b \lambda_t}^J d_{\lambda, -\mu}^J(\theta) \quad (2-3)$$

where $\lambda = \lambda_b - \lambda_t$, and

$$H_{\mu; \lambda_b \lambda_t}^J = \sum_{L_p L_\pi s} \frac{[(2L_p+1)(2L_\pi+1)]^{1/2}}{(2J+1)} \times \langle 1/2 \lambda_b, 1/2 -\lambda_t | s \mu \rangle \langle L_p 0, s \mu | J \mu \rangle \langle L_\pi 0, 1-\mu | J -\mu \rangle \alpha_{L_p L_\pi}^s(J) \quad (2-4)$$

$s=0,1$ for singlet and triplet pp states.

Since $\mu = \pm 1, 0$ and $\lambda_b, \lambda_t = \pm 1/2$ the elements of the helicity matrix

$H_{\mu; \lambda_b \lambda_t}$ will form a 3 by 4 matrix:

$$H = \begin{pmatrix} H_{+1,++} & H_{+1,+} & H_{+1,-} & H_{+1,--} \\ H_{0,++} & H_{0,+} & H_{0,-} & H_{0,--} \\ H_{-1,++} & H_{-1,+} & H_{-1,-} & H_{-1,--} \end{pmatrix} \quad (2-5)$$

The helicity matrix must obey certain known symmetry requirements.

Parity: Since both the deuteron and pion have integer spin but the pion has odd parity, while the deuteron has even, the matrix must transform under space inversion like a pseudo-scalar. This will require the elements of H to have the following property,

$$H_{-\mu; -\lambda_b -\lambda_t}(\theta, \phi) = -(-1)^{\lambda - \mu} H_{\mu; \lambda_b \lambda_t}(\theta, \pi - \phi) \quad (2-6)$$

This leaves only 6 independent helicity amplitudes which can be used to rewrite H as,

$$H = \begin{pmatrix} M_1 & T_2 e^{i\phi} & T_3 e^{-i\phi} & M_4 \\ S & T_6 e^{i\phi} & T_5 e^{-i\phi} & S \\ M_4 & -T_3 e^{i\phi} & -T_2 e^{-i\phi} & M_1 \end{pmatrix} \quad (2-7)$$

The letters S, T, and M are used to represent respectively, pure singlet, pure triplet, and mixed singlet-triplet amplitudes.

Exclusion Principle: Since there are two identical particles in the initial state its wave function must be anti-symmetric with respect to change in particle labels. This will require the helicity amplitudes to have the following property.

$$H_{u;\lambda_b\lambda_t}(\theta,\phi) = (-1)^u H_{u;\lambda_t\lambda_b}(\pi-\theta,\phi) \quad (2-8)$$

Thus S and T_6 must be symmetric about $\theta = \pi/2$ and M_1 and M_4 must be anti-symmetric about $\pi/2$, while $T_2(\theta) = -T_3(\pi-\theta)$.

Knowing H, the differential cross-section (σ) for an interaction where no final state spins are observed will be,

$$\sigma = \text{Tr}(\rho_{in} H^\dagger H) \quad (2-9)$$

where ρ_{in} is the initial spin density matrix of the two protons,

$$\rho_{in} = \frac{1}{4}(1 + \vec{P}^b \cdot \vec{\sigma}^b)(1 + \vec{P}^t \cdot \vec{\sigma}^t) \quad (2-10)$$

where $\vec{P}$ is the average polarization for the ensemble of particles,

$\vec{\sigma}$ are the Pauli spin matrix, and superscripts b and t refer to the beam and target. This definition of ρ_{in} can be used to write the differential cross-section as,

$$\sigma = \frac{1}{4} \text{Tr } W + \frac{1}{4} \sum_i p_i^b \text{Tr}(\sigma_i^b W) + \frac{1}{4} \sum_j p_j^t \text{Tr}(\sigma_j^t W) + \frac{1}{4} \sum_i p_i^b p_j^t \text{Tr}(\sigma_i^b \sigma_j^t W) \quad (2-11)$$

where $W = H^\dagger H$, and $i, j = x, y, z$. The traces represent the unpolarized and polarized differential cross-sections:

$$\sigma_{\alpha\beta} = \frac{1}{4} \text{Tr}(\sigma_\alpha^b \sigma_\beta^t W) \quad (2-12)$$

where $\alpha, \beta = 0, x, y, z$. The spin correlation parameters $A_{\alpha\beta}$ can be defined in terms of the differential cross-sections:

$$A_{\alpha\beta} = \frac{\sigma_{\alpha\beta}}{\sigma_{00}} = \frac{1}{4\sigma_{00}} \text{Tr}(\sigma_\alpha^b \sigma_\beta^t W) \quad (2-13)$$

where A_{00} has been normalized to 1. A list of all the non zero parameters is given in Table 2-1.

From the symmetry requirements of the helicity amplitudes one finds that the spin correlation parameters must have the following symmetry relations,

$$A_{y0}(\theta) = A_{0y}(\pi-\theta) \quad (2-14a)$$

$$A_{xz}(\theta) = A_{zx}(\pi-\theta) \quad (2-14b)$$

$$A_{xx}(\theta) = A_{xx}(\pi - \theta) \quad (2-14c)$$

$$A_{yy}(\theta) = A_{yy}(\pi - \theta) \quad (2-14d)$$

$$A_{zz}(\theta) = A_{zz}(\pi - \theta) \quad (2-14e)$$

The orthogonality relations of the helicity amplitudes can be used to find expressions for the four non-zero helicity amplitudes at $\theta = 90^\circ$ in terms of the spin correlation parameters,

$$|S|^2 = \sigma_{oo} (1 + A_{zz}) \quad (2-15)$$

$$|T_2|^2 = |T_3|^2 = \frac{\sigma_{oo}}{2} (1 - A_{yy}) \quad (2-16)$$

$$|T_6|^2 = \sigma_{oo} (A_{yy} - A_{zz}) \quad (2-17)$$

Table 2-1. Spin correlation parameters in terms of the helicity amplitudes.

CM LAB

$$A_{oo} = A_{00} = (1/(2\sigma_{oo})) (|M_1|^2 + |T_2|^2 + |T_3|^2 + |M_4|^2 + |S|^2 + |T_6|^2) \quad (2-18a)$$

$$A_{yo} = A_{N0} = (1/\sigma_{oo}) \operatorname{Im}(-M_4 T_2^* + M_1 T_3^* + S T_6^*) \quad (2-18b)$$

$$A_{oy} = -A_{ON} = (1/\sigma_{oo}) \operatorname{Im}(-M_4 T_3^* + M_1 T_2^* + S T_6^*) \quad (2-18c)$$

$$A_{zx} = -A_{SL} = (1/\sigma_{oo}) \operatorname{Re}(-M_4 T_2^* + M_1 T_3^* + S T_6^*) \quad (2-18d)$$

$$A_{zx} = A_{LS} = (1/\sigma_{oo}) \operatorname{Re}(-M_4 T_3^* + M_1 T_2^* + S T_6^*) \quad (2-18e)$$

$$A_{xx} = A_{SS} = (1/\sigma_{oo}) (\operatorname{Re}(M_1 M_4^* + T_2 T_3^*) - 1/2 |S|^2 + 1/2 |T_6|^2) \quad (2-18f)$$

$$A_{yy} = -A_{NN} = (1/\sigma_{oo}) (\operatorname{Re}(T_2 T_3^* - M_1 M_4^*) + 1/2 |S|^2 + 1/2 |T_6|^2) \quad (2-18g)$$

$$A_{zz} = -A_{LL} = (1/(2\sigma_{oo})) (|M_1|^2 - |T_2|^2 - |T_3|^2 + |M_4|^2 + |S|^2 - |T_6|^2) \quad (2-18h)$$

In addition δ , the relative phase between S and T_6 , can be found at $\theta = 90^\circ$ from the ratio of A_{y0} over A_{xz} ,

$$\delta = \tan^{-1}(A_{y0} / A_{xz}) \quad (2-19)$$

Thus model independent measurements of the singlet and triplet amplitudes and phase δ can be made at $\theta = 90^\circ$.

Two other model independent measurements, that can be made at all angles, are $\sigma^T \equiv \sigma_{00}(1-A_{zz})$ which is the sum of the squares of the triplet amplitudes, and $\sigma^{SM} \equiv \sigma_{00}(1+A_{zz})$ which is the sum of the squares of the singlet and mixed amplitudes.

To determine all six helicity amplitudes and their phases requires a minimum of 11 independent measurements over the angular range from 0 to 90° . Eight of these use polarized beam and/or target but do not include measurements of the deuteron's spin (e.g. σ_{00} , A_{y0} , A_{oy} , A_{xx} , A_{yy} , A_{zz} , A_{xz} , and A_{zx}). The remaining three measurements with polarized beam and target require that the spin of the final state deuteron be measured, (three of the observables t_{11} , t_{21} , and t_{20} or t_{22}).

By writing the general expression for the differential cross-section out in terms of the spin correlation parameters one can see how these quantities can be measured.

$$\begin{aligned} \sigma = \sigma_{00} \big(& 1 + (\bar{P}^b \cdot \hat{y})A_{y0} + (\bar{P}^t \cdot \hat{y})A_{oy} + (\bar{P}^b \cdot \hat{x})(\bar{P}^t \cdot \hat{z})A_{xz} + (\bar{P}^b \cdot \hat{z})(\bar{P}^t \cdot \hat{x})A_{zx} \\ & + (\bar{P}^b \cdot \hat{x})(\bar{P}^t \cdot \hat{x})A_{xx} + (\bar{P}^b \cdot \hat{y})(\bar{P}^t \cdot \hat{y})A_{yy} + (\bar{P}^b \cdot \hat{z})(\bar{P}^t \cdot \hat{z})A_{zz} \big) \end{aligned} \quad (2-20)$$

For example if both the beam and target are polarized along the z axis then equation 2-20 reduces to,

$$\sigma = \sigma_{00} (1 + (\vec{P}^b \cdot \vec{z})(\vec{P}^t \cdot \vec{z})A_{zz}) \quad (2-21)$$

By reversing the polarization of either the beam or target and measuring the differential cross-section for each polarization state the scattering asymmetry ϵ can be defined as,

$$\epsilon = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} \quad (2-22)$$

where $\uparrow$ indicates polarization along the $+z$ axis and $\downarrow$ along the $-z$ axis. Dividing ϵ by the beam and target polarizations gives the spin correlation parameter A_{zz} :

$$A_{zz} = \frac{\epsilon}{|\vec{P}^b| |\vec{P}^t|} \quad (2-23)$$

Thus measuring the spin correlation parameters is simply a matter of measuring the beam and target polarizations and the scattering asymmetry with the beam and target oriented along the various axis.

CHAPTER III

THE EXPERIMENT

Introduction

The experiments which constitute the subject of this dissertation were performed at the BR experimental area of the Los Alamos Meson Physics Facility (LAMPF). The purpose of the experiments was to measure the spin correlation parameters A_{SL} and A_{LL} of the reaction $pp \rightarrow \pi d$, within the energy range of 500 to 800 MeV. The reaction was studied using an incident beam of either longitudinally or transversely polarized protons and a target of longitudinally polarized protons. The scattered pions and deuterons were detected in a two-armed detector system which had a magnetic spectrometer for the deuterons and either a wire chamber telescope or a scintillation counter for the pions. The experimental set-up consisted of the following principal components; polarized proton beam, beam monitoring and control system, polarized proton target, deuteron spectrometer, pion detectors, and the data acquisition and on-line analysis system. Each of these components will be described in detail in the following sections.

The Beam

The beam of protons used in the present experiments was provided by the LAMPF linear proton accelerator.³³ The LAMPF accelerator consists of a 750 KeV Cockcroft-Walton injector, followed by a 100 MeV Alvarez-type drift tube linac, and finally a 805 MHz side-coupled cavity linac. The RF nature of the accelerator allows it to be

operated in an AC mode where both a high intensity H^+ beam and a low intensity H^- beam may be accelerated simultaneously. The beam current has a time structure characterized by 500 μs long macro-pulses which occur at a rate of 120 Hz. Each macro-pulse is further divided into 0.25 ns micro-pulses which occur every 5 ns.

The beam of polarized H^- ions used in the experiments was produced by a Lamb-shift ion source³⁴ which was capable of orienting the polarization vector in any desired direction. Since the several experimental areas which shared the polarized beam were all at different locations with respect to the main beam line the beam polarization vector was not the same at each area. This condition often resulted in a spin orientation which was chosen as a compromise between the requirements of the various experiments sharing the beam.

To reduce systematic effects in asymmetry measurements the beam polarization direction was reversed by the source every 2 to 3 minutes. The source also provided a means to measure the polarization by the "quench ratio" technique.³⁴ By detuning the source the polarized part of the beam can be quenched leaving only the unpolarized beam. The beam polarization is then given by the ratio of the two beam intensities. In practice the quenched beam intensity was measured for only a few seconds before each spin change. Because of the short duration of the quenched beam any anomaly in the beam intensity, unconnected with the quench, which might occur during this time could effect the measurement. This effect could be reduced by averaging the data from numerous quench ratio measurements. Because of the intensity fluctuations the quench ratio technique was a better measure of the

beam polarization over a long period (several hours), then over a short period (less than an hour).

The beam for this experiment had a polarization between 70 and 80% and an intensity from 0.1 to 1 pa. Data were taken over the summer of 1982 during two beam production cycles at a variety of beam energies and spin orientations which are listed in Table 3-1.

Table 3-1. Beam Energy and Spin Orientations.

<u>ENERGY (MeV)</u>	<u>ORIENTATION</u>	<u>CYCLE</u>	<u>DATES</u>
500	Mixed longitudinal and transverse	33	July 7-July 16
600	Longitudinal	34	Sep. 15-Sep. 18
650	Mixed longitudinal and transverse	33	July 18-July 26
700	Longitudinal	34	Sep. 11-Sep. 14
750	Longitudinal	34	Sep. 7-Sep. 10
800	Mixed longitudinal and transverse	34	Aug. 16-Sep. 2

The BR Beam Line

The BR beam line provided the means to control and monitor the incident proton beam. The beam to BR was diverted from the H^- beam by using a thin foil to strip the electrons off some of the H^- atoms in the beam to produce the H^+ beam which was then deflected by a dipole magnet. The intensity of the H^+ beam could be adjusted by varying the amount of foil which intercepted the beam. Once the H^+ beam had been diverted it was fine tuned to give a 1 cm diameter beam spot centered on the target by passing it through a series of bending, focusing, and

steering magnets. The beam also passed through a solenoid magnet which was capable of rotating the transverse spin component of the beam by as much as $\pm 26^\circ$. Figure 3-1 shows the components of the beam line in the experimental area.

The location and spot size of the beam could be monitored at various points along the beam line by profile monitors or by polaroid film burns. A continuous monitor of the beam quality was provided by the beam-location-counter (BLC). BLC was 5 cm square by 0.6 cm thick plastic scintillator with a 1.5 cm diameter hole in the center. The hole was centered on the beam axis so that any shift in the beam location would cause a change in the counting rate of BLC.

The integrated beam current was measured by an ion chamber (ICH) located about 1 m upstream of the target. The ion chamber measured the beam current by collecting the electrons ionized from gas molecules by the passage of charged particles through the chamber. The current output signal was amplified and converted to a frequency by a current to frequency converter. The frequency output was then shaped into NIM pulses which could be counted by the data acquisition hardware.

The Polarimeter

A second measure of the beam's polarization was made by the beam line polarimeter which was located 2 m upstream from the target. A schematic diagram of the polarimeter is shown in Figure 3-2. The polarimeter determined the average of the normal and reverse beam polarization by measuring the asymmetry of protons which scatter elastically from a hydrogen target, ($1/8$ " thick CH_2).³⁵ Four pairs of

Figure 3-1. The BR Beam Line.

Figure 3-2. The Polarimeter.

plastic scintillator detectors were located above and below and to the left and right of the beam axis at angles which would detect the scattered and recoil protons at angles near 30° c.m. An elastic event was defined as a coincidence between two conjugate detectors. Since an up scattered event for a normal beam is equivalent to a down scattered event for a reverse beam the asymmetry can be defined as,

$$\epsilon_{ud} = \frac{\sqrt{U_n D_r} - \sqrt{D_n U_r}}{\sqrt{U_n D_r} + \sqrt{D_n U_r}} \quad (3-1)$$

where, U_n , D_n , U_r , and D_r are the up and down yields for normal and

reverse beams. By defining the asymmetry in this way it has been shown that instrumental uncertainties will cancel out to high order.³⁶ The left-right asymmetry, ϵ_{lr} , can be defined similarly in terms of L_n , R_n , L_r , and R_r . As a result of parity conservation the asymmetry is related only to the spin component perpendicular to the scattering plane of the polarimeter. Thus the up-down asymmetry measures the polarization along the sideways $\hat{S}$ axis and the left-right asymmetry measures the polarization along the normal $\hat{N}$ axis. Since the $\hat{L}$ vector will always lie in the scattering plane no measure of the beam polarization along this direction could be made by the polarimeter. The up-down and left-right asymmetries could be used to calculate the $\hat{S}$ and $\hat{N}$ components of the beam polarization by dividing the measured asymmetries by their respective analyzing powers, A_{ud} and A_{lr} . The analyzing powers were found at each energy by dividing the polarimeter asymmetries by the polarization determined by the quench ratio, using the average of all the available data. Since the quench ratio was used to calibrate the polarimeter, the polarimeter was only a secondary measure of the beam polarization. However in the short run the polarimeter was expected to give a better measure of the polarization because it is not effected by the beam intensity fluctuations which limit the accuracy of measurements made using the quench ratio technique.

Although the polarimeter's primary function was to measure the incident beam polarization it also served as a backup beam current monitor. The integrated beam intensity was proportional to the sum of counts in all the polarimeter counters.

The Polarized Proton Target (PPT)

The target of polarized protons for this experiment was provided by the polarized proton target system (PPT). Polarization of the target protons was achieved by an optical pumping technique. A brief and somewhat over simplified description of this technique is given below. A much more detailed and quantitative discussion can be found in the thesis of Tippens.³⁷ Propanediol ($C_3H_8O_2$) doped with Cr^{VI} was used as the target material. Free electrons from the Cr^{VI} radical could combine with the protons bound in the propanediol molecule to form atomic hydrogen. By placing the material in a region of high magnetic field the energy levels of the hydrogen atom could be split into four states in proportion to the strength of the field and according to the spin orientation of the proton and electron. The relative population P of each state is determined by the Boltzmann distribution,

$$P \propto \exp(-(\mu_e - \mu_p)B/kT) \quad (3-2)$$

where μ_e and μ_p are the electron and proton electromagnetic moments respectively, B is the magnetic field, k is the Boltzmann constant, and T is the temperature of the target material. To get high polarization one needs a high field B , and a low temperature T . For this target $B = 25$ kG, and $T = 0.5$ K which yielded a net polarization of only $1/2\%$. To generate much higher polarizations in the 70 to 80% range optical pumping was used. Figure 3-3 is helpful in seeing how this process works. By selecting the proper microwave frequency ν , such that $h\nu = \mu_e B - \mu_p B$, (≈ 71 GHz), transitions between $|-, +\rangle$ and $|+, -\rangle$ states

Figure 3-3. Energy level diagram for the electron-proton system. Populations are shown before and after induced transitions. $|+, +\rangle$ denotes electron and proton spins respectively, parallel to the magnetic field.

will be induced in an effort to equalize the populations of the two states. The notation for the states is that the first sign refers to the electron spin and the second to the proton spin parallel (+) or antiparallel (-) to the magnetic field. The induced transitions will cause the electron and proton spins to flip simultaneously. After the electron and proton flip one another they can realign themselves with the magnetic field. Since the proton relaxation time is typically an hour or more it will remain oriented. On the other hand the electron relaxation time is only about 40 ms so it quickly realigns itself and is ready to flip another proton. Thus only a small number of electrons can service a large number of protons. According to the Boltzmann distribution, when there are no microwaves to induce transitions and the

target is at its operating temperature of 0.5 K and field of 25 kG, the relative populations of the - and + electron states is expected to be 800 to 1. If microwaves are used to equalize the populations P_{+-} and P_{-+} of the $|+-\rangle$ and $| -+\rangle$ states at 800 for each state then according to the Boltzmann distribution, when equilibrium is reached, the population P_{++} of the $|++\rangle$ state will be $\frac{1}{800} \times P_{-+}$ or 1 while the population P_{--} of the $|--\rangle$ state will be $800 \times P_{+-}$ or 640,000. Thus there will be 640,800 - protons for every 801 + protons yielding a net polarization of nearly 99.8%. By selecting a slightly higher frequency ν_+ , such that $h\nu_+ = \mu_e B + \mu_p B$, transition between the $|+,+\rangle$ and $|-, -\rangle$ states will be induced and the polarization of the target will be reversed. In practice such high target polarizations are never seen. The polarization can be reduced considerably if B or T vary over the target volume, or if B, T, or ν were not at their optimum values. Even if none of the above were true one would still not see such high polarizations because the atomic energy levels are broad enough that they overlap slightly allowing microwaves of one frequency to induce transitions between the other two states.

To reduce systematic effects in the asymmetry measurements the spin of the target was reversed every other data acquisition run. Data at a given angle setting were acquired in groups or cycles of four runs with two target reversals per cycle. Data for each run were accumulated for a predetermined integrated beam current, which was estimated would yield a statistically sufficient number of signal events. Runs typically lasted about an hour while target reversals took 30 minutes.

The polarized proton target system (PPT) consisted of five major components; the magnet, cryostat, target material, microwave source, and the polarization monitoring system. Each of these components will be discussed below.

The PPT Magnet (HERA)

The PPT magnet (HERA) consisted of a pair of super conducting Helmholtz coils which produced a 25 kG field at the target.³⁸ The coils of the superconducting magnet were cooled by a bath of liquid ^4He which was maintained at a temperature of 4 K by allowing it to boil off at atmospheric pressure. The field was uniform to within $\pm 0.01\%$ over the target volume and was oriented parallel to the incident beam axis. The coils of the magnet gave an unobstructed open cone angle of $\pm 45^\circ$ with respect to the beam axis. This limited the angular range of the pions detected outside the magnet to angles less than 75° c.m.

The magnetic fringe field was quite strong, up to 600 Gauss at distances over a meter away. The fringe field affected nearby electronics, altered the trajectory of scattered particles, and precessed the spin of the incident beam. The effect on nearby electronics was minimized by keeping all photomultiplier tubes as far away as possible and adding extra shielding to those nearby. The fringe fields altered the trajectory of scattered particles by rotating their trajectories counter-clockwise, (looking down stream), about the beam axis by an angle ϕ . Figure 3-4 shows a plot of ϕ at a distance of one meter from the target center versus momentum for several different θ_{lab} angles. The trajectories of scattered particles were also bent slightly towards

the beam axis by an angle $\Delta\theta$. Figure 3-5 shows a plot of $\Delta\theta$ at one meter versus momentum for several different θ_{lab} angles. Knowing the bend angles allowed the location of the pion and deuteron detectors to be adjusted to accommodate these deflections. The trajectory of the incident beam was not effected by the fringe field since the incident beam traveled down the axis of the magnetic field where its momentum was always parallel to the field lines. However the fringe field did act like a solenoid to precess the transverse spin component of the incident beam clockwise about the beam axis by an angle between 30 and 40° depending on the beam momentum. This rotation was partially compensated by the field of the spin precession solenoid located about 3 m upstream of the target.

The Cryostat

The target was cooled by a ^3He - ^4He refrigeration system. Since ^3He is such an expensive material it was circulated in a closed loop and was cooled by thermal contact with the ^4He which supplied the cooling power for the entire cryostat. Liquid ^4He , stored in a 1000 l dewar, entered the system at atmospheric pressure and temperature of 4 K, where it was cooled down to 2 K by allowing it to boil off at a pressure of 10 torr. At the same time ^3He gas entered the system at a pressure slightly below one half of an atmosphere. The ^3He gas was first cooled and liquified at 2 K by thermal contact with the ^4He gas and liquid. Then it was cooled to its final temperature of 1/2 K by thermal contact with the ^3He gas boiled from the target and by passing it through an expansion valve. The target was submersed in a bath of

Figure 3-4. Φ vs P . Figure 3-5. $\Delta\theta$ vs P .

^3He which flowed through the expansion valve. ^3He gas which boiled off the target was pumped out at a high rate at a pressure of 0.1 torr to be cleaned and recycled.

The Target Material

Propanediol, $\text{C}_3\text{H}_8\text{O}_2$, was used as the target material for the PPT.³⁹ The propanediol was doped with about 2% Cr^{V} by weight to provide the free electrons which are needed to polarize the protons. The propanediol which is a liquid at room temperature was formed into 1 mm diameter beads by dripping it into liquid nitrogen. Beads were used to improve the thermal contact with the liquid ^3He bath and allow the energy of the absorbed microwaves to be dissipated more readily. The beads were contained in a perforated 10 mil thick teflon cylinder 5.5 cm long and 2 cm in diameter. The packing fraction of the beads was about $2/3$ which yielded an effective hydrogen density of about 0.073 gm/cm^3 . A carbon target was also available to give an indication of the background contamination caused by the non-hydrogenic target nuclei. The carbon target consisted of a teflon cylinder identical to the propanediol container filled with hollow graphite beads which yielded approximately the same net quasi-free proton density as the oxygen and carbon in the propanediol target.

The Microwaves

The microwaves were provided by a 400 mw, 71 GHz klystron, and fed to the target by a wave guide. The frequency could be adjusted to the optimum frequency for + and - polarization by changing the klystron's

cathode voltage. The microwave power could be varied by adjusting an attenuator. Too much power would cause the propanedioide beads to heat up and too little power would not saturate the desired transitions.

The Nuclear Magnetic Resonance System

The NMR system was used to measure the relative polarization of the target. The energy difference between protons in the + and - target polarization states will be $2\mu_p B$. Transitions between the two states can be induced by irradiating the target material with an RF field of frequency ν such that $h\nu = 2\mu_p B$, (106.4 MHz). If the populations of the two states are unequal then transitions will be induced from one state to another in an attempt to equalize the two populations, (and depolarize the target). This will either release or absorb energy from the RF field causing the amplitude of the signal to be modulated in proportion to the target polarization. To minimize target depolarization the frequency of the RF field was only swept through resonance once during each measurement.

The system was calibrated by measuring the NMR signal of a target of known polarization. By turning the microwaves off and allowing the target to come to thermal equilibrium the polarization could be determined from Boltzmann statistics knowing B and T . The magnetic field B was known to better than $\pm 0.01\%$ and the temperature T was measured indirectly to within $\pm 0.1\%$ using a capacitance manometer to measure the ^3He gas pressure at the target and converting the pressure to temperature. During the course of the experiment a number of such thermal equilibrium calibration measurements were made. Using the cal-

ibration the absolute polarization of the enhanced target could be determined to within $\pm 4\%$.

The Deuteron Spectrometer

The deuteron spectrometer measured the momenta, scattering angle, and time-of-flight of particles scattered into it. A sketch of the deuteron and pion detectors is shown in Figure 3-6. The momenta and scattering angles were determined using four multi wire proportional counters (MWPC) to measure the particles trajectories before and after being bent by the spectrometer magnet. A brief description of the MWPC's is given in Appendix A. Each of the chambers gives the horizontal and vertical location of the particles to within ± 0.6 mm, which in combination with multiple scattering determined the momentum and angles to $\pm 2\%$ and $\pm 0.5^\circ$ respectively. The solid angle of the spectrometer was limited by the second wire chamber to be 12 msr. Scintillators S1, S2, and S3 were used to measure the time-of-flight over the spectrometer's 3.6 meter flight path and as part of the deuteron event trigger. The entire spectrometer assembly was mounted on air pads which allowed it to be rotated about a pivot point beneath the target center from 0 to 42° . Angle settings were indicated to within $\pm 0.1^\circ$ by a marker fixed to the spectrometer which pointed to angle markings painted on the floor. To compensate for the unevenness of the floor upon which the spectrometer rested, the spectrometer's height and level could be adjusted using a set of jacks which supported it when it was not being moved on the air pads.

Figure 3-6. The deuteron and pion detector system.

The Pion Telescope

The pion telescope, shown in Figure 3-7, used two MWPC's to measure the angle of particles scattered into it. Each MWPC had an X and a Y plane capable of measuring the coordinates of hits to within ± 0.6 mm. The front chamber, W5, defined the solid angle of the telescope to be 65 msr. A set of four scintillators, located behind W6, provided part of the pion event trigger as well as timing information. The entire pion telescope assembly was mounted on a set of wheels which allowed it to be rotated about the pivot point from 0 to -44° . Like the deuteron spectrometer the angle settings could be measured to within $\pm 0.1^\circ$ by a marker fixed to the telescope which pointed to angle markings painted on the floor, and the height and level could be adjusted by a set of jacks.

The pion telescope was also designed to accommodate the bending of the scattered particles trajectories caused by the fringe field of the PPT magnet. Since the deuterons were detected in a plane parallel to the floor the bending of the trajectories by the PPT fringe field required that pions be detected out of the horizontal plane. To accommodate this vertical bending the pion telescope's wire chambers were mounted on a platform which could be raised a distance H above the beam axis and tilted an angle α about a point beneath the front wire chamber. H could be adjusted anywhere from 0 to 180 mm, and α could be adjusted in 1° steps from 0 to 15° . The rear scintillators could also be raised to the height necessary to detect all the pions which passed through the wire chambers.

Figure 3-7. The Pion Telescope.

The Inside Counter

The coils of the PPT magnet limited the angular range of pions detected outside the magnet bore to lab angles less than $\pm 45^\circ$ or pion c.m. angles less than 75° . To detect pions with c.m. angles of 75° or greater the inside counter shown in Figure 3-8 was used. The inside counter consisted of a scintillator, (S4), and a small wire chamber, (W7), mounted inside the bore of the magnet. W7 had an X and a Y plane both capable of determining the location of hits to within ± 0.6 mm over an active area of 6.4 cm square, while S4 had an active area of 9 by 10 cm. The location of the inside counter could be adjusted to whatever position the recoiling pions were predicted to intercept it. Because W7 was mounted so close to the target it had very poor angular resolution and subtended a large solid angle. W7's large solid angle resulted in a high counting rate and a low efficiency. Because of its low efficiency a good hit in W7 was not required as part of the inside counter event trigger. This requirement could be added in the software during later data analysis.

Detection of pions using the inside counter gave a poor quality signal compared to the pion telescope. However the deuteron spectrometer provided enough information to allow the signal to background ratio to be kept at a reasonable level.

Data Acquisition and On-Line Analysis

Data were acquired using a CAMAC system interfaced to a PDP 11/60 computer through a microprogrammable branch driver (MBD). The data acquisition hardware was located in the BR counting house some 40 m

Figure 3-8. The Inside Counter. (Looking up stream.)

N.W. of the experimental area. Software for the MBD and the PDP computer was written using the LAMPF RSX-11D general data acquisition and analysis system, "Q".⁴⁰ A special CAMAC unit called the LAMPF trigger module (LTM) was used to alert the MBD that a certain type of event had occurred. Each event caused the MBD to read in a specific set of CAMAC registers and transfer the data to the computer through buffers shared by the MBD and PDP. As requested the computer could either write the raw data to tape or process it using the analyzer. A description of the event trigger logic followed by a discussion of the analyzer is given below.

The Event Trigger Logic

The event trigger logic was used to define and trigger LTM EVENTS 4, 5, and 8, which caused data to be read in and passed to the computer. EVENT 4 dumped the MBD data buffer and was triggered at the end of every beam macro-pulse or at the end of a run. Dumping the buffer between macro-pulses insured that the time between macro-pulses was put to good use processing events and that the buffer would be cleared and ready to accept data from the next macro-pulse. EVENT 5 was triggered every spin change or at the end of a run and caused the CAMAC scalars to be read in and cleared. EVENT 8 indicated that a good two body event had occurred in the deuteron and pion detectors. EVENT 8 caused the ADC, TDC, and wire chamber information to be read in.

The event trigger logic was separated into two parts, the run control logic and the main event logic. The run control logic, which monitored the status of the beam and run, was used to trigger EVENTS 4

and 5 as well as to define a number of CAMAC scaler inhibits. The appropriate signals were provided by a pair of LAMPF gate generators, LGG1 and LGG2. A schematic diagram of the run control logic is shown in Figure 3-9. The logical expression for each of the inverted AND (NAND) gates is given in the schematic. Note a bar above an expression indicates the complement. The following notes concerning some of the inputs and outputs should enable the reader to interpret the logic. The beam gate BG, sent from the central control room, was held true throughout the duration of each macro-pulse. The polarized beam signal P, from the ion source, was true for polarized beam and false for quenched. Beam intensity BI was a signal generated in the counting house from signals sent from the polarimeter. It remained true as long as beam was entering the experimental area. The LGG1 run gate RUN was set by the computer to be true at the start of a run and false at the end. NN and RR were two signals which originated at the ion source. A true NN or RR signal indicated normal and reverse beam respectively, while both NN and RR false indicated a spin change was in progress. Since there tended to be some noise in these signals when they dropped a 10 s monostable pulse was added to prevent the noise from causing multiple EVENT 5 triggers. The NN and RR signals were connected to the LGG2 start and stop inputs respectively. This caused the LGG2 run gate to be true when NN was true and false when RR was true. Thus the LGG2 run gate and its complement were used to indicate the beam polarization state. Using the LGG2 run gate signals to set bits in the coincidence buffer allowed the beam polarization state to be recorded for each event. The two signals were also AND'ed together with a 10 KHz clock

Figure 3-9. The run control logic.

to generate the normal and reverse clock signals. The B, C, P, and Q scaler inhibit signals were used to inhibit various CAMAC scalers. The B inhibit signal was also used by the main trigger logic which will be discussed next.

The Main Trigger Logic

The main trigger logic was used to trigger an EVENT 8 whenever a good two body event had occurred. A good two body event was defined as the simultaneous detection of a charged particle by the deuteron and pion detector scintillators as well as sufficient wire chamber information to determine the trajectories of the particles. A schematic diagram of the main trigger logic is shown in Figure 3-10.

To minimize event processing time the main trigger logic was divided into two stages, the PP fast gate PPFG, and the PP master gate PPMG. Output signals from the PPFG and PPMG were gated through the fast trigger or FTOR, and the master trigger or MTOR. This allowed the main trigger logic to be easily modified to handle a neutral particle event. Since such events were not part of this experiment these gates will not be discussed. The PPFG was triggered by a coincidence between the spectrometer scintillator gate SSG and the recoil or gate ROR. If the inside counter was used then the PPFG was triggered by a coincidence between SSG and S4. The PPFG could also be inhibited by a veto signal from the master inhibit. SSG was formed by a coincidence between the front spectrometer scintillator, S1, and either of the two rear scintillators, S2 or S3, while ROR was formed by a hit in any of the four recoil counter scintillators, S8, S9, S10, or S20. A pulse

Figure 3-10. The main trigger logic.

from PPFG would start the TDC's and pulse the ADC's gates to avoid the need for more delays in the TDC and ADC inputs. The PPFG signal also formed part of the PPMG logic. The PPMG was triggered by a three fold coincidence between the PPFG, the spectrometer wire chamber gate SWCG and the recoil wire chamber gate RWCG. If the inside counter was being used then only a two fold coincidence between PPFG and SWCG was required. In order to reconstruct a spectrometer event only 3 out of the 4 spectrometer X and Y planes need be hit. Hence the spectrometer wire chamber fast discriminator outputs were used to define SWCG as $SWCG = {}^{3/4}(W_x) \cdot {}^{3/4}(W_y)$, where ${}^{3/4}$ indicates that only 3 out of the 4 need be hit. Similarly recoil counter events could be reconstructed using only the X and Y hits of either of the two wire chambers W5 or W6. Thus $RWCG = (W5_x \cdot W5_y) + (W6_x \cdot W6_y)$. Triggering PPMG caused the event to be accepted and read in as a good EVENT 8. If PPMG was not triggered a PP fast clear (PPFC) pulse would be generated by the PPFG and would clear the TDC and ADC inputs. Reading in an EVENT 8 required about 300 μ s, during which time the main trigger logic was inhibited by a busy signal from the LAMPF trigger module. If PPFG was triggered but PPMG was not then the event was rejected. Rejecting an event at this point required that the TDC's and ADC's be reset and the coincidence buffer be cleared. Since the process required about 2 μ s to complete, a 4 μ s monostable pulse was triggered which inhibited the electronics during this time. A measure of the live time of the system could be obtained using the master inhibit to gate the BR polarimeter scalers. The live time was given by the ratio of the number of counts with

(master inhibit)*(inhibit B) over the number of counts with just inhibit B.

The Analyzer

On-line data analysis was done with a variety of programs written using the standard LAMPF "Q" system software. These programs were designed to give sufficient information on-line to indicate the performance of the experiment and quality of the data. Data from EVENT 8's were processed using the event analysis program EX518A. Other programs included an NMR program and two CAMAC scaler routines. Since data taking was inhibited while an event was being processed EVENT 8's were handled using the "may process mode". In this mode data was first written to tape and then, if time permitted, analyzed on-line. EX518A used the raw data to calculate a number of physical quantities such as deuteron and pion time-of-flight, lab and c.m. scattering angles, momenta, and target projections. Each of these quantities could be displayed in the form of a histogram on which gates or cuts could be placed to reject non-signal events. Since all events were first recorded on tape before being processed the cuts had no effect on data stored on tape. By using cuts the on-line analyzer was able to give a very good picture of what the signal data was like.

The NMR program was automatically started at the beginning of each run for which data was being recorded on tape. The program communicated with the NMR system through the MBD and CAMAC. The target polarization was sampled every two to three minutes and the NMR signal was recorded and saved in a disk file. Each NMR signal area and an

estimate of the target's polarization were output on a Decwriter as they were read in giving a continuous monitor of the target's performance.

CAMAC scalers were handled using two programs, SLR and POL. SLR printed out a table listing the current value of all the normal and reverse scalers. These scalers were then used to calculate a number of ratios and asymmetries which were printed out following the scalers. By examining the output it was easy to spot malfunctioning hardware or anomalous experimental conditions. POL was simply a program which used the polarimeter and quench ratio scalers to calculate the beam polarization as well as the beam alignment on the polarimeter target.

CHAPTER IV

OFF-LINE ANALYSIS AND SYSTEMATIC UNCERTAINTY

Introduction

Although the data were analyzed on-line during data acquisition, a more careful and more thorough analysis is required to extract the final spin correlation parameters. In this chapter we present the details of this analysis as well as a discussion of the systematic errors in the final results.

Summary Taping

The off-line event analysis of the raw data written to tape during data acquisition was done in two steps, summary taping using a PDP 11/70 computer, and replay using a VAX 11/780 computer. The summary tape analyzer corrected the raw data for the spectrometer time-of-flight (TOF) and for missing wire chamber hits before separating out the π d events and writing them to a second tape. Missing hits in the deuteron spectrometer and pion telescope wire chambers were corrected using information from hits in the other chambers to estimate where the missing hit should have occurred. Since the inside counter had only a single wire chamber no correction for missing hits in it was possible. The spectrometer event trigger requirement that 3 out of the 4 X and Y planes be hit made it possible to correct missing hits using the assumption that the projection of the incident and exiting trajectories of particles which pass through the spectrome-

ter intersect at the symmetry plane of the spectrometer magnet. This assumption was verified using perfect events to show that the intersection of the trajectories did indeed lie on a plane which coincided with the spectrometer magnet's symmetry plane. The two good hits on one side of the magnet were used to determine the point of intersection with the symmetry plane. A line drawn through this point and the good hit on the other side passed through the missing plane at the point where the missing hit should have occurred. The pion telescope event trigger requirement that there be a good X and Y hit in one of the two chambers was chosen to allow missing hits to be corrected using perfect events to determine the correlation between hits in the two wire chamber X and Y planes. Once the correlation function was found it was used to calculate the location of missing hits. Since the correlation function varied with the pion telescope setting a new function was determined for each setting. Multiple hits for both detectors were corrected like missing hits except that the location of the missing hit was used to choose the closest of the multiple hits as the correct hit. Events with more than one multiple hit in a set of planes were rejected.

Corrections to the spectrometer time-of-flight were also made to improve the time resolution of the two rear scintillators S2 and S3. Since both these 65 cm long scintillators were viewed from only one end, the time resolution was limited by the propagation time for light to travel the length of the scintillator. A correction of up to 10% was made using the location of the X hit in the wire chamber W4 to determine where the particle passed through the scintillator and estimate

the time delay for light to reach the end viewed by the photomultiplier tube.

After the corrections had been made the summary tape analyzer separated out the possible πd events from the many pp events using a crude cut on the deuteron peak in the corrected spectrometer TOF histogram. Typically this would reject 60 to 80% of events recorded on the raw data tape. This meant that data stored on many raw data tapes could be reorganized and condensed on to just a few summary tapes which allowed the subsequent replay of these tapes to proceed more easily and to require much less computer time.

Replay

The second step of the off-line event analysis was to analyze, or replay, the summary tapes using the analyzer ANA518. Like the on-line event analysis program, ANA518 used the MWPC and time-of-flight data to calculate a number of physical quantities which were displayed as histograms which could be cut to reject non-signal events. A list of some of these histograms along with their function is given in Table 4-1. The momentum and angles of all events were corrected for the incident and exiting energy loss in the target and for the bending caused by the fringe field of HERA. Events whose kinematics proved impossible to calculate were rejected.

Two-body reactions such as $pp \rightarrow \pi d$ have the advantage that the vector momentum of both final particles can be uniquely determined by a measure of the vector momentum of just one particle. That is, the kinematics of the reaction are completely determined by the spectrometer's

Table 4-1. Replay histograms and their functions.

<u>HISTOGRAM</u>	<u>DESCRIPTION</u>	<u>FUNCTION</u>
PMOM	Deuteron momentum	Signal cuts
PMASS	Measured deuteron mass	Signal cuts
TOF	Spectrometer time-of-flight	Signal cuts
TIR	Time between spectrometer scintillator S1 and pion telescope scintillators	Signal cuts
MM	Missing mass, where $MM = 2M_p + T_p$ $- M_d - T_d - M_\pi - T_\pi$	Signal cuts, or background fits
TGTSX	Spectrometer X target projection	Signal cuts
TGTSY	Spectrometer Y target projection	Signal cuts
TGTRX	Pion telescope X target projection	Signal cuts
TGTRY	Pion telescope Y target projection	Signal cuts
DPHI	Coplanarity. Measured - expected pion azimuthal angles	Signal cuts
DTHR	Measured - expected pion polar c.m. angle	Background fits
THRCM	Pion polar c.m. angle	Angle bin cuts
THSCM	Deuteron polar c.m. angle	Angle bin cuts

measurement of the deuteron momentum and lab scattering angle. The additional information provided by the pion detectors could be used to compare measured pion polar and azimuthal c.m. angles with the angles predicted knowing the deuteron vector momentum. These two angle differences could be displayed as histograms DTHR and DPHI respectively.

Histograms DTHR and DPHI were useful in distinguishing background from signal events since events with measured angles which differ significantly from the expected were probably not from the desired reaction. Such background events were most likely the result of quasi-free scattering from the non-hydrogenic target nuclei.

ANA518 sorted events into three angle bins according to their c.m. scattering angles by placing special cuts on either the deuteron or pion c.m. angle histograms THSCM or THRCM. Since the pion c.m. angles are more spread out in the lab frame than the deuteron, THRCM was chosen as the angle bin histogram for the pion telescope data. For data taken with the pion telescope DTHR was chosen as the histogram that best displayed a sharp signal peak that sat upon a broad background. No cuts were placed on DTHR during replay to preserve the full extent of the background for fitting during later data analysis. Using the angle bin and beam spin state the signal histogram DTHR was displayed as a two parameter histogram $Z(x,y)$, where $x = \text{DTHR}$, $y = \text{beam spin} \times \text{angle bin}$, and $Z = \text{number of counts}$. This allowed each of the six possible angle bin and beam spin combinations to be displayed as separate histograms. Figures 4-1, and 4-2 show typical THRCM and DTHR histograms from a run taken with the pion telescope. The same cuts were used to replay each run at a given beam energy and angle setting. At the conclusion of the replay of each run the histograms and CAMAC scalars were saved in a disk file.

Replay of data taken with the inside counter was done similar to that from the pion telescope. However it was found that the efficiency of the inside wire chamber was so low that its inclusion introduced

Figure 4-1. THRCM angle bin histogram for pion telescope data.

Figure 4-2. DTHR signal histogram for pion telescope data.

large systematic errors to the data which could not be corrected. Therefore W7 was not used. With only the inside scintillator left to detect pions, such histograms as TGTRX, TGTRY, T1R, DPHI, DTHR, and THRCM were meaningless and could not be cut to reject non-signal events. For inside counter data MM was chosen as the signal histogram and was replayed without cuts and displayed as a two parameter histogram. THSCM was also chosen as the angle bin histogram for inside counter data. Figures 4-3 and 4-4 show typical THSCM and MM histograms from a run taken with the inside counter. Since there was no measure of the pion's kinematics the quasi-free background contamination of the signal increased considerably. In addition THSCM gave a poorer measure of the c.m. angle due to the compression of the deuterons kinematics in the lab frame.

Background

Although histogram cuts were used to reject non-signal events there were always a small fraction of these background events which managed to pass all the cuts and contaminated the signal. A program CALBGD was used to estimate the ratio of background to signal events. To run CALBGD the position of four markers, 2, 3 and 1, 4 were input to define the location and extent of the signal and background peaks respectively in the signal histogram. CALBGD called the subroutine PEKFIT⁴¹ which used the four markers to fit the signal histogram with a gaussian signal peak superimposed upon a quadratic background. The fitted background area was then used to calculate the ratio of back-

Figure 4-3. THSCM angle bin histogram for inside counter data.

Figure 4-4. MM signal histogram for inside counter data.

ground events over the total number of events in the signal peak region defined by markers 2 and 3.

In order to improve statistics and reduce the amount of fitting required, all runs for a given incident beam energy, angle setting, and target polarization state were summed together and fit by CALBGD. Since the background ratios varied with beam spin and angle bin CALBGD fit each of the six combinations separately and calculated a ratio for each one. After fitting, CALBGD saved the results for later use by writing the marker locations and background ratios to a disk file.

Background ratios were typically 3 to 8% for pion telescope data, and 10 to 30% for inside counter data. The accuracy of these ratios could be verified by comparing the fitted background to the signal seen using the carbon target. Since the carbon target contained approximately the same volume and density of quasi-free protons as the propanediol target the carbon target signal should give a very good estimate of the size and shape of the quasi-free background contamination of the polarized target data. Figures 4-5 and 4-6 show typical DTHR and MM histograms, background fits, and corresponding carbon target signals. The backgrounds calculated by CALBGD were found to agree to within a few percent of the carbon target signal areas.

NMR Calibration

The NMR system was calibrated using the thermal equilibrium (microwaves off) data to measure the NMR signal of a target with polarization that could be found from Boltzman statistics knowing B and T. The magnet shunt voltage, target ^3He vapor pressure, and NMR signal

Figure 4-5. DTHR signal histogram with background fit and carbon target data.

Figure 4-6. MM signal histogram with background fit and carbon target data.

area were recorded for each thermal equilibrium measurement. The magnetic field B was given by the shunt voltage and the temperature T could be found from the ^3He vapor pressure using the empirical formula⁴²,

$$T = .7086 + .0435 \times P - .0010 \times P^2 \quad (.71 \text{ K} < T < 1.14 \text{ K}) \quad (4-1)$$

where $T = ^3\text{He}$ temperature in K, and $P = ^3\text{He}$ pressure in torr.

Thermal equilibrium target polarizations were typically only 0.25%. For this reason the size of the NMR signal had to be increased by a gain factor and by multiple sweeps of the NMR frequency through the resonance. The area of each sweep was added to form an accumulated area. Knowing the net area and the polarization the NMR calibration constant POLCAL was given by,

$$\text{POLCAL} = \frac{(\text{thermal equil. pol.}) \times (\# \text{ of sweeps}) \times (\text{gain})}{(\text{net NMR signal area})} \quad (4-2)$$

A set of thermal equilibrium measurements was taken about once a week during data taking. Each set consisted of about 20 to 40 measurements taken over a period of about an hour. An average value of POLCAL and its standard deviation was found for each set of measurements. Figure 4-7 shows a plot of POLCAL vs. time. The calibration was assumed to remain constant with time and so a weighted average value of POLCAL was used as the calibration constant. Data for the experiment was taken over two time periods, Cycles 33 and 34, separated by some 22 days. Since the target material was removed and the target system mod-

Figure 4-7. POLCAL vs time.

ified between cycles a separate weighted average was calculated for each cycle. Since the enhanced (polarized) target NMR signal was measured with just one sweep and a gain of one, the enhanced target polarization was given by the product of POLCAL times the NMR signal area.

NMR

NMR data files created during data acquisition were analyzed by the program NMRPOL. NMRPOL determined the signal area of each NMR measurement by calling the subroutine PEKFIT to fit the background with a quadratic function and then subtract it from the total area. The average area and its standard deviation were calculated for each run and saved in a disk file for later use.

Polarimeter Calibration

In order to use the polarimeter to measure the beam polarization its analyzing power must be determined at each energy. To obtain these analyzing powers the weighted average of the up-down and left-right polarimeter asymmetries $\langle \epsilon_{ud} \rangle$ and $\langle \epsilon_{lr} \rangle$ for all runs at a given energy were divided by the weighted average polarization given by the quench ratio $\langle P_{qr} \rangle$. These two quantities were then divided by the $\hat{S}$ or $\hat{N}$ spin components of the beam at the polarimeter target ($|\hat{P} \cdot \hat{S}|$ or $|\hat{P} \cdot \hat{N}|$) to give the up-down and left-right analyzing powers A_{ud} and A_{lr} ,

$$A_{ud} = \frac{\langle \epsilon_{ud} \rangle}{\langle P_{qr} \rangle \times |\hat{P} \cdot \hat{S}|} \quad (4-3a)$$

$$A_{lr} = \frac{\langle \epsilon_{lr} \rangle}{\langle P_{qr} \rangle \times |\hat{P} \cdot \hat{N}|} \quad (4-3b)$$

The spin orientation of the beam could be determined to within $\pm 3^\circ$ at any point along the BR beam by knowledge of its orientation at the source and its precession through the beam transport system, the bend angles along the beam line, and the field of the spin precession and PPT magnets. A plot of the two analyzing powers vs. incident beam energy is shown in Figure 4-8. The average of the normal and reverse $\hat{S}$ and $\hat{N}$ spin components of the beam measured by the polarimeter ($P_{pol}(S)$ or $P_{pol}(N)$) will be given by,

$$P_{\text{pol}}(\text{S}) = \epsilon_{\text{ud}} / A_{\text{ud}} \quad (4-4a)$$

$$P_{\text{pol}}(\text{N}) = \epsilon_{\text{lr}} / A_{\text{lr}} \quad (4-4b)$$

Asymmetry Analysis

Once the runs had been summary taped and replayed, background ratios calculated, NMR areas averaged, and polarimeter and NMR system had been calibrated the asymmetry analysis program EASY could be run. A schematic diagram of EASY is shown in Figure 4-9. EASY used data stored in various data and histogram files to calculate the beam and target polarizations and the relative yields for each run. Once these quantities had been found EASY calculated the spin correlation param-

Figure 4-8. Up-down and left-right polarimeter analyzing power vs. incident beam energy.

Figure 4-9. A schematic of the asymmetry analysis program EASY.

eters using equation 4-5 which was derived from equation 2-20 for a longitudinally polarized target.

$$I = I_0 \left(1 + P^b |\hat{P}^b \cdot \hat{N}| A_{NO} + P^b P^t (|\hat{P}^b \cdot \hat{S}| A_{SL} + |\hat{P}^b \cdot \hat{L}| A_{LL}) \right) \quad (4-5)$$

Combining a pair of runs with the same incident beam energy and angle setting, the two different target polarization states and the two different beam polarization states gave four equations, one for each combination of beam and target polarization state. These four equations were then used to solve for the four unknowns, I_0 , A_{NO} , A_{SL} , and A_{LL} . Since A_{SL} and A_{LL} are always summed together with the same $|\hat{P}^b \cdot \hat{S}|$ and $|\hat{P}^b \cdot \hat{L}|$ coefficients they could not be determined independently at this point. The three unknowns that could be determined at this point were I_0 , A_{NO} , and A' , where $A' = |\hat{P}^b \cdot \hat{S}| A_{SL} + |\hat{P}^b \cdot \hat{L}| A_{LL}$. Since the four measurements overdetermine the three unknowns, χ^2 minimization could be used to reduce the four equations to three. The problem then becomes a matter of inverting a symmetric 3×3 matrix to solve for the three unknowns. Details of the χ^2 minimization as well as the yield and polarization calculations are given in Appendix B. EASY also calculated the random error of the spin correlation parameters from the statistical errors of the yields and uncertainties of the beam and target polarizations measurements. The pion c.m. angle for each angle bin was also calculated by EASY to be the average c.m. angle of counts in each angle bin.

Separating A_{SL} and A_{LL} from A' sometimes required further calculations. If the beam was pure longitudinal then $A' = A_{LL}$ and no further

calculations were necessary. Otherwise data from two different beam spin orientations were used to give two equations for A' to solve for the two unknowns A_{SL} and A_{LL} . Further details are given in Appendix B.

Systematic Uncertainty

The errors computed by EASY and quoted in Tables 5-1 and 5-2 of Chapter V reflect the statistical uncertainties in the yield and polarization measurements. In addition to the statistical uncertainties there are a number of systematic errors in these quantities which should be considered. A discussion of the various sources of systematic error is presented below and a summary of these errors is given in Table 4-2.

Target Polarization

Systematic error in determining the absolute target polarization was the result of systematic uncertainty in the calibration coefficient POLCAL. A secondary measure of the calibration, by comparing the measured $pp \rightarrow pp$ target asymmetry A_{ON} to the beam asymmetry A_{NO} , was not possible with a longitudinal target. However a previous experiment at LAMPF³⁷, which used a target polarized along the $\hat{N}$ axis and a similar NMR system, was able to use this technique to show that the calibration was good to within $\pm 2\%$. A second source of systematic error came from the assumption that the calibration remains constant with time. A plot of POLCAL vs. time shows the systematic error from this drift to be less than $\pm 2\%$.

Beam Polarization

The systematic error of the beam polarization varied depending on the method used to calculate it. If the polarimeter was used the systematic error in the beam polarization was determined by the uncertainty of the polarimeter's analyzing power to be $\pm 1/2\%$. If the beam's transverse spin component was too small to use the polarimeter, the quench ratio was used. The systematic error of quench ratio measurements was estimated to be $\pm 2\%$ for data taken during Cycle 33 and $\pm 1\%$ for Cycle 34.

In addition, the error in determining the spin orientation at the polarized proton target PPT must be considered. The spin orientation of the beam entering the experimental area was known to within $\pm 2^\circ$. If the beam had any transverse component, the $\pm 1^\circ$ uncertainty of its rotation through the spin precession and PPT magnets must be added to this.

Yield

For asymmetry experiments it is not necessary to determine the absolute yields, only the relative yields of the four beam and target states need be measured, and only systematic errors in these yields will effect the measurement of the spin correlation parameters. Since the data for each angle setting were taken in a cycle of four runs with two target reversals per cycle, while every thing else was kept the same, many such errors were eliminated. One source of systematic error came from the error of the integrated beam current measured by the ion chamber. An estimate of this error was made from measurements of the

relative beam current made by the polarimeter compared to that of the ion chamber. From this comparison it was found that for data taken during Cycle 33 (500 and 650 MeV), the two measurements agreed to within $\pm 3\%$ and $\pm 2\%$ respectively. For data taken during Cycle 34 the two measurements agree to better than $\pm 1\%$. The systematic error in the relative yield due to the uncertainty of the integrated beam current is expected to be about half this difference.

A second source of error was caused by variations in the beam tune. The yield would be reduced if the location and diameter of the beam spot changed to the extent that part of the beam no longer hit the target. The tune of the beam was checked periodically using the profile monitors and film burns. A continuous monitor of the beam quality was also provided by the beam-location-counter BLC. In general if the number of counts in BLC were to change by a factor of two or more the beam was checked with a film burn and retuned if necessary. Plots of yield vs. BLC showed no correlation as BLC varied by a factor of two or more. The systematic error due to bad beam tunes should be small ($< 1\%$).

A third source of systematic error came from the fact that events with more than one multiple hit per set of wire chamber planes were rejected by the analyzer. Multiple hits were most likely the result of a random background event occurring in coincidence with a true event. If the ratio of true to random events were to vary between beam and target spin states the number of rejected true events would also vary. This would introduce a false asymmetry into the final results. Since the analyzer is capable of correcting events with only one multiple hit

per set of planes this effect is removed to second order. One way the ratio of true to random events could be effected was by variations in the beam intensity. This happens because true events are proportional to the beam intensity while random events are proportional to the beam intensity squared. Care was taken during data taking to insure that the beam intensity remained constant to within 20% during each data taking cycle. Plots of yield vs. beam intensity for cycles of runs with beam intensity fluctuations showed no correlation between the two. The systematic error in the relative yield from beam intensity effects is estimated to be small ($\leq 1\%$).

A second way in which the ratio of true to random events could vary is if the random events themselves possessed asymmetry. Most of the random events came from quasi-free pp scattering which should not show any asymmetry for a beam with no $\hat{N}$ spin component. However some of the random events are the result of elastic pp scattering. These events will have an asymmetry due to the non zero pp+pp spin correlation parameters A_{SL} and A_{LL} . Calculations of the asymmetry between the normal and reverse ratios of rejected multiple hit events to good events showed no such effect. The error in yield due to random event asymmetry should therefore be small ($\leq 1\%$).

Background Subtraction

One final contribution to the systematic error came from the background subtraction. These background subtraction errors can be used to estimate an upper bound on the systematic error in the determination the relative yields. For data taken with the pion telescope the signal

peak was sharp and well defined and the background was quite broad and small, 5% or less. This shape allowed these backgrounds to be fit with precision. For data taken using the inside counter the signal peak tended to be much broader and sat upon a large 10 to 30% background. This condition made the fits much less precise. The accuracy of the fitted backgrounds could be checked by comparing the fitted background ratio to the ratio calculated using the carbon target data. For telescope data the two background ratios agreed to within $\pm 2\%$ absolute. The systematic error should be about half this value or $\pm 1\%$ absolute. For inside data the two ratios agreed to within only $\pm 8\%$ giving an error of about $\pm 4\%$ absolute. Since the background is subtracted by multiplying the yield by one minus the background ratio, an absolute percent error in the ratio is equivalent to a relative percent error in the yield.

In situations with small signals and large backgrounds, namely the 500 and 800 MeV inside counter data, the signal peak was too broad and the background too large to allow the background to be fit as a quadratic function beneath a gaussian shaped signal peak. For these two cases the background was fit without specifying a signal peak. The resulting over estimate of the background fit added an extra 5% to the systematic error of the background ratio.

Pion θ_{cm}

The pion polar center-of-mass angle θ_{cm} was determined two different ways depending on which pion detector was used. For data taken with the inside counter only the deuteron kinematics measured by the

spectrometer were used to determine θ_{cm} . Since the deuteron kinematics were highly compressed in the lab frame this gave a poor measure of θ_{cm} . For this case the systematic error of θ_{cm} was about $\pm 3^\circ$. When data was taken with the pion telescope information from both arms was used to calculate θ_{cm} . This gave a much better measure of θ_{cm} . The systematic error for this case was about $\pm 0.5^\circ$.

Table 4-2. Systematic uncertainties.

Target Polarization:	$\pm 4\%$	
Beam Polarization:	$\pm 0.5\%$	(Polarimeter)
	$\leq \pm 2\%$	(Quench Ratio)
Beam Spin Orientation:	$\leq \pm 3^\circ$	
Relative Yield:	$\pm 1.5\%$	(Cycle 33, 500 MeV data)
	$\pm 1\%$	(Cycle 33, 650 MeV data)
	$\pm 0.5\%$	(Cycle 34 data)
Background Subtraction:	$\pm 1\%$	(Pion telescope data)
	$\pm 4\%$	(Inside counter data)
	$\pm 9\%$	(Inside data w/o sig. peak fit)
θ_{cm} :	$\pm 0.5^\circ$	(Pion telescope data)
	$\pm 3^\circ$	(Inside data)

CHAPTER V

RESULTS AND CONCLUSIONS

Experimental Results

Numerical results of the two spin correlation parameters, A_{LL} and A_{SL} are given in Tables 5-1 and 5-2. These data are also plotted along with several partial wave analysis and theoretical predictions in figures to be discussed later. Since A_{LL} is symmetric about $\theta_{cm} = 90^\circ$, data taken at $\theta_{cm} > 90^\circ$ have been folded over to produce plots which range from 0 to 90° . Errors indicated on the plots and given in the tables are purely statistical. Systematic errors are estimated in Chapter IV to be less than 7%. The angle bin width of each point is approximately $\pm 5^\circ$.

The actual kinetic energy of the incident proton beam delivered to the experiment was often a few MeV less than the quoted value. In addition the energy of the incident beam was reduced further by energy loss as it passed through the target material and surrounding cryostat. Table 5-3 lists the true incident kinetic energy after the expected energy loss for each of the six nominal energies. The uncertainty of the value of the true incident energy minus the expected energy loss is estimated to be ± 4 MeV.

Comparison of the data at 500 MeV with that of Aprile et al.⁴³ of SIN is shown in Figure 5-1. Considerable differences exist between the LAMPF and the SIN A_{LL} results near 90° . The disagreement with the SIN result is not presently understood. However one major difference between the two experiments was that this experiment used a magnetic

Table 5-1. A_{LL} vs θ_{cm}

500 MeV			600 MeV			650 MeV		
A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}
-0.635	.037	41.3	-0.457	.020	39.7	-0.267	.028	37.2
-0.597	.040	49.9	-0.399	.022	48.3	-0.291	.029	40.9
-0.598	.035	50.7	-0.376	.020	49.6	-0.188	.027	46.4
-0.568	.035	54.9	-0.361	.022	57.1	-0.222	.040	50.0
-0.526	.041	59.2	-0.336	.027	57.3	-0.126	.029	50.5
-0.618	.036	60.2	-0.341	.020	60.5	-0.225	.027	55.5
-0.578	.033	61.5	-0.359	.028	63.7	-0.188	.050	59.0
-0.628	.042	68.2	-0.317	.030	63.9	-0.145	.039	59.3
-0.572	.034	69.3	-0.317	.022	67.4	-0.112	.029	59.9
-0.446	.034	92.4	-0.354	.031	68.3	-0.129	.056	63.4
-0.532	.040	92.6	-0.332	.028	71.0	-0.080	.052	65.9
-0.518	.031	93.8	-0.305	.036	73.6	-0.110	.060	68.6
-0.548	.033	105.9	-0.369	.033	73.9	-0.102	.040	68.8
-0.494	.031	106.9	-0.376	.034	89.5	-0.079	.053	73.2
-0.527	.028	108.8	-0.290	.033	103.2	-0.045	.060	74.6
-0.532	.034	116.1	-0.346	.032	105.5	-0.030	.028	82.0
-0.476	.036	117.8	-0.297	.030	117.9	-0.006	.027	97.6
-0.495	.031	119.4	-0.329	.027	127.8	-0.090	.027	110.3

700 MeV			750 MeV			800 MeV		
A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}	A_{LL}	ERROR	θ_{cm}
-0.290	.022	39.7	-0.330	.025	36.3	-0.080	.022	49.6
-0.151	.022	48.8	-0.248	.030	39.8	0.031	.028	58.2
-0.141	.022	49.6	-0.187	.024	45.9	0.082	.023	58.4
-0.095	.023	57.6	-0.136	.023	48.7	0.139	.027	64.5
-0.066	.025	57.9	-0.105	.029	49.6	0.152	.036	67.2
-0.027	.021	60.3	-0.033	.023	55.9	0.242	.022	68.3
-0.044	.032	63.8	0.003	.023	57.9	0.243	.037	71.4
0.001	.025	64.6	0.009	.026	58.2	0.277	.026	72.3
0.029	.022	67.9	0.019	.029	60.4	0.304	.039	76.7
0.031	.032	68.5	0.045	.032	64.1	0.401	.043	83.4
0.052	.026	72.5	0.092	.027	64.9	0.413	.049	96.4
0.080	.031	74.1	0.135	.024	68.1	0.354	.042	103.1
0.155	.040	86.3	0.157	.034	68.9	0.336	.045	107.8
0.132	.037	94.1	0.205	.027	72.4	0.241	.037	114.7
0.122	.039	100.2	0.217	.033	74.5	0.062	.033	123.9
0.137	.032	103.6	0.243	.026	83.4			
0.100	.033	108.3	0.359	.039	87.3			
-0.002	.038	111.1	0.321	.026	97.8			
0.094	.029	111.9	0.257	.037	102.1			
0.034	.031	115.2	0.222	.046	109.8			
-0.053	.033	118.6	0.185	.026	110.6			
-0.075	.028	122.6	0.111	.038	114.2			
-0.031	.028	123.5	0.065	.037	119.9			
-0.139	.024	130.9	-0.022	.033	127.4			

Table 5-2. A_{SL} vs θ_{cm}

500 MeV			650 MeV			800 MeV		
A_{SL}	ERROR	θ_{cm}	A_{SL}	ERROR	θ_{cm}	A_{SL}	ERROR	θ_{cm}
-0.475	.031	41.3	-0.623	.064	37.2	-0.836	.026	49.6
-0.556	.050	49.9	-0.670	.049	40.9	-0.877	.030	58.2
-0.475	.030	50.7	-0.673	.062	46.4	-0.844	.028	58.4
-0.493	.033	54.9	-0.742	.050	50.0	-0.762	.029	64.5
-0.530	.052	59.2	-0.711	.045	50.5	-0.806	.039	67.2
-0.570	.030	60.2	-0.717	.056	55.5	-0.812	.027	68.3
-0.577	.033	61.5	-0.668	.070	59.0	-0.759	.040	71.4
-0.570	.054	68.2	-0.728	.046	59.3	-0.774	.028	72.3
-0.566	.034	69.3	-0.750	.043	59.9	-0.765	.043	76.7
-0.481	.032	92.4	-0.793	.064	63.4	-0.697	.046	83.4
-0.367	.033	92.6	-0.787	.077	65.9	-0.739	.046	96.4
-0.420	.033	93.8	-0.841	.069	68.6	-0.740	.048	103.1
-0.382	.029	105.9	-0.836	.044	68.8	-0.689	.042	107.8
-0.400	.028	106.9	-0.746	.075	73.2	-0.640	.046	114.7
-0.416	.027	108.8	-0.809	.064	74.6	-0.580	.041	123.9
-0.351	.033	116.1	-0.790	.028	82.0			
-0.395	.032	117.8	-0.730	.026	97.6			
-0.419	.030	119.4	-0.654	.026	110.3			

Table 5-3. Nominal vs True incident proton energies.

Nominal kinetic energy	True kinetic energy - energy loss
500 MeV	488 MeV
600 MeV	589 MeV
650 MeV	640 MeV
700 MeV	692 MeV
750 MeV	743 MeV
800 MeV	793 MeV

Figure 5-1. LAMPF vs SIN A_{LL} and A_{SL} measurements at 500 MeV.
Dots: LAMPF (this experiment), Crosses: SIN (Aprile et al.)

spectrometer to momentum analyze the scattered deuterons while the SIN experiment of Aprile et al. did not. Analysis of the deuteron momentum was found to be important in reducing the background contamination of the signal events in this region which were about 20% for this

experiment. In addition the discrepancy may be the result of using different background subtraction techniques. The SIN experiment subtracted backgrounds empirically using carbon target data while we subtracted backgrounds analytically by fitting peak shapes.

Three Levels of Analysis

The experimental results can be analyzed at three different levels: purely phenomenological analysis, partial wave analysis, and comparison with theory. Phenomenological, or model independent analysis, interprets basic properties of the experimental observables, such as symmetries, without the use of any detailed theoretical input. Although the amount of information that can be learned from this approach is limited its conclusions are completely reliable. Partial wave analysis (PWA) is not a theory. It is a parameterization of the experimental observables in terms of the partial wave amplitudes in one particular reaction channel. It correlates different types of data in that channel and is capable of revealing inconsistencies in the data, making predictions of unmeasured observables, and revealing structure in the partial wave amplitudes. Finally there is "theory" which predicts the partial wave amplitudes and experimental observables, in one or more of the reaction channels, by describing the reaction in terms of the interactions involved. As described in Chap. II a number of theories have been developed which have varying degrees of sophistication and success. We present below a discussion of our results in terms of each of these levels of analysis.

Phenomenological Analysis

As described in Chapter II we can derive the amplitudes $|T_6|$ and $|S|$ and the relative phase δ at $\theta_{cm} = 90^\circ$, in a completely model independent manner. These are plotted as a function of the incident beam energy in Figures 5-2 and 5-3. Similarly we can obtain in a purely phenomenological manner the spin dependent cross-sections σ^T and σ^{SM} , which are respectively the sum of the squared triplet amplitudes, and the sum of the squared singlet and mixed amplitudes. These are plotted as a function of energy at $\theta_{cm} = 50, 70$, and 90° in Figures 5-4 and 5-5. Errors shown in these plots are statistical errors only. Values of A_{NN} , and A_{NO} used to calculate $|T_6|$, and δ were taken from Tippens et al.⁴⁴, and Saha et al.⁴⁵ respectively. The unpolarized cross-sections σ_{00} were calculated from coefficients of fits to the world data by Saha et al.⁴⁵ These figures include the measurements of Aprile et al.⁴³ along with several theoretical and partial wave analysis predictions to be discussed later.

From early cross-section measurements it is well known that the $pp \rightarrow \pi d$ reaction within the 500 to 800 MeV energy range is dominated by the effects of the NA intermediate state. Within this energy range partial waves up to $L_\pi = 2$ are the most important while higher partial waves are suppressed by the centrifugal barrier. A list of the partial wave amplitudes up to $L_\pi = 5$, as defined by Mandl and Regge²⁷ and extended by Blankleider and Afnan²⁴, in terms of the initial pp and final pion states, is given in Table 5-4. Also listed are the L_Δ , the relative angular momentum between the nucleon and the Δ if the reaction proceeds through the NA intermediate state. $L_\Delta = *$ indicates that no

Figure 5-2. $|T_6|$, $|S|$, and δ vs T_p , (Experiment and Partial Wave Analysis). Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Hiroshige et al. D type solution (Ref. 46), Dashed curve: Watari et al. (Ref. 47).

Figure 5-3. $|T_6|$, $|S|$, and δ vs T_p , (Experiment and Theory).

Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Lyon (Ref. 48), Dot Dash curve: Blankleider and Afnan (Ref. 24), Dashed curve: Popping and Sauer (Ref. 49).

Figure 5-4. σ^{SM} and σ^{T} vs T_p at $\theta_{\text{cm}} = 50, 70,$ and 90° , (Experiment and Partial Wave Analysis). Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Hiroshige et al. D type solution (Ref. 46), Dashed curve: Watari et al. (Ref. 47).

Figure 5-5. σ^{SM} and σ^T vs T_p at $\theta_{cm} = 50, 70$, and 90° , (Experiment and Theory). Dots: LAMPF (This experiment), Crosses: SIN (Aprile et al. Ref. 43), Solid curve: Lyon (Ref. 47), Dot Dash curve: Blankleider and Afnan (Ref. 24), Dashed curve: Popping and Sauer (Ref. 49).

Table 5-4. Notation for the partial wave amplitudes.

Amplitude	$2s+1L_{PJ}$	L_π	L_Δ	Amplitude	$2s+1L_{PJ}$	L_π	L_Δ
a_0	$1S_0$	1	*	a_8	$1G_4$	3	2
a_1	$3P_1$	0	1	a_9	$3F_3$	4	1
a_2	$1D_2$	1	0	a_{10}	$3F_4$	4	3
a_3	$3P_1$	2	1	a_{11}	$3H_4$	4	3
a_4	$3P_2$	2	1	a_{12}	$3H_5$	4	3
a_5	$3F_2$	2	1	a_{13}	$1G_4$	5	2
a_6	$3F_3$	2	1	a_{14}	$1I_6$	5	4
a_7	$1D_2$	3	0				

$N\Delta$ intermediate state is possible. If the partial wave amplitudes are in fact being dominated by the $N\Delta$ resonance this should show up as a peak in the energy dependence of the amplitudes at an energy corresponding to the formation of an $N\Delta$ intermediate state. If the deuteron had no binding energy, and hence no fermi motion, one would expect $L_\Delta=0$ intermediate $N\Delta$ states to be formed at a pion lab energy of 175 MeV which corresponds to an incident proton lab energy of 637 MeV. However as explained by Bugg⁵⁰, this energy will be shifted down by approximately 67 MeV due to the 70 MeV/c spectator momentum of the nucleons and the kinematics which favor the formation of $L_\Delta=0$ $N\Delta$ states through a head-on collision between the proton and the pion. For intermediate $N\Delta$ states with relative angular momentum $L_\Delta=1$ or greater, the centrifugal barrier will cause the peaks to occur at progressively higher energies. Thus the singlet amplitude $1D_2(1)$ which has an

intermediate $L_{\Delta}=0$ $N\Delta$ state should peak near 570 MeV, while the $L_{\Delta}=1$ amplitudes ${}^3P_1(2)$, ${}^3P_2(2)$, ${}^3F_2(2)$, and ${}^3F_3(2)$ should peak near 660 MeV.

From the angular distributions of A_{SL} and A_{LL} it is difficult to tell which of the amplitudes are the more important. However from equation 2-18h we can see that if the reaction is dominated by the triplet amplitudes the value of A_{LL} should be near +1. Conversely if the reaction is dominated by the singlets A_{LL} should be near -1. As the values of A_{LL} indicate neither the singlet or triplet amplitudes are dominant at all energies. The general trend appears to be that the singlet amplitudes are stronger at lower energies while the triplets are stronger at higher energies. Plots of σ^T , σ^{SM} and amplitudes $|T_6|$, $|S|$ (Figures 5-2 through 5-5) also confirm this trend. These plots also show that σ^{SM} , which is dominated by the 1D_2 amplitude, peaks near 570 MeV. Similarly the triplet cross-section, which are fed by the 3P_1 , 3P_2 , 3F_2 , and 3F_3 initial states, peak near 660 MeV. This is precisely what we expected if the reaction is dominated by the $N\Delta$ initial state.

Although the phase δ cannot reveal anything about the relative strengths of the amplitudes S and T_6 it is sensitive to the presence of any resonance like phenomena. Since δ is observed to vary by less than 33° over the measured energy range this is a good indication that there are no resonance effects in the amplitudes S and T_6 which determine δ .

Partial Wave Analysis

In Chapter II it was described how the spin observables are formed from bilinear combinations of the six complex helicity amplitudes M_1 ,

T_2 , T_3 , M_4 , S , and T_6 , which in turn can be expressed as sums over the partial wave amplitudes $\alpha_{L_p L_\pi}^S(J)$. It is the purpose of partial wave analysis (PWA) to determine the partial wave amplitudes which will give the best fit to the experimental data over the given energy range. In principle, given a complete set of data over some energy range, different PWA should arrive at the same set of partial wave amplitudes. In practice this is never the case. One never has a complete set of data. In addition only a finite number of amplitudes can be determined requiring the series of partial waves to be terminated at some value of L_π or L_p where the amplitudes are expected to be small. Higher partial waves can be set to zero or taken from theory. Furthermore restrictions on permissible energy variations of the parameters as well as the choice of starting points for the parameter search can also influence the outcome of the PWA. To date a number of energy dependent partial wave analysis of the $pp \rightarrow \pi d$ channel have been completed. One such analysis is that of Strakovsky et al.⁵¹ at Leningrad. These authors used over 1000 data points from the global data available as of 1982 to make an analysis of the partial wave amplitudes with $L_\pi \leq 4$ in the energy range from 440 to 1240 MeV. Higher partial waves, which should be small, were set to zero. The global data set as of 1982 consisted primarily of differential cross-section and asymmetry measurements. The only spin correlation data that were available were that of Aprile et al.⁴³ and of Hoftiezer et al.⁵² from SIN which were all at energies below 580 MeV. By omitting some of the older less reliable data to minimize the χ^2 of the resulting solution, and by requiring a

resonance like energy dependence of the amplitudes, these authors arrived at a single energy dependent solution.

Several partial wave analysis of the $pp \rightarrow \pi d$ channel have also been made by the group of Watari et al. at Osaka.^{46,47} Their initial analysis (Hiroshige et al.⁴⁶) was similar to that of Strakovsky et al.⁵¹ in that they also used the global data available as of 1982 to find solutions to the partial wave amplitudes with $L_\pi \leq 4$ while higher partial waves were set to zero. However their energy range was from near threshold (≈ 288 MeV) to 810 MeV. This analysis resulted in two sets of solutions referred to as the S and the D type solutions. The D solutions, which have large $^1D_2(1)$ and $^3F_3(2)$ amplitudes, were preferred over the S solutions, which had large $^1S_0(1)$ amplitudes, because the S solutions violated the two channel unitarity condition. The Osaka group have recently completed a second analysis (Watari et al.⁴⁷) in the same energy range. This analysis uses the same data set as before plus the additional spin correlation data of this experiment as well as that of Tippens et al.⁴⁴ to calculate the amplitudes a_0 to a_8 ($L_\pi \leq 3$) from threshold up to 810 MeV. Higher partial wave amplitudes are either taken from the theory of Lyon group⁴⁸ or set to zero. Given only nine amplitudes to determine with an extended data set as well as some restrictions on the higher partial wave amplitudes, this second analysis arrives at just one solution.

Finally a partial wave analysis has recently been completed by Bugg.⁵⁰ Bugg's analysis uses essentially the same data set as the Osaka group's latest analysis to determine the partial wave amplitudes up to a_6 ($L_\pi \leq 2$) from 450 to 800 MeV. Amplitudes a_7 to a_{14} are taken

from the theory of Blankleider and Afnan²⁴ while still higher partial waves are set to zero. In addition Bugg finds that the value of a_3 is small and that the χ^2 of the solution is improved by setting it to zero. Given only six amplitudes to determine, Bugg's analysis finds just one solution. However the choice of $a_3=0$ and the reliance on theory to predict more of the higher partial wave amplitudes leaves Bugg's analysis considerably more model dependent than the analysis of Watari et al. Both Watari et al. and Bugg determine the energy dependence of the amplitudes by finding a number of energy independent solutions within the energy range and requiring these solutions to have a smoothly varying energy dependence which can be interpolated to find the amplitudes at any energy within the energy range.

Results of the different PWA calculations are plotted along with the data in Figure 5-6. Due to the lack of spin correlation data above 600 MeV the initial PWA predictions of Hiroshige et al.⁴⁶ and Strakovsky et al.⁵¹ do a poor job of fitting the data above this energy. The difference between the Osaka group's two results show how much the analysis have been improved by the inclusion of the new data. Comparison of Bugg's⁵⁰ and Watari et al.'s⁴⁷ latest PWA predictions to the data shows that these analysis are now able to fit the data reasonably well. As shown in Figure 5-7 both these analysis predict large a_2 and a_6 amplitudes which peak near energies of 570 and 660 MeV respectively, indicating that the interaction is dominated by the NA intermediate state through the 1D_2 and 3F_3 initial pp states. The energy dependence and phases of the amplitudes predicted by these analysis also fail to show any evidence of dibaryon resonances.

Figure 5-6. A_{LL} and A_{SL} vs θ_{cm} , (Experiment and Partial Wave Analysis).
Dots: This experiment, Dot Dash curve: Strakovsky et al. (Ref. 51),
Solid curve: Hiroshige et al. D type solution (Ref. 46), Dashed curve:
Watari et al. (Ref. 47), Dotted curve: Bugg (Ref. 50).

Figure 5-7. The Energy dependence of the partial wave amplitudes a_2 and a_6 . Dotted curve: Bugg (Ref. 50), Dashed curve: Watari et al. (Ref. 47).

Theoretical Analysis

Results of the unified theory calculations of the Lyon group⁴⁸, Blankleider and Afnan²⁴, and Popping and Sauer⁴⁹ are compared to the data of this experiment in Figure 5-8. Despite the fact that these authors agree on the basic ingredients there are still large differences among them as to how pion absorption should be taken into account

Figure 5-8. A_{LL} and A_{SL} vs θ_{cm} . (Experiment and Theory).
 Dots: This experiment, Solid curve: Lyon (Ref. 48), Dot Dash curve: Blankleider and Afnan (Ref. 24), Dashed curve: Popping and Sauer (Ref. 49).

and what the πN and NN scattering potentials should be. Heavy vector meson exchange was not included in either calculation. None of the theories are able to predict more than the general trend of the data. Plots of σ^{SM} and σ^{T} (Figure 5-5) show the underlying reason for this. All of these calculations do reasonably well in predicting the 1D_2 dominated singlet contribution but both the Lyon group and Blankleider and Afnan significantly underestimate the triplet contribution. Popping and Sauer do somewhat better, especially above 650 MeV, but have a peculiar oscillation in the triplet contribution, σ^{T} , around 575 MeV. It is not clear at this stage what ingredient has been left out in all these theories and what accounts for the often substantial differences between them. With such divergence between the results of these theories it would hardly be prudent to try to improve the agreement between any one of them and the data by adding artificial constructs such as dibaryons or other six-quark constructs.

Concluding Remarks

New and precise measurements of the $pp \rightarrow \pi d$ spin correlation parameters A_{SL} and A_{LL} have been obtained in the 500 to 800 MeV energy range. With the exception of the 500 MeV A_{LL} measurement near 90° there seems to be no disagreement with previous data when they exist (< 600 MeV). The partial wave analysis of the Osaka group and Bugg have been much improved by the inclusion of this new data. The results do not demonstrate the existence any structures other than those expected from the dominance of this reaction by the $N\Delta$ intermediate state with $L_\Delta = 0$ and 1. Results of the theoretical predictions based on different

variants of unified model look promising but are not yet at the point at which new constructs such as dibaryons may be built upon them. Hopefully the present experiment will contribute towards improving the theories and lead to a definitive conclusion about possible dibaryon resonances with masses less than 2241 MeV.

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APPENDIX A

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Figure A-1. Cut away view of the wire chamber W2.

Figure A-2. The MWPC read out system.

pulse to the files. If the event was not good no such signal was returned. The discriminator outputs also triggered a 750 ns monostable delay pulse for each struck wire. The delays were adjusted to allow a coincidence between the falling edge of the monostable delays and the write gate to activate flip-flops for each struck wire. This defined the hit pattern. After setting the flip-flops, the write gate caused the hit pattern of modules with one or more struck wires to be converted into 16 bit data words. The first 8 bits of each word specified the file and module. The second 8 bits recorded the analog hit pattern of the module's 8 sense wires. This allowed multiple hits to be easily handled. The 16 bit data words were sent through a data bus to the scratch pad memory, located in the counting house, which acted as an intermediate buffer to speed up data taking.³ The contents of the scratch pad memory could be read by the CAMAC system and passed on to the PDP 11/60 computer via the MBD.

References Appendix A

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APPENDIX B

ASYMMETRY CALCULATIONS

Intoduction

A derivation of the equations used to calculate the polarizations, yields, and spin correlation parameters is presented below.

Target Polarization

The absolute target polarization P^t was calculated for each run as the product of the calibration coefficient times the average NMR area,

$$P^t = \text{POLCAL} \times \text{AREA} \quad (\text{B-1})$$

where POLCAL = Calibration constant,

and AREA = Average NMR signal area.

Beam Polarization

The normal and reverse beam polarizations for each run were calculated in one of two ways depending on the spin orientation of the incident beam. If the beam had an $\hat{S}$ spin component at the polarimeter target greater than 0.35 the polarimeter was used to measure the average of the normal and reverse polarization and the quench ratio was used to measure the difference. If the beam's $\hat{S}$ component was less than 0.35 only the quench ratio measured by the polarimeter was used.

Case 1: $|\hat{p}^b \cdot \hat{S}| < 0.35$ Use quench ratio only.

$$p_{\alpha}^b = 1.0 - (1.0 - 0.03) \times \frac{(U+D - U+D_a)_{\alpha,q}}{(U+D - U+D_a)_{\alpha,p}} \times \frac{Ck_{\alpha,p}}{Ck_{\alpha,q}} \quad (B-2)$$

where:

$\hat{p}^b$ = beam polarization unit vector.

$U+D$ = (Up + Down) polarimeter counts.

$U+D_a$ = (Up + Down) accidental polarimeter counts.

CK = 10 KHz clock counts.

α = Beam spin state, (normal or reverse).

p = Polarized beam.

q = Quenched beam.

The (1.0-0.03) term is included to account for the estimated 3% polarization of the quenched beam.¹

Case 2: $|\hat{p}^b \cdot \hat{S}| > 0.35$ Use quench ratio and polarimeter.

Defining:

$$UP_n = (U - U_a)_n$$

$$UP_r = (D - D_a)_r$$

$$DN_n = (D - D_a)_n$$

$$DN_r = (D - D_a)_r$$

$$\epsilon_{ud} = \frac{\sqrt{UP_n \times UP_r} - \sqrt{DN_n \times DN_r}}{\sqrt{UP_n \times UP_r} + \sqrt{DN_n \times DN_r}} \quad (B-3)$$

$$p^b_{(ave)} = \frac{\epsilon_{ud}}{|\hat{P} \cdot \hat{S}| \times A_{ud}} \quad (B-4)$$

$$\delta_p = \frac{p^b_{q,n} - p^b_{q,r}}{p^b_{q,n} + p^b_{q,r}} \quad (B-5)$$

$$p^b_n = p^b_{(ave)} + \delta_p \quad (B-6a)$$

$$p^b_r = p^b_{(ave)} - \delta_p \quad (B-6b)$$

where:

n,r = Normal or reverse beam state.

U = Up polarimeter counts.

U_a = Accidental up polarimeter counts.

D = Down polarimeter counts.

D_a = Accidental down polarimeter counts.

A_{ud} = Up-down polarimeter analyzing power.

p_q^b = Beam polarization from quench ratio.

Yields

The raw yield of each beam spin state and angle bin for each run was calculated as the sum of counts in the signal histogram between the markers 2 and 3 (m₂ and m₃) which were determined during background analysis. The raw yield was normalized for the integrated beam current

and live time and a portion was subtracted to account for the estimated background fraction.

$$Y_{\alpha,i} = \left(\sum_{m2}^{m3} \{ \text{Sig. Hist. Counts} \}_{\alpha,i} \right) (\text{NORM}_{\alpha}) (1 - R_{\text{bgd}_{\alpha,i}}) \quad (\text{B-7})$$

α = Beam spin state.

i = Angle bin.

$$\text{NORM}_{\alpha} = (\text{ICH}_{\alpha} \times \text{LT}_{\alpha})^{-1} \quad (\text{B-8})$$

ICH_{α} = Sum of α beam spin state ion chamber counts.

$$\text{LT}_{\alpha} = \frac{(\text{U+D} - \text{U+D}_a)_{\alpha} (\text{Master inhibit} \times \text{Inhibit B})}{(\text{U+D} - \text{U+D}_a)_{\alpha} (\text{Inhibit B})} \quad (\text{B-9})$$

$R_{\text{bgd}_{\alpha,i}}$ = Background ratio of α,i bin.

Spin Correlation Parameters

The spin correlation parameters were found for each angle bin from the yields and polarizations using equation 2-20 derived in Chapter II.

$$Y_i = I_o (1 + P_i^b |\hat{P}^b \cdot \hat{N}|_{A_{NO}} + P_i^b P_i^t A') \quad (B-10)$$

i = Beam and target state.

i = 1: Normal beam, + target.

i = 2: Reverse beam, + target.

i = 3: Normal beam, - target.

i = 4: Reverse beam, - target.

Y_i = Relative yield with background subtracted.

P_i^b, P_i^t = Magnitude of beam and target polarizations.

Note that the signs of P_i^b and P_i^t are implicit.

$$A' = |\hat{P}^b \cdot \hat{S}|_{A_{SL}} + |\hat{P}^b \cdot \hat{L}|_{A_{LL}}$$

We use χ^2 minimization to reduce the four equations to three.

$$\text{Let } \chi^2 = \frac{1}{\sigma^2} \sum_i^4 (Y_i - I_o (1 + P_i^b |\hat{P}^b \cdot \hat{N}|_{A_{NO}} + P_i^b P_i^t A'))^2 \quad (B-11)$$

$$\text{Require: } \frac{\partial \chi^2}{\partial I_o} = \frac{\partial \chi^2}{\partial A_{NO}} = \frac{\partial \chi^2}{\partial A'} = 0$$

This gives the following three equations.

$$\sum_i^4 Y_i = 4I_o + I_o |\hat{P}^b \cdot \hat{N}|_{A_{NO}} \sum_i^4 P_i^b + I_o A' \sum_i^4 P_i^b P_i^t \quad (B-12)$$

$$\sum_i^4 Y_i P_i^b = I_o \sum_i^4 P_i^b + I_o |\hat{P}^b \cdot \hat{N}|_{A_{NO}} \sum_i^4 P_i^b + I_o A' \sum_i^4 (P_i^b)^2 P_i^t \quad (B-13)$$

$$\sum_i^4 Y_i P_i^b P_i^t = I_o \sum_i P_i^b P_i^t + I_o |\hat{P}^b \cdot \hat{N}| A_{NO} \sum_i (P_i^b)^2 P_i^t + I_o A' \sum_i (P_i^b P_i^t)^2 \quad (B-14)$$

These equations can be written in the form of a matrix equation which can be inverted to solve for the three unknowns.

$$\begin{pmatrix} I_o \\ I_o |\hat{P}^b \cdot \hat{N}| A_{NO} \\ I_o A' \end{pmatrix} = \begin{pmatrix} 4 & \sum_i P_i^b & \sum_i P_i^b P_i^t \\ \sum_i P_i^b & \sum_i (P_i^b)^2 & \sum_i (P_i^b)^2 P_i^t \\ \sum_i P_i^b P_i^t & \sum_i (P_i^b)^2 P_i^t & \sum_i (P_i^b P_i^t)^2 \end{pmatrix}^{-1} \begin{pmatrix} \sum_i Y_i \\ \sum_i Y_i P_i^b \\ \sum_i Y_i P_i^b P_i^t \end{pmatrix} \quad (B-15)$$

Separating A_{SL} and A_{LL} from A'

If the incident beam was longitudinal, then $|\hat{P}^b \cdot \hat{N}| = |\hat{P}^b \cdot \hat{S}| = 0$, and $A' = A_{LL}$. If the beam contained transverse as well as longitudinal spin components then A_{SL} and A_{LL} were separated from A' by using two measurements of A' made with two different beam spin orientations 1 and 2.

$$A'_1 = (|\hat{P}^b \cdot \hat{S}|_1 A_{SL} + |\hat{P}^b \cdot \hat{L}|_1 A_{LL}) \quad (B-16a)$$

$$A'_2 = (|\hat{P}^b \cdot \hat{S}|_2 A_{SL} + |\hat{P}^b \cdot \hat{L}|_2 A_{LL}) \quad (B-16b)$$

The two equations for A' can be solved for A_{SL} and A_{LL} .

$$A_{LL} = \frac{A'_1 |\hat{p}^b \cdot \hat{s}|_2 - A'_2 |\hat{p}^b \cdot \hat{s}|_1}{|\hat{p}^b \cdot \hat{s}|_2 |\hat{p}^b \cdot \hat{L}|_1 - |\hat{p}^b \cdot \hat{s}|_1 |\hat{p}^b \cdot \hat{L}|_2} \quad (B-17a)$$

$$A_{SL} = \frac{A'_1 |\hat{p}^b \cdot \hat{L}|_2 - A'_2 |\hat{p}^b \cdot \hat{L}|_1}{|\hat{p}^b \cdot \hat{s}|_1 |\hat{p}^b \cdot \hat{L}|_2 - |\hat{p}^b \cdot \hat{s}|_2 |\hat{p}^b \cdot \hat{L}|_1} \quad (B-17b)$$

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where:

$\hat{P}^b$ = beam polarization unit vector.

$U+D$ = (Up + Down) polarimeter counts.

$U+D_a$ = (Up + Down) accidental polarimeter counts.

CK = 10 KHz clock counts.

α = Beam spin state, (normal or reverse).

p = Polarized beam.

q = Quenched beam.

The (1.0-0.03) term is included to account for the estimated 3% polarization of the quenched beam.¹

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Defining:

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$$P^b(\text{ave}) = \frac{\epsilon_{ud}}{|\hat{P} \cdot \hat{S}| \times A_{ud}} \quad (B-4)$$

$$\delta_p = \frac{P_{q,n}^b - P_{q,r}^b}{P_{q,n}^b + P_{q,r}^b} \quad (B-5)$$

$$P_n^b = P^b(\text{ave}) + \delta_p \quad (B-6a)$$

$$P_r^b = P^b(\text{ave}) - \delta_p \quad (B-6b)$$

where:

n,r = Normal or reverse beam state.

U = Up polarimeter counts.

U_a = Accidental up polarimeter counts.

D = Down polarimeter counts.

D_a = Accidental down polarimeter counts.

A_{ud} = Up-down polarimeter analyzing power.

P_q^b = Beam polarization from quench ratio.

Yields

The raw yield of each beam spin state and angle bin for each run was calculated as the sum of counts in the signal histogram between the markers 2 and 3 (m₂ and m₃) which were determined during background analysis. The raw yield was normalized for the integrated beam current

and live time and a portion was subtracted to account for the estimated background fraction.

$$Y_{\alpha,i} = \left(\sum_{m_2}^{m_3} \{ \text{Sig. Hist. Counts} \}_{\alpha,i} \right) (\text{NORM}_{\alpha}) (1 - R_{\text{bgd}_{\alpha,i}}) \quad (\text{B-7})$$

α = Beam spin state.

i = Angle bin.

$$\text{NORM}_{\alpha} = (\text{ICH}_{\alpha} \times \text{LT}_{\alpha})^{-1} \quad (\text{B-8})$$

ICH_{α} = Sum of α beam spin state ion chamber counts.

$$\text{LT}_{\alpha} = \frac{(U+D - U+D_a)_{\alpha} (\text{Master inhibit} \times \text{Inhibit B})}{(U+D - U+D_a)_{\alpha} (\text{Inhibit B})} \quad (\text{B-9})$$

$R_{\text{bgd}_{\alpha,i}}$ = Background ratio of α,i bin.

Spin Correlation Parameters

The spin correlation parameters were found for each angle bin from the yields and polarizations using equation 2-20 derived in Chapter II.

$$Y_i = I_o (1 + P_i^b |\hat{P}^b \cdot \hat{N}| A_{NO} + P_i^b P_i^t A') \quad (B-10)$$

i = Beam and target state.

$i = 1$: Normal beam, + target.

$i = 2$: Reverse beam, + target.

$i = 3$: Normal beam, - target.

$i = 4$: Reverse beam, - target.

Y_i = Relative yield with background subtracted.

P_i^b, P_i^t = Magnitude of beam and target polarizations.

Note that the signs of P_i^b and P_i^t are implicit.

$$A' = |\hat{P}^b \cdot \hat{S}| A_{SL} + |\hat{P}^b \cdot \hat{L}| A_{LL}$$

We use χ^2 minimization to reduce the four equations to three.

$$\text{Let } \chi^2 = \frac{1}{\sigma^2} \sum_1^4 (Y_i - I_o (1 + P_i^b |\hat{P}^b \cdot \hat{N}| A_{NO} + P_i^b P_i^t A'))^2 \quad (B-11)$$

$$\text{Require: } \frac{\partial \chi^2}{\partial I_o} = \frac{\partial \chi^2}{\partial A_{NO}} = \frac{\partial \chi^2}{\partial A'} = 0$$

This gives the following three equations.

$$\sum_1^4 Y_i = 4 I_o + I_o |\hat{P}^b \cdot \hat{N}| A_{NO} \sum_1^4 P_i^b + I_o A' \sum_1^4 P_i^b P_i^t \quad (B-12)$$

$$\sum_1^4 Y_i P_i^b = I_o \sum_1^4 P_i^b + I_o |\hat{P}^b \cdot \hat{N}| A_{NO} \sum_1^4 P_i^b + I_o A' \sum_1^4 (P_i^b)^2 P_i^t \quad (B-13)$$

$$\sum_1^4 Y_1 P_1^b P_1^t = I_0 \sum P_1^b P_1^t + I_0 |\hat{P}^b \cdot \hat{N}| A_{NO} \sum (P_1^b)^2 P_1^t + I_0 A' \sum (P_1^b P_1^t)^2 \quad (B-14)$$

These equations can be written in the form of a matrix equation which can be inverted to solve for the three unknowns.

$$\begin{pmatrix} I_0 \\ I_0 |\hat{P}^b \cdot \hat{N}| A_{NO} \\ I_0 A' \end{pmatrix} = \begin{pmatrix} 4 & \sum P_1^b & \sum P_1^b P_1^t \\ \sum P_1^b & \sum (P_1^b)^2 & \sum (P_1^b)^2 P_1^t \\ \sum P_1^b P_1^t & \sum (P_1^b)^2 P_1^t & \sum (P_1^b P_1^t)^2 \end{pmatrix}^{-1} \begin{pmatrix} \sum Y_1 \\ \sum Y_1 P_1^b \\ \sum Y_1 P_1^b P_1^t \end{pmatrix} \quad (B-15)$$

Separating A_{SL} and A_{LL} from A'

If the incident beam was longitudinal, then $|\hat{P}^b \cdot \hat{N}| = |\hat{P}^b \cdot \hat{S}| = 0$, and $A' = A_{LL}$. If the beam contained transverse as well as longitudinal spin components then A_{SL} and A_{LL} were separated from A' by using two measurements of A' made with two different beam spin orientations 1 and 2.

$$A'_1 = (|\hat{P}^b \cdot \hat{S}|_1 A_{SL} + |\hat{P}^b \cdot \hat{L}|_1 A_{LL}) \quad (B-16a)$$

$$A'_2 = (|\hat{P}^b \cdot \hat{S}|_2 A_{SL} + |\hat{P}^b \cdot \hat{L}|_2 A_{LL}) \quad (B-16b)$$

The two equations for A' can be solved for A_{SL} and A_{LL} .

$$A_{LL} = \frac{A'_1 |\hat{P}^b \cdot \hat{S}|_2 - A'_2 |\hat{P}^b \cdot \hat{S}|_1}{|\hat{P}^b \cdot \hat{S}|_2 |\hat{P}^b \cdot \hat{L}|_1 - |\hat{P}^b \cdot \hat{S}|_1 |\hat{P}^b \cdot \hat{L}|_2} \quad (B-17a)$$

$$A_{SL} = \frac{A'_1 |\hat{P}^b \cdot \hat{L}|_2 - A'_2 |\hat{P}^b \cdot \hat{L}|_1}{|\hat{P}^b \cdot \hat{S}|_1 |\hat{P}^b \cdot \hat{L}|_2 - |\hat{P}^b \cdot \hat{S}|_2 |\hat{P}^b \cdot \hat{L}|_1} \quad (B-17b)$$

REFERENCES APPENDIX B

1. M. W. McNaughton, LAMPF Beam Line Polarimeters, LANL Report LA-8307-MS (1980).

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