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Thesis

Forward Angle Quasi-Free Proton-Neutron Analyzing Powers at 0.8 GeV

University of California



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Martin Lynn Barlett*

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FORWARD ANGLE QUASI-FREE PROTON-NEUTRON ANALYZING POWERS AT 0.8 GeV

by

Martin Lynn Barlett

ABSTRACT

As the first step in determining the nucleon-nucleon scattering amplitudes at small momentum transfers at 0.8 GeV, quasi-free $\vec{p} + n$ and $\vec{p} + p$ analyzing powers were obtained at laboratory scattering angles from 6° to 32.9° by scattering 800 MeV polarized protons from a liquid deuterium target. Forward scattered protons were detected by the High Resolution Spectrometer (HRS) while recoil neutrons and protons were detected in coincidence with the event detected with the HRS by a 5×5 array of scintillators. A thin scintillator placed between the target and the array enabled discrimination of recoil particle type and facilitated the simultaneous measurement of both $\vec{p}n$ and $\vec{p}p$ analyzing powers. A comparison of the results with previously measured free $\vec{p}p$ and $n\vec{p}$ analyzing powers shows excellent agreement between the free and quasi-free $\vec{p}p$ analyzing powers. Poorer agreement is seen for the $\vec{p}n$ analyzing powers. The results of phase-shift analyses are presented in order to study the effects of the quasi-free analyzing power measurements on the determination of the pn scattering amplitudes. Amplitudes obtained from the phase-shift analyses are then used in KMT calculations. The results indicate that further nucleon-nucleon measurements are necessary in order to unambiguously determine the nucleon-nucleon amplitudes at 800 MeV.

CHAPTER 1

PURPOSE AND MOTIVATION OF THE EXPERIMENT

INTRODUCTION

A considerable amount of work on $\vec{p} + \text{nucleus}$ elastic scattering at 0.8 GeV has shown that analyses of the data are capable (in principle) of providing detailed information about ground state neutron density distributions.⁽¹⁻⁵⁾ This is not surprising since the deBroglie wavelength ($\lambda = h/p$) of an 800 MeV proton is about 0.85 fm and is comparable to the internucleon "spacing" (~ 1.8 fm) of nuclear matter. The analyses are done in terms of microscopic proton-nucleus scattering theories, such as the multiple scattering theory of Glauber⁽⁶⁾ or the optical potential formalism of Kerman, McManus, and Thaler (KMT).⁽⁷⁾ In first order, both approaches require as input the free nucleon-nucleon scattering amplitudes and the proton and neutron density distributions of the target nucleus. Thus, to empirically determine neutron densities, the nucleon-nucleon scattering amplitudes and the proton density distribution of the target nucleus must be known. The proton densities can be determined from the charge densities obtained from electron scattering data, while the nucleon-nucleon amplitudes can, in principle, be obtained from a complete set of proton-proton and proton-neutron scattering data.

Equally important are tests of the theory (KMT) and the many approximations involved in the numerical calculations. Absolute neutron radii extracted for nuclei such as ^{16}O and ^{40}Ca , as well as analyzing power predictions for $\vec{p} + \text{nucleus}$ scattering, constitute rigorous tests of the theory and the approximations made to facilitate numerical calculations.

This chapter begins with a discussion of KMT theory and the conventional applications of it to analyze 800 MeV proton-nucleus elastic scattering data, and follows with a discussion of the present uncertainty in the key nucleon-nucleon amplitudes needed for the calculations - the motivation for the experiment reported here and others to be done in the future.

KMT THEORY AND ELASTIC SCATTERING

The KMT formalism provides a method for obtaining an optical potential from the non-relativistic many-body Schrödinger equation. The many-body Schrödinger equation may be written as

$$(E - h_0 - H_A - \sum_i^A v_{oi})\Psi^{(+)} = 0, \quad (1.1)$$

where h_0 is the kinetic energy operator of the incident particle, H_A is the Hamiltonian of the target nucleus A, and v_{oi} is the two-body interaction between the incident particle and the i^{th} target nucleon. If antisymmetrization of the projectile-nucleus system is neglected and only the nuclear wavefunction is

antisymmetrized, the Schrödinger equation may be rewritten as a many-body Lippmann-Schwinger equation of the form

$$\psi^{(+)} = \phi + G^{(+)} \tilde{A} (Av) \psi^{(+)} , \quad (1.2)$$

where

$$G^{(+)} = (E - h_o - H_A + i\epsilon)^{-1}$$

$\tilde{A}$ = projection operator of antisymmetric nuclear states.

Here the independence of the two-body interaction, v_{oi} , on the target nucleon label (i) for an antisymmetrized nuclear wavefunction has been included by setting $\sum_i v_{oi} = Av$. If the scattering matrix, T , is defined such that

$$T\phi = (Av)\psi^{(+)} , \quad (1.3)$$

then the integral equation for the scattering matrix becomes

$$T = (Av) + (Av)G^{(+)}\tilde{A}T. \quad (1.4)$$

By defining the operator $\tilde{t}$ such that

$$\tilde{t} = v + vG^{(+)}\tilde{A}\tilde{t} , \quad (1.5)$$

Equation 1.5 can be solved for v and substituted into Equation 1.4

to give

$$T = A\tilde{t} + (A - 1)\tilde{t}G^{(+)}\tilde{A}T. \quad (1.6)$$

Defining a pseudo-scattering matrix T' such that $T' = \frac{A - 1}{A}T$, we get a Lippmann-Schwinger equation of the form

$$T' = (A - 1)\tilde{t} + (A - 1)\tilde{t}G^{(+)}\tilde{A}T'. \quad (1.7)$$

When this equation is operated on from the left with P (the elastic projection operator) and Q (the non-elastic projection operator), where $P + Q = \tilde{A}$, we get two equations:

$$PT' = (A - 1)P\tilde{t} + (A - 1)P\tilde{t}G^{(+)}(P + Q)T', \quad (1.8a)$$

and

$$QT' = (A - 1)Q\tilde{t} + (A - 1)Q\tilde{t}G^{(+)}(P + Q)T'. \quad (1.8b)$$

By solving Equation 1.8b for QT' and substituting the result into Equation 1.8a, the equation for the elastic channel is

$$PT' = PU' + PU'G^{(+)}PT', \quad (1.9)$$

where

$$U' = (A-1)\tilde{t} + (A-1)\tilde{t}G^{(+)}(1-(A-1)Q\tilde{t}G^{(+)})^{-1}(A-1)Q\tilde{t}. \quad (1.10)$$

Equation 1.9 is the dynamical equation to be solved in practice,

while Equation 1.10 is the explicit second order form of the KMT potential.⁽⁸⁾

From Equation 1.10 it is possible to obtain an expression for the first order KMT potential for elastic scattering in the coordinate space representation. Consider an elastic scattering process where the initial state is given by $|\phi_A, \vec{k}\rangle$ and the final state given by $\langle \vec{k}', \phi_A |$ where ϕ_A is the nuclear ground state and $\vec{k}$ and $\vec{k}'$ are the initial and final projectile momenta. The first order KMT potential may then be written as

$$\tilde{U}^{(1)} = \langle \vec{k}', \phi_A | (A - 1) \tilde{t} | \phi_A, \vec{k} \rangle. \quad (1.11)$$

By defining a one-body density matrix as

$$\begin{aligned} \rho(\vec{r}'_1, \vec{r}_1) &= \int d\vec{r}_2 \dots d\vec{r}_A \langle \phi_A | \vec{r}'_1, \vec{r}_2 \dots \vec{r}_A \rangle \\ &\times \langle \vec{r}_1, \vec{r}_2 \dots \vec{r}_A | \phi_A \rangle, \end{aligned} \quad (1.12)$$

the first order KMT potential may be written as

$$\tilde{U}^{(1)} = (A-1) \int d\vec{r}_1 d\vec{r}'_1 \langle \vec{k}', \vec{r}'_1 | \tilde{t} | \vec{r}_1, \vec{k} \rangle \rho(\vec{r}'_1, \vec{r}_1). \quad (1.13)$$

Here the two-nucleon t-matrix is in a mixed representation with the projectile being described in momentum space and the target nucleon in coordinate space.

The two-nucleon t-matrix of Equation 1.13 may be rewritten in momentum space by the use of Fourier transforms and Equation 1.13 becomes

$$\begin{aligned} \tilde{U}^{(1)} = & (A-1) \int d\vec{r}_1 d\vec{r}'_1 d\vec{k}_0 d\vec{k}'_0 \exp[i(\vec{k}'_0 \cdot \vec{r}'_1 - \vec{k}_0 \cdot \vec{r}_1)] \\ & \times \langle \vec{k}', \vec{k}'_0 | \tilde{t} | \vec{k}_0, \vec{k} \rangle \rho(\vec{r}'_1, \vec{r}_1) , \end{aligned} \quad (1.14)$$

where $\vec{k}_0$ and $\vec{k}'_0$ are the initial and final momenta of the target nucleon, respectively. We now require momentum conservation and write the scattering matrix as

$$\begin{aligned} \langle \vec{k}', \vec{k}'_0 | \tilde{t} | \vec{k}_0, \vec{k} \rangle = & \langle \vec{k}' - \vec{k}'_0 | \tilde{t} | \vec{k}_0 - \vec{k} \rangle \\ & \times \delta(\vec{k} - \vec{k}' + \vec{k}_0 - \vec{k}'_0) , \end{aligned} \quad (1.15)$$

where the delta function assures momentum conservation. When this condition is applied to Equation 1.14 and the integral over the final target nucleon momentum ($\vec{k}'_0$) is performed, the first order KMT potential becomes

$$\begin{aligned} \tilde{U}^{(1)} = & (A-1) \int d\vec{r}_1 d\vec{r}'_1 d\vec{k}_0 \exp(i[(\vec{k} - \vec{k}' + \vec{k}_0) \cdot \vec{r}'_1 - \vec{k}_0 \cdot \vec{r}_1]) \\ & \times \langle \vec{k}' - (\vec{k} - \vec{k}' + \vec{k}_0) | \tilde{t} | \vec{k}_0 - \vec{k} \rangle \rho(\vec{r}'_1, \vec{r}_1) . \end{aligned} \quad (1.16)$$

We now assume that the target nucleon momentum can be ignored ($\vec{k}_0 = 0$) and rewrite Equation 1.16 as

$$\begin{aligned} \tilde{U}^{(1)} = (A-1) \int d\vec{r}_1 d\vec{r}_1' d\vec{k}_0 \exp(i[(\vec{k}-\vec{k}') \cdot \vec{r}_1' + (\vec{r}_1' - \vec{r}_1) \cdot \vec{k}_0]) \\ \times \langle \vec{k}' - (\vec{k} - \vec{k}') | \tilde{t} | \vec{k} \rangle \rho(\vec{r}_1', \vec{r}_1). \end{aligned} \quad (1.17)$$

Using the Fourier transform of the one-body density and integrating over $\vec{k}_0$ and $\vec{r}_1$, the optical potential reduces to

$$\tilde{U}^{(1)} = (A-1) \langle \vec{k}' | \tilde{t} | \vec{k} \rangle \tilde{\rho}(\vec{q}) \quad (1.18)$$

where

$$\vec{q} = \vec{k}' - \vec{k},$$

and where

$$\tilde{\rho}(\vec{q}) = \int d\vec{r} \exp[-i(\vec{q} \cdot \vec{r})] \rho(\vec{r}).$$

To express the optical potential in coordinate space we now define $\vec{K} = 1/2(\vec{k} + \vec{k}')$, $\vec{R} = 1/2(\vec{r} + \vec{r}')$, and $\vec{S} = (\vec{r} - \vec{r}')$ and Fourier transform Equation 1.18 in order to obtain the first-order KMT potential in terms of $\vec{K}$ and $\vec{S}$. The optical potential is then given by

$$U^{(1)} = (A-1) \int d\vec{R} d\vec{q} \exp[i(\vec{q} \cdot \vec{R} - \vec{K} \cdot \vec{S})] \tilde{t}(\vec{K}, \vec{q}) \tilde{\rho}(\vec{q}). \quad (1.19)$$

We now assume that the scattering matrix is only weakly dependent on the total momentum ($\vec{K}$) and approximate $\tilde{t}(\vec{K}, \vec{q})$ with $\tilde{t}(\vec{q})$. Then by integrating over the total momentum ($\vec{K}$) we find

$$U^{(1)} \approx (A-1)\delta(\vec{r}-\vec{r}')\int d\vec{q}\exp(i\vec{q}\cdot\vec{r})\tilde{t}(\vec{q})\tilde{\rho}(\vec{q}). \quad (1.20)$$

Thus we have now obtained a local potential.

The final approximation, known as the impulse approximation,⁽⁷⁾ involves replacing $\tilde{t}$ with t , the free nucleon-nucleon scattering amplitude. When this is done, we arrive at the simplest form of the first-order KMT optical potential:

$$U^{(1)}(\vec{r}) \approx (A-1)\int d\vec{q}\exp(i\vec{q}\cdot\vec{r})t(\vec{q})\tilde{\rho}(\vec{q}). \quad (1.21)$$

Thus we have found an expression for the optical potential in terms of the free nucleon-nucleon scattering amplitudes and the Fourier transform of the nuclear ground state density.

The nucleon-nucleon scattering amplitudes which are consistent with the principles of space reflection, rotation, and time-reversal invariances and charge independence may be written in terms of five complex amplitudes as⁽⁹⁾

$$\begin{aligned} M = & a + ic(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{n} + m(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) \\ & + g[(\vec{\sigma}_1 \cdot \hat{p})(\vec{\sigma}_2 \cdot \hat{p}) + (\vec{\sigma}_1 \cdot \hat{k})(\vec{\sigma}_2 \cdot \hat{k})] \\ & + h[(\vec{\sigma}_1 \cdot \hat{p})(\vec{\sigma}_2 \cdot \hat{p}) - (\vec{\sigma}_1 \cdot \hat{k})(\vec{\sigma}_2 \cdot \hat{k})] , \end{aligned} \quad (1.22)$$

where the unit vectors $\hat{n}$, $\hat{p}$, and $\hat{K}$ are defined as

$$\hat{n} = \frac{(\vec{k}_i \times \vec{k}_f)}{|\vec{k}_i \times \vec{k}_f|}$$

$$\hat{p} = \frac{(\vec{k}_i + \vec{k}_f)}{|\vec{k}_i + \vec{k}_f|}$$

$$\hat{K} = \frac{(\vec{k}_f - \vec{k}_i)}{|\vec{k}_f - \vec{k}_i|} .$$

The on-shell nucleon-nucleon scattering matrix, M , in the nucleon-nucleon center-of-momentum (c.m.) system is expressed as a t-matrix in the nucleon-nucleus c.m. system as

$$t = \frac{-2\pi(\hbar c)^2}{E_L} \frac{k_L}{k_0} \eta M , \quad (1.23)$$

where k_L and E_L are the incident momentum and total energy of the projectile in the laboratory system, k_0 is the nucleon-nucleon c.m. momentum, and η is defined as

$$\eta = \frac{1 + \frac{2A}{A^2 + 1} \frac{E_L}{m}}{1 + \frac{A}{A^2 + 1} \left(\frac{E_L}{m} + \frac{m}{E_L} \right)} .$$

We now consider the scattering of a spin 1/2 particle from a spin zero target nucleus. The local optical potential may be written as,⁽⁷⁾

$$V(r) = V_c(r) + \frac{1}{r} \frac{d}{dr} V_{so}(r) \vec{l} \cdot \vec{s}. \quad (1.24)$$

The corresponding potential matrix in momentum space may be written as,

$$\tilde{U}(q) = \langle \vec{k}' | V(r) | \vec{k} \rangle = \frac{1}{(2\pi)^3} \int \exp(-i\vec{k}' \cdot \vec{r}) V(\vec{r}) \exp(i\vec{k} \cdot \vec{r}) d\vec{r}. \quad (1.25)$$

If Equation 1.24 is substituted into Equation 1.25, we find that the potential matrix may be expressed as⁽⁷⁾

$$\tilde{U}(q) = V_c(\vec{q}) - iV_{so}(\vec{q}) \vec{\sigma} \cdot (\vec{k}_i \times \vec{k}_f). \quad (1.26)$$

By comparison of the above equation with the corresponding first-order KMT potential in momentum-transfer space (analogous to Equation 1.21) and using Equation 1.22 and 1.23, it can be seen that only the spin-independent and spin-dependent amplitudes of the nucleon-nucleon scattering matrix (a,c) are necessary to generate the first-order KMT optical potential for describing elastic scattering of protons from spin zero nuclei. This potential may

now be expressed explicitly in terms of the neutron and proton form factors and the proton-proton (pp) and proton-neutron (pn) amplitudes as⁽¹⁰⁾

$$\begin{aligned}
 U^{(1)} \approx & 4\pi\bar{\eta} \int q^2 dq (a_{pp}(q^2) \tilde{\rho}_p(q^2) + a_{pn}(q^2) \tilde{\rho}_n(q^2)) j_0(qr) \\
 & + 4\pi\bar{\eta} \frac{1}{r} \frac{d}{dr} \int q^2 dq (\tilde{c}_{pp}(q^2) \tilde{\rho}_p(q^2) + \tilde{c}_{pn}(q^2) \tilde{\rho}_n(q^2)) \\
 & \times j_0(qr) \vec{\sigma} \cdot \vec{k} , \tag{1.27}
 \end{aligned}$$

where

$$\bar{\eta} = - \frac{A-1}{A} \frac{(\hbar c)^2}{E_L (2\pi)^2} \frac{k_L}{k_0} \frac{1 + \frac{2A}{A^2+1} \frac{E_L}{m}}{1 + \frac{A}{A^2+1} \left(\frac{E_L}{m} + \frac{m}{E_L} \right)}$$

and

$$\tilde{c} = \frac{k_0}{k_N} \frac{c(q^2)}{|\vec{k}'_0 \times \vec{k}_0|} .$$

Here k_N is the incident proton momentum in the proton-nucleus c.m. system.

ELASTIC SCATTERING ANALYSES

The first-order KMT potential (Equation 1.27) has been used in several analyses of intermediate energy proton-nucleus elastic scattering data.^(4,11,12) In these analyses, the Schrödinger equation

with relativistic kinematics⁽¹³⁾ is solved using the partial-wave formalism. In addition, the more recent analyses of 0.8 GeV elastic scattering data have treated as perturbations to the first-order KMT potential second-order terms arising from target nucleon correlations and the leading corrections to the point-proton density due to the neutron's electric and magnetic form factors and the magnetic form factor of the proton.⁽⁵⁾ Even though the spin-independent and spin-dependent amplitudes (a and c of Equation 1.22) are the only amplitudes required in the analysis of proton scattering from a spin-zero nucleus,⁽¹¹⁾ these amplitudes cannot be determined independent of the remaining three double-spin-flip amplitudes (m, g, and h). It is necessary to have a complete set of proton-nucleon measurements spanning the range of momentum transfer covered by the proton-nucleus scattering data in order to unambiguously determine a and c.⁽⁵⁾

Unfortunately, a complete set of proton-nucleon measurements at 0.8 GeV does not exist. Because of this, the spin-independent and spin-dependent amplitudes of Equation 1.27 are generally parameterized as⁽⁵⁾

$$a_{pj}(q^2) = (ik_o \sigma_{pj}^T / 4\pi)(1 - i\alpha_{pj}) \exp(-B_{pj} q^2) , \quad (1.28a)$$

and

$$c_{pj}(q^2) = (ik_o \theta_{pj}/4\pi)(1-i\alpha_{spj})(q^2/4m^2)^{1/2} \times \exp(-B_{spj}q^2), \quad (1.28b)$$

where j refers to either a proton (p) or a neutron (n), k_o is the nucleon momentum in the nucleon-nucleon c.m. system, m is the nucleon mass, and σ_{pj}^T is the spin averaged total cross section.

The above equations contain 12 parameters which must be determined. Four of these parameters (σ_{pp}^T , σ_{pn}^T , α_{pp} , and α_{pn}) are essentially fixed by existing proton-nucleon data and dispersion-theory estimates,⁽⁵⁾ but the remaining eight parameters cannot be uniquely determined at present. One approach is to assume that the double-spin-flip amplitudes (m , g , and h of Equation 1.22) are zero and to optimize the parameters B_{pj} , θ_{pj} , α_{spj} , and B_{spj} to fit the pp and pn cross section and polarization data. If we assume m , g , and h to be zero, then the nucleon-nucleon cross section and polarization are given by

$$\frac{d\sigma}{d\Omega} = (\sigma_{pj}^T k_o/4\pi)^2 (1+\alpha_{pj}^2) \exp(-2B_{pj}q^2) + 2(\theta_{pj} k_o/4\pi)^2 (1+\alpha_{spj}^2) \times (q^2/4m^2) \exp(-2B_{spj}q^2) \quad (1.29a)$$

$$P\left(\frac{d\sigma}{d\Omega}\right) = \sigma_{pj}^T (k_o/4\pi)^2 [\theta_{pj}(\alpha_{spj} - \alpha_{pj})] (\hbar c q/mc^2) \times \exp[-(B_{spj} + B_{pj})q^2]. \quad (1.29b)$$

It is found⁽⁵⁾ that the quantities $\theta_{pj}(\alpha_{spj} - \alpha_{pj})$ and $(B_{spj} + B_{pj})$ are

well determined by fitting $P(\frac{d\sigma}{d\Omega})/q$. Thus, even under the unrealistic assumptions leading to this result, two free parameters (for pp and pn) remain.

Using Equations 1.29a and 1.29b and performing $|\chi^2|$ searches on the available pp and pn cross section and polarization data near 0.8 GeV leads to three discrete solutions⁽⁵⁾ for each of the pp and pn amplitudes. These three sets of proton-nucleon parameters, together with the point-proton matter density obtained from the charge distribution determined from electron scattering data, were used in the KMT calculations to fit the 0.8 GeV $p + {}^{40}\text{Ca}$ elastic scattering data.⁽⁵⁾ In these calculations, the neutron density distribution was varied for each of the three sets of proton-nucleon parameters to obtain the best fit to the data. The neutron-proton root-mean-square radius difference, Δr_{np} , was then deduced for each solution. The results indicated that significant ambiguities exist in the determination of Δr_{np} due to the lack of a unique set of proton-nucleon parameters.⁽⁵⁾ One solution gave $\Delta r_{np} \approx 0.06$ fm while the other two gave $\Delta r_{np} \approx -0.15$ fm.

The above result suggests that a complete set of proton-nucleon experiments is necessary in order to resolve these ambiguities. Until the proton-nucleon amplitudes are known over the region covered by the $p + \text{nucleus}$ data, a definitive statement about the ground-state neutron density distributions cannot be made. Our experimental group has initiated a program to determine some of the key nucleon-nucleon parameters and the experiment

described in this dissertation constitutes the first of these measurements. The experiment was an accurate determination of the forward-angle $\vec{p} + n$ analyzing power.

CHAPTER 2

EXPERIMENTAL METHOD

INTRODUCTION

The experiment to measure the forward-angle $\vec{p} + n$ quasi-free analyzing powers at $E_p = 800$ MeV was done at the High Resolution Spectrometer (HRS) experimental area of the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). A liquid deuterium target served as the source of quasi-free neutrons. The HRS detected the forward-scattered protons while an array of 25 scintillators detected recoil neutrons or protons in coincidence with the HRS. A thin scintillator located between the target and the recoil array enabled discrimination between recoil protons and neutrons. Thus, $\vec{p} + n$ and $\vec{p} + p$ quasi-free analyzing powers were obtained simultaneously. A detailed description of the experimental technique follows.

POLARIZED PROTON BEAM

The polarized proton beam used in the experiment was provided by the LAMPF linear accelerator. The accelerator is capable of accelerating simultaneously both protons (H^+) and negative hydrogen ions (polarized (P^-) or unpolarized (H^-)) to a

maximum energy of 0.8 GeV. Three ion sources provide the different species of particles used by the accelerator. The Lamb-shift polarized ion source⁽¹⁴⁾ used for this experiment is housed within the high-voltage terminal of its associated Cockcroft-Walton preaccelerator. The main features of the polarized ion source are schematically illustrated in Fig. 2.1. Protons are extracted from the duoplasmatron by a set of accelerating electrodes, and are then decelerated to 500 eV. These protons then pass through a cloud of cesium gas where neutral hydrogen atoms are obtained through electron pickup from the cesium atoms. A portion, optimally 43%, of the neutral atoms formed are in the metastable (2s) state rather than the ground (1s) state. These metastable hydrogen atoms are then polarized by the Lamb-shift source.

After leaving the cesium cell, the beam enters the spin filter region of the ion source. The spin filter consists of a solenoid-produced axial magnetic field of 540 Gauss, a transverse static electric field of 20 V/cm, and an axial RF field of about 20 V/cm. The Breit-Rabi diagram for hydrogen, Fig. 2.2, shows the metastable ($2s_{1/2}$) state hyperfine level splitting in a magnetic field as well as the hyperfine level splitting for the ($2p_{1/2}$) states of hydrogen. As can be seen from the Figure, the magnetic and static electric fields of the spin filter couple the $2s_{1/2}$ β -states to the $2p_{1/2}$ states while the RF and magnetic fields couple the lower $2s_{1/2}$ α -state to the $2p_{1/2}$ states. Once these states are coupled they quickly ($\tau \approx 1\text{ns}$) decay to the ground state

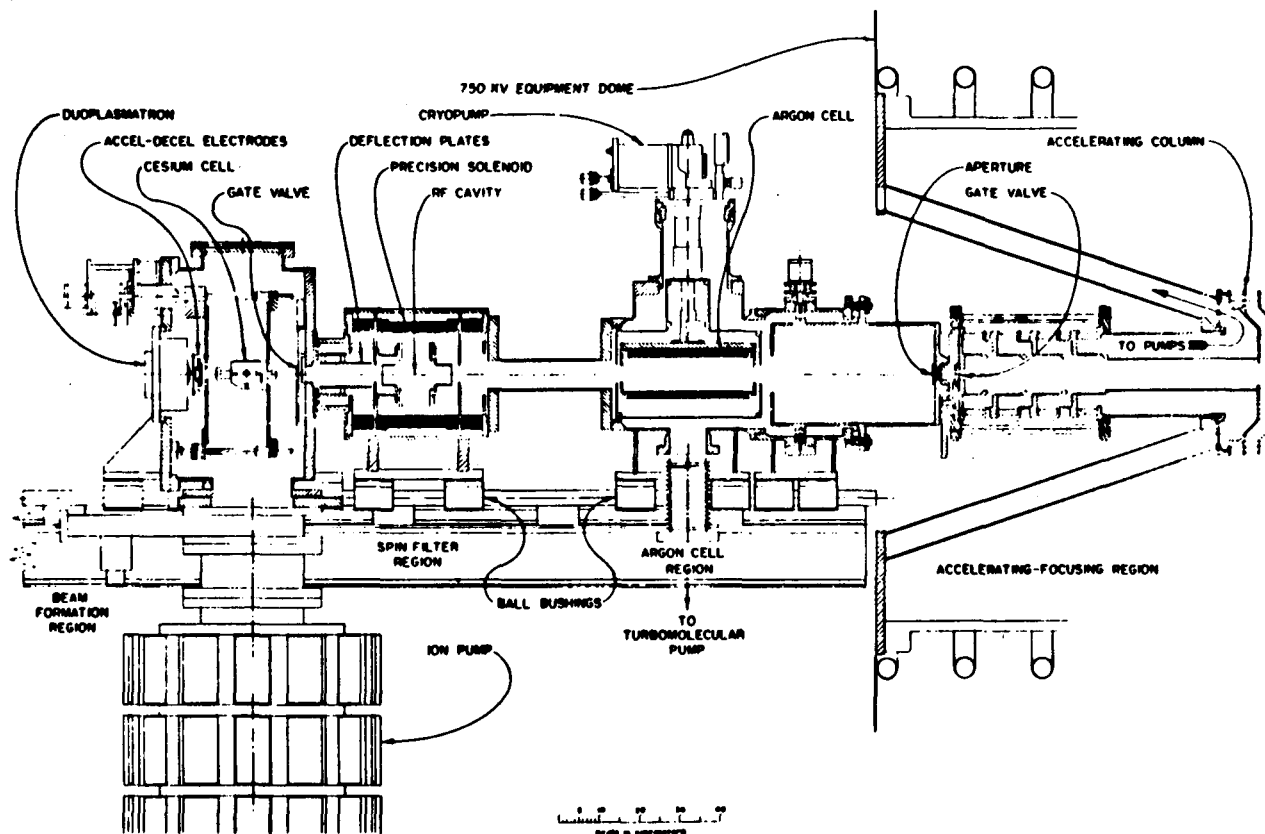


Figure 2.1: A drawing of the LAMPF Lamb-shift polarized ion source (P^-) which provided the polarized protons used in this experiment. The major components of the source are identified in the drawing.

HYDROGEN BREIT-RABI DIAGRAM

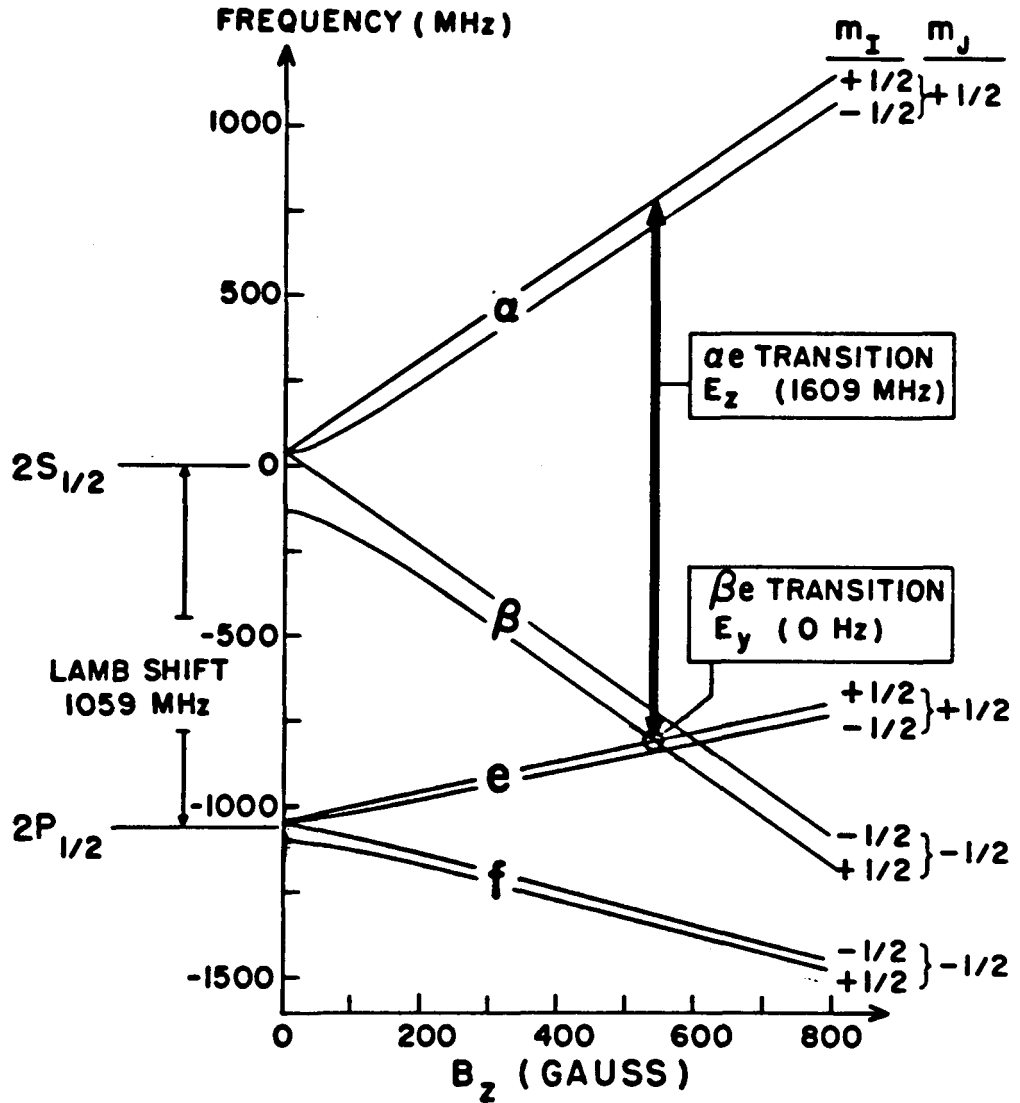


Figure 2.2: A Breit-Rabi diagram for hydrogen showing the hyperfine level splitting of the $2s_{1/2}$ and $2p_{1/2}$ states in a magnetic field, B_z . Also indicated are the proton spin components (m_I) and the electron spin components (m_J) for the resulting levels.

leaving only one component of the $2s_{1/2}$ metastable state. The remaining metastable state has a specific nuclear polarization, $m_1 = +1/2$, with the proton spin vector aligned along the axial magnetic field of the spin filter.

The beam, now comprised of about 90% atomic hydrogen in the ground state and 10% atomic hydrogen in the polarized metastable state, then enters a solenoid containing argon gas and an axial magnetic field of about 10 Gauss. In this argon cell the metastable hydrogen atoms are selectively ionized to form negative polarized hydrogen ions (P^-). A small percentage of the ground state hydrogen atoms also ionize in the argon cell and form unpolarized negative hydrogen ions (H^-). For this reason, the beam polarization is never 100%; typical polarizations range from 70-85%.

Spin reversal is accomplished by reversing the magnetic fields in the spin filter and argon cell. Using this method two states of beam polarization are provided, one parallel to the beam direction and one anti-parallel to the beam direction. During the experiment spin reversal occurred every 3 minutes with data acquisition being interrupted for 10-15 seconds during the reversal to allow time for the fields in the spin filter and argon cell to stabilize.

After passing through the argon cell, the beam is focused and accelerated to 750 KeV. A spin precessor system is then used to orient the spin direction properly for on-line experiments. The

beam is then bunched and injected into the first stage of the drift-tube linac.

The drift-tube linac⁽¹⁵⁾ is an adaptation of the Alvarez design and consists of four copper-lined tanks with progressively longer drift-tubes mounted along the centerline. The drift-tube section operates at a frequency of 201.25 MHz and accelerates the injected particles from 750 KeV to 100 MeV. Quadrupole magnets within the drift-tubes are used to focus the beam during acceleration; tuning and stabilization of the RF structure in each tank is accomplished by means of movable post couplers. The total length of the drift-tube linac including intertank spacing is about 61.75 m or 202.5 ft.

After leaving the drift-tube linac the beam enters the final stage of the LAMPF accelerator, the side-coupled linac.⁽¹⁵⁾ The side-coupled linac operates at 805 MHz and the final beam energy is determined by the number of tanks used in the acceleration process. A total of 352 accelerating tanks make up this half-mile long section and final beam energy is 0.8 GeV when all the tanks are used.

The side-coupled-cavity design utilizes external resonant cavities which connect each pair of successive accelerating cavities. This coupling mechanism provides a means for fine-tuning the accelerator by applying small physical distortions to the coupling cavities and provides small power losses between

accelerating sections. The cavities also provide the phase shifts in the RF power necessary for proper beam acceleration.

At the end of the accelerator the beam enters the switchyard where the P^- (or H^-) beam is magnetically separated from the H^+ beam. The H^+ beam proceeds down Line A to the main experimental hall where it passes through a series of pion production targets. The P^- beam is bent into Line X where a series of anti-strippers can be used to improve beam emittance by phase space trimming. A stripper foil (or mesh) at the end of Line X is then used to provide a polarized proton beam for Line C (HRS). The remaining P^- beam, magnetically separated from the polarized proton beam, enters Line B.

LINE C AND HRS

Line C transports the beam to the HRS experimental area. The beam line, shown schematically in Fig. 2.3, consists of a separation section, a dispersion section, and a section for matching dispersion and rotating the dispersion plane. A detailed description of the beam line has been given elsewhere⁽¹³⁾ and only a brief synopsis is presented here.

The separation section (LCBM01-03,QM01,02) magnetically separates the two types of beam in Line X and focuses the proton beam in the horizontal plane at the point (LCII02) which serves as the object for the dispersion-producing section. Horizontal dispersion is produced by the two large dipole magnets in Line C,

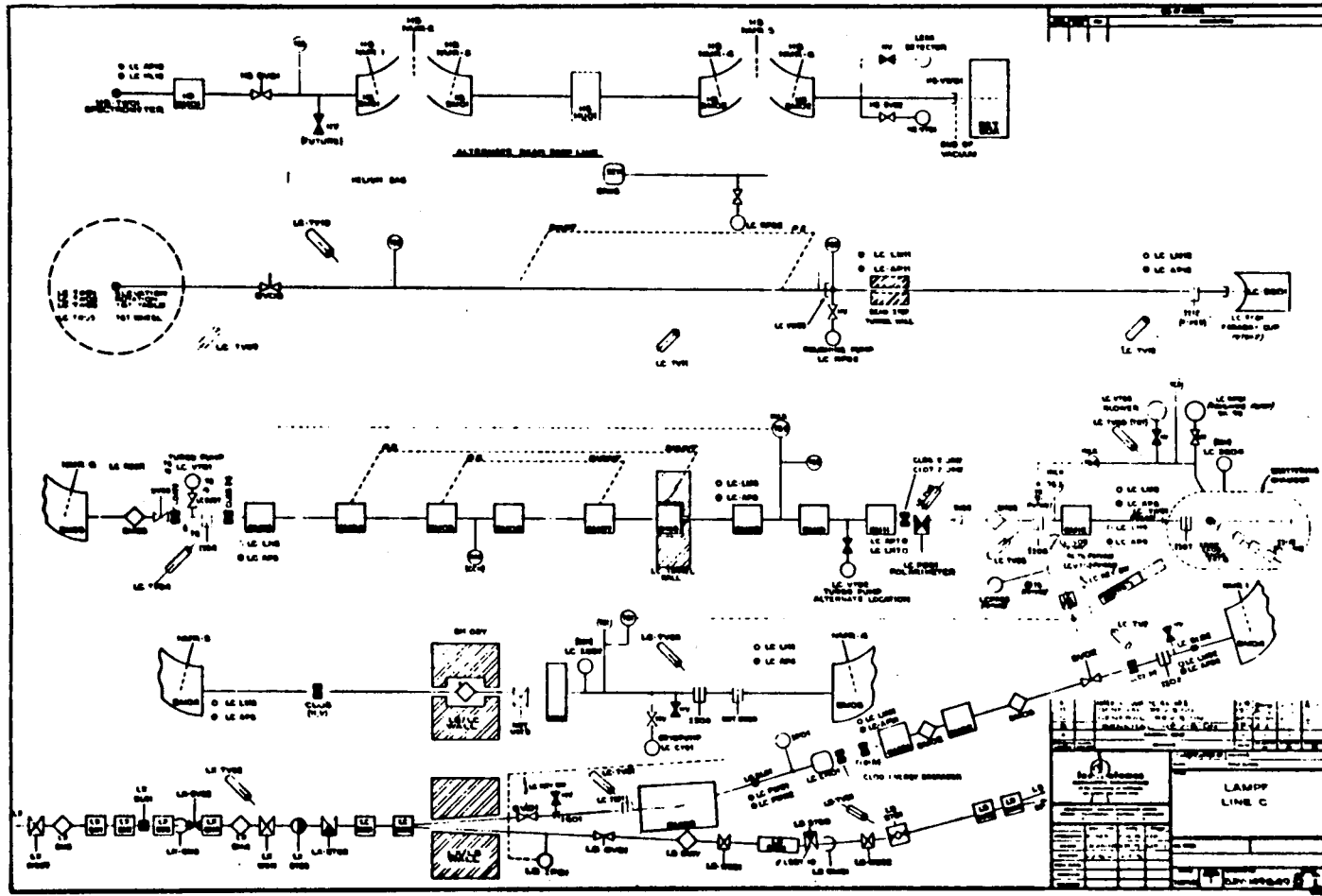


Figure 2.3: A schematic drawing of Line C (HRS) showing the major components of the beam line.

LCBM04 and LCBM05. The optics in the horizontal plane from LCII02 to LCII04 are such that they provide point-to-point focusing. A system of eight quadrupole magnets follows the dispersion section; five of these quadrupoles (LCQM04-08) rotate the beam phase space by 90° (producing vertical dispersion). Additional quadrupoles (LCQM03,09,10,11) are used to adjust the beam dispersion on target to match the HRS dispersion requirements. Seven sets of collimating jaws (LCCL01-07) allow control of the proton beam phase space as well as the beam intensity. The beam line polarimeter, LCPO01, is used as an on-line monitor of beam polarization and is discussed in the next section in more detail.

After the beam traverses Line C, it strikes a target located at the center of the scattering chamber. The scattering chamber is 1 m in radius and is vacuum-coupled both to the beam line and the spectrometer. Unscattered beam exits through the side of the scattering chamber and enters a shielded beam dump. Targets are normally mounted on a target wheel at the center of the scattering chamber; this enables remote selection of the targets mounted on the wheel. However, for the present experiment the target wheel was removed in order to accommodate the cryogenic liquid target system. This target system is also described in a later section.

Some of the protons (or other particles) scattered from the target enter the HRS. The HRS consists of one quadrupole and two dipole magnets (QDD) with a 75° bend in each dipole. A section

view of the HRS is shown in Fig. 2.4. The HRS was designed to operate in the VHV (vertical dispersion, horizontal scattering, vertical analysis) energy loss mode for measurements of two-body reactions, $B(A,C)D$, initiated by the proton beam. Here A is the incident beam proton, C is the detected particle, B is the target nucleus, and D is the residual nucleus. In the energy loss mode it is only necessary to know the momentum difference between the incident particle A and the outgoing detected particle C in order to determine the scattering angle and the state of the residual nucleus D.⁽¹⁶⁾ This is accomplished by properly matching the dispersion of the beam line to that of the spectrometer. The conditions for proper dispersion matching as well as kinematic corrections for light nuclei are discussed elsewhere.⁽¹³⁾

After travelling about 20 m through the HRS the scattered particles pass through a series of detectors (scintillators and two-dimensional wire counters) near the focal plane of the spectrometer. The scintillators provide time-of-flight (TOF) and pulse height (PH) information for particle identification, while the wire counters provide focal plane coordinates (X,Y,XANGLE,YANGLE) of the particle trajectories. The operation and use of the focal plane detectors are discussed in more detail later in this chapter.

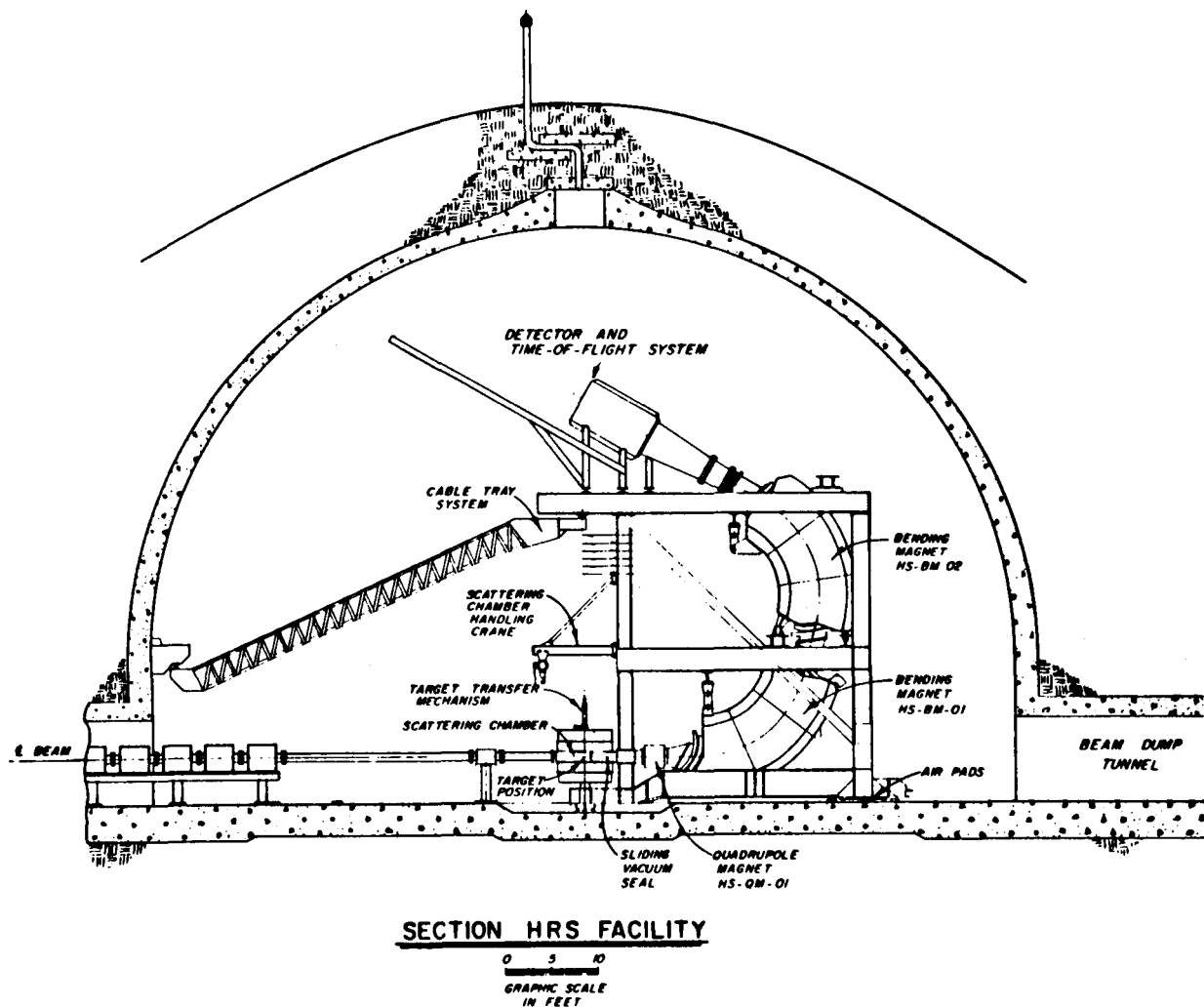


Figure 2.4: A section view of the High Resolution Spectrometer (HRS), in which the VHV mode of operation is evident.

BEAM LINE POLARIMETER

The Line C beam polarimeter, shown schematically in Fig. 2.5, was used to measure and monitor the beam polarization during the experiment. Data were obtained during Cycle 24 (June, 1979) and Cycle 26 (March, 1980) and slightly different polarimeter configurations existed for each Cycle. The relevant parameters of each polarimeter configuration are listed in Table 2.1.

Beam line polarimeters determine average beam polarizations by measuring left-right asymmetries in polarized proton scattering from a target of known analyzing power. The Line C polarimeter has several CH₂ targets installed on a remotely operated target ladder. The counter configuration monitors p + p elastic scattering near the maximum in the free $\vec{p}p$ analyzing power. During the experiment, 32 mil and 8 mil CH₂ targets were used as polarimeter targets.

The beam polarization is determined by measuring $L^{\uparrow}$, $L^{\downarrow}$, $R^{\uparrow}$, and $R^{\downarrow}$ yields in the polarimeter detectors, where $L(R)^{\uparrow(\downarrow)}$ is the yield scattered left(right) with beam spin up(down). A left(right) scattering is defined by a coincidence between Detector 3(Detector 1) which detects the scattered beam particle and Detector 4(Detector 2) which detects the recoil proton from the hydrogen in the CH₂ target. Then if the analyzing power A_y of the target is known at the beam energy and the reaction angle at which the detectors are set, the beam polarization is given by

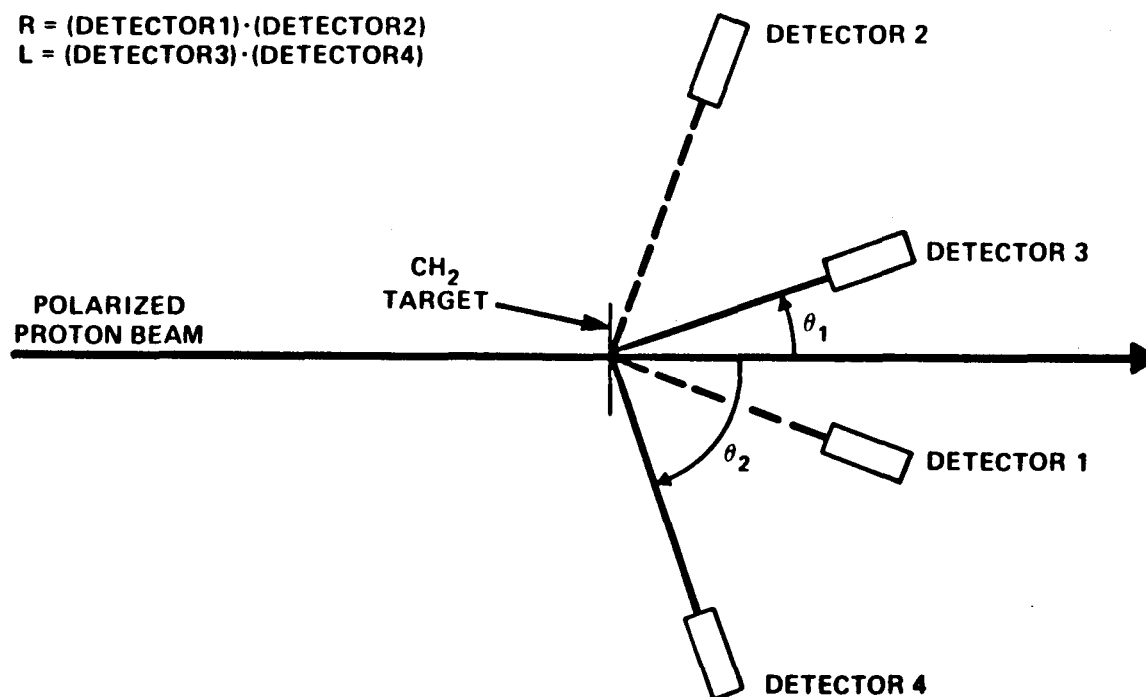


Figure 2.5: A schematic drawing of the Line C beam line polarimeter. Detector angles θ_1 and θ_2 are given in Table 2.1 for the two configurations used during the experiment. The detectors are located in the horizontal plane and are used to determine the $\hat{n}$ -type (spin up or down) beam polarization.

Table 2.1

Relevant beam line polarimeter parameters for Cycle 24 and Cycle 26

	<u>Cycle 24</u>	<u>Cycle 26</u>
Number of detectors and type	4 fixed plastic scintillators	4 fixed plastic scintillators
Forward detector angle ⁽¹⁾ (lab)	19.1°	23.0°
Recoil detector angle ⁽²⁾ (lab)	63.7°	58.8°
Polarimeter tgt. material	CH ₂	CH ₂
Effective analyzing power (800 MeV)	0.490±0.020	0.460±0.020
Target thickness	8 mil, 32 mil	8 mil, 32 mil

(1) This corresponds to θ_1 of Fig. 2.5.

(2) This corresponds to θ_2 of Fig. 2.5.

$$P_{\text{BEAM}} = \frac{\epsilon}{A_y}, \quad (2.1)$$

where ϵ is known as the asymmetry and is defined by

$$\epsilon = \frac{L - R}{L + R}. \quad (2.2)$$

Here $L = \sqrt{L \uparrow R \downarrow}$ and $R = \sqrt{R \uparrow L \downarrow}$ since a particle scattered left(right) with beam spin up(down) is the same as a particle scattered right(left) with beam spin down(up).

A polarimeter which simultaneously measures particles scattered left and right (such as the Line C polarimeter) has an advantage in that almost all uncertainties and instrumental asymmetries cancel to a high order.⁽¹⁷⁾ It is important to note that the analyzing power of the polarimeter target is not the free $\vec{p} + p$ analyzing power because of the ^{12}C contained in the target. Quasi-elastic events from the carbon are also detected by the polarimeter detectors. The angular correlations of the events from the carbon are spread over a larger phase space ($\approx 10^\circ$) than for $p + p$ (due to the Fermi motions of the nuclei), and the analyzing power for quasi-elastic scattering from carbon is significantly lower ($A_y \approx 0.275 \pm 0.015$ at 800 MeV) than the free $\vec{p} + p$ analyzing power. As a result, the effective analyzing power is lowered by a few percent from the free $\vec{p} + p$ analyzing power depending upon the geometry of the polarimeter.⁽¹⁷⁾ However, the effective analyzing

power of the polarimeter system can be determined using the quench-ratio technique,⁽¹⁸⁾ as was done for this experiment.

Another concern is the effect of accidental (random) coincidences among the conjugate polarimeter detectors. During the experiment, random coincidences were determined using a delayed coincidence circuit and recorded. By subtracting the random coincidences from the prompt coincidences (real plus random), the real asymmetries were obtained. Other, less important considerations for the proper operation of beam line polarimeters are described elsewhere.⁽¹⁷⁾ However, these considerations are not important for the present experiment.

BEAM CURRENT MONITORS

In addition to knowing the beam polarization, it is necessary to know the relative beam currents for the two beam polarizations; this is accomplished using beam current monitors. Ion chambers (IC) and secondary emission monitors (SEM) are the primary beam monitors at the HRS facility although the beam line polarimeter can also be used as a current monitor by adding the properly corrected left and right yields for the given beam polarization. In this experiment, the IC's and beam line polarimeter were used as current monitors since the SEM's gain was too small to effectively monitor the low beam current used during the experiment. During Cycle 24 a single ion chamber served as the primary means of beam current measurement and the polarimeter was

used as a backup current monitor. During Cycle 26 another ion chamber became available, and two ion chambers were used as primary and backup current monitors. Beam current ratios of the primary and backup current monitors tracked to 1.5% during Cycle 24 and to better than 1% during Cycle 26.

The standard HRS ion chamber consists of a series of thin aluminum foils contained in an aluminum case filled with a gas mixture (90% Ar, 10% CO₂). The case has thin entrance and exit windows for the beam. The foils are connected in series and electrically isolated from the case. The positive terminal of a 128 V battery is connected to a lead coming from the foils while the other terminal of the battery serves as the input to an ORTEC 439 current integrator. The case of the ion chamber is held at ground potential. The ArCO₂ pressure was 50 mm of Hg for Cycle 24 and 200 mm of Hg for Cycle 26. The pulses from the current integrator are counted by scalars which are gated by signals generated at the ion source which indicate the state of polarization of the ion source. More details of the scalars and the gating signals will be presented in a later section of this chapter.

HRS FOCAL PLANE DETECTORS

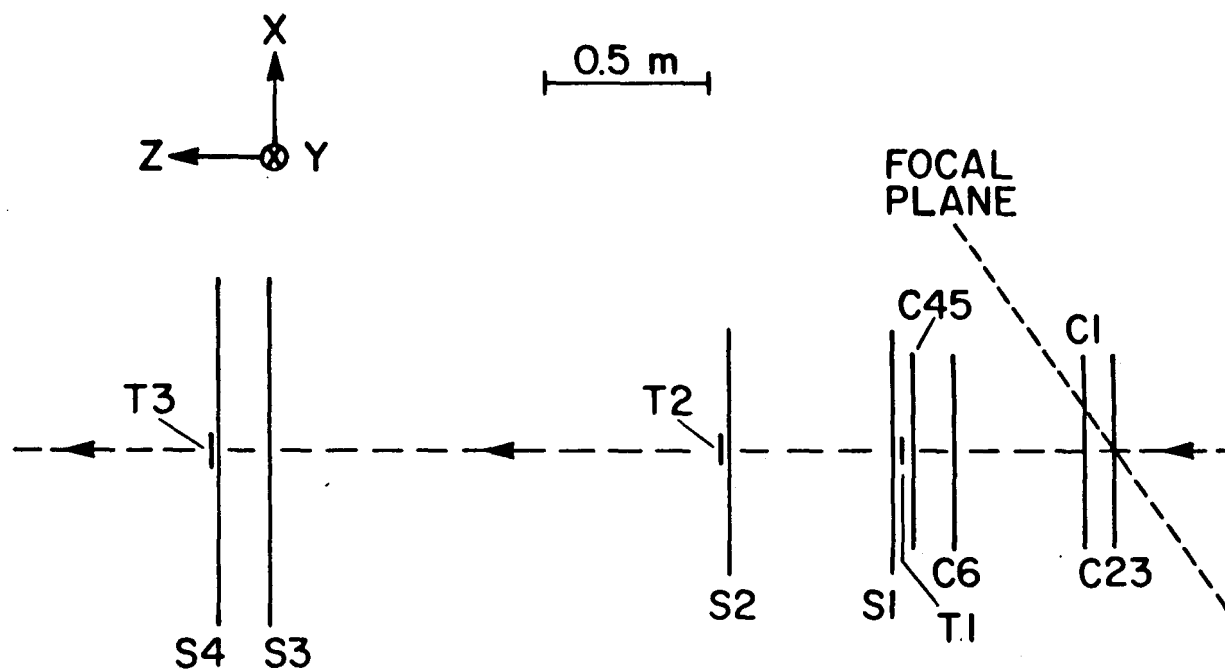
The HRS focal plane detection system provides particle identification (PID) and focal plane coordinates for each trajectory which passes through the spectrometer. A schematic

of the detector arrangement used in the experiment is shown in Fig. 2.6. The detectors consisted of three position sensitive wire chambers (C2,C3,C6) (four wire chambers, C2-C5, during Cycle 26), four event scintillators (S1-S4), and three test counter scintillators (T1-T3). The function of each of these detectors is explained below.

The four counters, S1-S4, are plastic scintillators spaced over an interval of about 2 m after the focal plane. Their geometries are given in Table 2.2. A four-fold coincidence among these scintillators indicates an EVENT. Time-of-flight between S1 and S4, as well as pulse heights in S4, are obtained for each event in order to determine particle type.

The test counters, T1-T3, are used to monitor the HRS event detection efficiency. The test counters consist of small plastic scintillators located along the optic axis of the spectrometer. As seen in Fig. 2.6, any particle detected by all three test counters should also be detected by the four event scintillators. By monitoring the ratio $T1 \cdot T2 \cdot T3 \cdot \text{EVENT} / T1 \cdot T2 \cdot T3$, the event detection efficiency is obtained. Efficiencies measured in this way were found to be >99.99% for all runs during the experiment.

Trajectory focal plane position and angle information was provided by delay line (DL) chamber C6 and drift (DR) chambers C2 and C3 during Cycle 24 and DR chambers C2-C5 during Cycle 26. These chambers, spread over a distance of about 0.5 m, each provide X and Y (two-dimensional) coordinates for each trajectory. The



HRS FOCAL PLANE DETECTORS

Figure 2.6: A schematic drawing of the HRS focal plane detection system used in the experiment. Particles exiting the spectrometer travel from right to left in the Figure. Scintillators S1-S4 provide particle identification while drift chambers C2 and C3 and delay line chamber C6 (drift chambers C2-C5 in Cycle 26) provide position information about event trajectories. The function and use of the test counters, T1-T3, are explained in the text.

Table 2.2

Specifications of event scintillator geometries used in the experiment

<u>Detector</u>	<u>Material</u>	<u>Size(cm)</u>	<u>Distance from Focal Plane(cm)</u>
S1	Pilot B	$76.2 \times 1.27 \times 0.64$	68.6
S2	Pilot F	$77.5 \times 10.8 \times 0.64$	119.4
S3	NE110	$106.7 \times 14.0 \times 0.95$	259.1
S4	NE110	$106.7 \times 14.0 \times 0.95$	274.3

computer (PDP 11/45) software uses this position information to determine the exact focal plane position and angle for each trajectory. This information is then used to compute such quantities as missing mass and space scattering angle. Since the experiment was concerned with quasi-elastic scattering, event trajectory information requirements were minimal and only a brief description of the wire chambers is given here.

Both the DL and DR chambers consist of planes of wires running vertically (Y-plane) and horizontally (X-plane). The wires of each plane are connected at regular intervals to a printed circuit delay line. The delay lines are held at high voltage and a mixture of gases (Argon, Isobutane, and 98% Argon-2% Freon) serves as a gas for ionization. When a charged particle passes through the chambers, it ionizes the gas; the ionization is detected by the wires nearest the trajectory, and the pulse generated travels to each end of the delay line. These signals are discriminated, delayed, and then used as stops for multichannel CAMAC TDC's which are started by a TRIGGER signal (the TRIGGER signal is explained in a later section of the chapter). Time sums and differences between the ends of the delay lines, along with charge drift time information from the DR chambers, are then used to calculate the event position in each chamber. More detailed information concerning the designs and operation of the wire chambers can be found elsewhere.^(13,19,20)

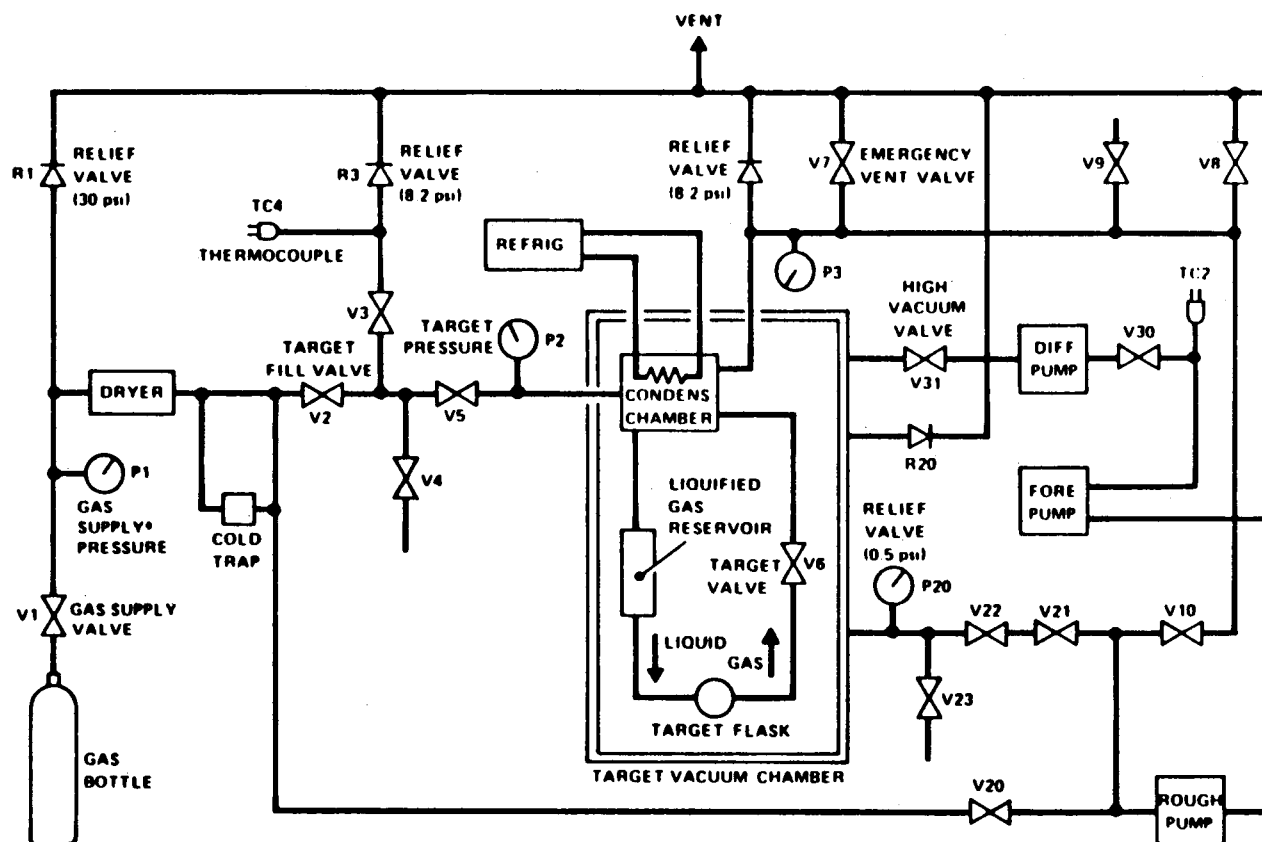
RECOIL DETECTION SYSTEM

The recoil detection system consisted of 25 scintillators, N1-N25, in a 5×5 array and a thin scintillator located between the target and the array. The thin scintillator was used to tag recoil protons. The detectors which made up the array were $3" \times 3" \times 6"$ Pilot B scintillators coupled to photomultiplier tubes with light pipes. The proton-tagging counter was a $24" \times 17 \frac{1}{2}" \times \frac{1}{4}"$ Pilot B scintillator with light pipes and photomultiplier tubes on each of the narrow ($17 \frac{1}{2}"$) sides. The recoil array detectors and the proton-tagging counter were mounted on an aluminum frame which was attached to the scattering chamber about 1 m from the target. Details of how this system was set up and interfaced with the data acquisition system are described later in the chapter.

CRYOGENIC TARGET SYSTEM

The targets used in the experiment consisted of a liquid deuterium (LD_2) target and a liquid hydrogen (LH_2) target. The LH_2 target was used during the initial setup and testing of the detection and data acquisition systems. The hydrogen and deuterium were supplied in gaseous form and liquefied by the cryogenic target system, shown schematically in Fig. 2.7.

The target flask was contained within a vacuum jacket in order to prevent any sudden boiling of the target in the event a vacuum leak occurred in the scattering chamber. In order to



CRYOGENIC TARGET SYSTEM

Figure 2.7: A schematic diagram of the cryogenic target system showing the major components. Hydrogen or deuterium gas was liquefied in the condensing chamber and used to fill the target flask. Additional liquefied gas was stored in the reservoir and ensured that the target flask remained full during the experiment. The target flask could be emptied by closing the remotely-operated target valve, V6.

minimize the amount of material through which the particles had to pass, the jacket had mylar windows at points where the beam and detected particles entered and exited through the jacket.

The target flask and vacuum jacket were modified between the two Cycles during which the experiment was performed. A sketch of the target flasks used during Cycles 24 and 26 is shown in Fig. 2.8. Relevant information concerning the materials and target thicknesses are tabulated in Table 2.3.

DATA ACQUISITION HARDWARE

The data acquisition system used in the experiment consisted of 124 channels of computer-readable (CAMAC) scalar output, 4 channels of CAMAC ADC output, 41 channels (46 channels in Cycle 26) of CAMAC TDC output, and the fast electronics associated with the system which process and define signals. In this section, both the fast electronics circuits of particular importance to the experiment and the generation of the data words associated with an event will be discussed. Certain descriptions of standard HRS systems will be omitted or greatly abbreviated based on their importance in determining the experimental results.

As mentioned previously, an EVENT is defined as a four-fold coincidence among the event scintillators, $S1 \cdot S2 \cdot S3 \cdot S4$ (or EVENT). The anode signals from photomultipliers on each end of the four event scintillators are transmitted to the HRS counting house (CCH) through about 300 ft of Belden 8214 low-loss cable. In CCH these

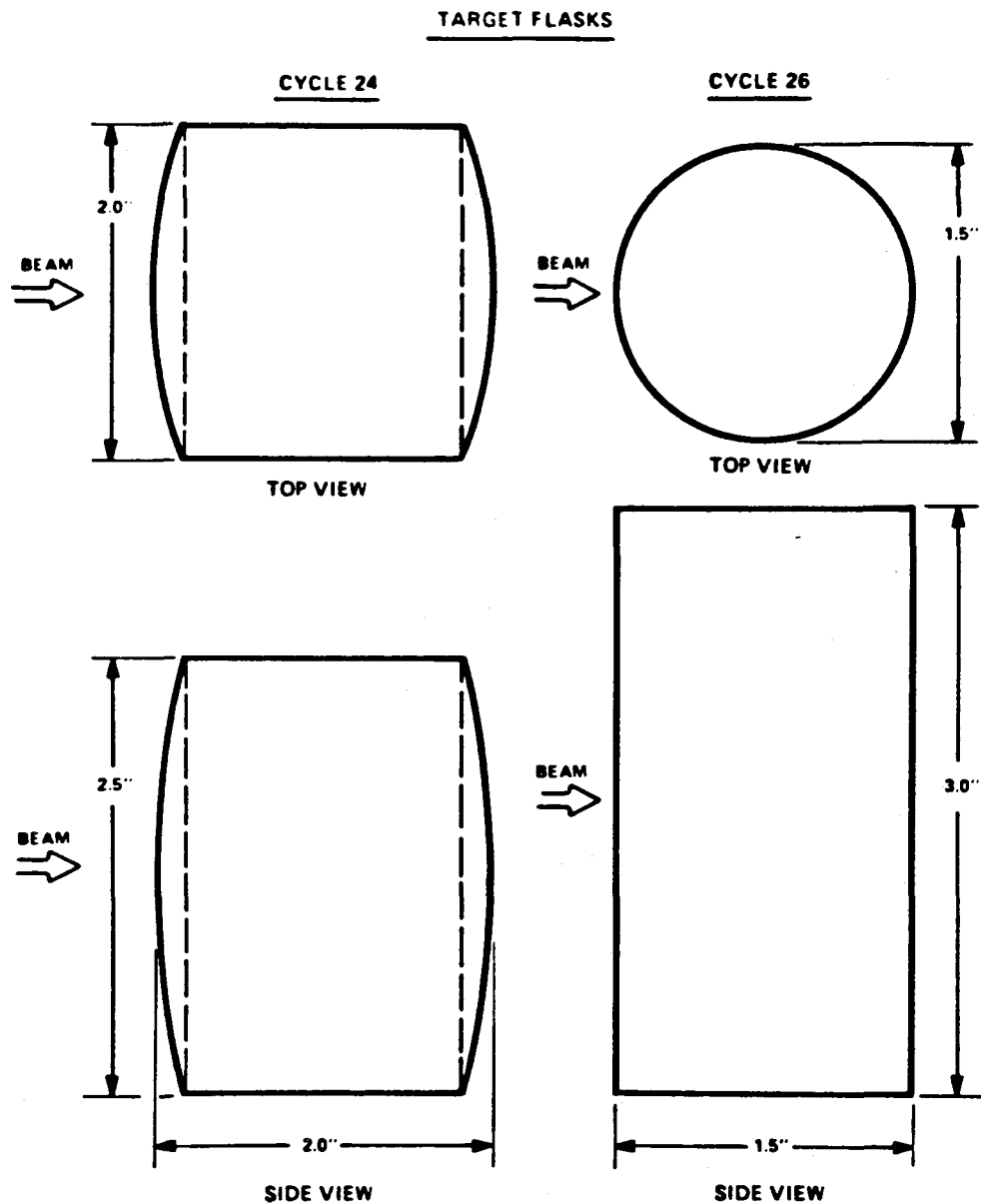


Figure 2.8: A drawing of the target flasks used during the experiment. Relevant parameters associated with the flasks are given in Table 2.3.

Table 2.3

Specifications of the cryogenic targets and vacuum jackets
used in the experiment

	<u>Cycle 24</u>	<u>Cycle 26</u>
Target centerline thickness(cm)	5.08	3.81
Effective LH ₂ target thickness	≈360 mg/cm ²	≈270 mg/cm ²
Effective LD ₂ target thickness	≈828 mg/cm ²	≈621 mg/cm ²
Target flask material and thickness	Kapton- 0.013 cm	Mylar- 0.005 cm
Vacuum jacket window material and thickness	Mylar- 0.013 cm	Mylar- 0.013 cm

signals serve as inputs to leading edge discriminators used to generate fast timing signals. Both signals for each scintillator serve as inputs to an LRS 624 octal meantimer. The meantimer provides an output at a time independent of where the trajectory passed through the scintillator. The meantimer outputs are called S1, S2, S3, and S4. Two-fold coincidences of $S1 \cdot S2$ and $S3 \cdot S4$ are then formed. These signals are combined to form the EVENT signal by another two-fold coincidence $(S1 \cdot S2) \cdot (S3 \cdot S4)$. The timing of the EVENT circuitry is such that the S1 signal always defines the time of an event.

Since every event detected cannot be written to tape or analyzed, an additional signal known as the TRIGGER is used to account for computer deadtime. The TRIGGER also serves as a start for the chamber and recoil detector TDC's. The TRIGGER is defined as $EVENT \cdot NOT \text{ BUSY}$. The LAMPF Event Trigger Module⁽²¹⁾ is used to generate a BUSY signal from the time an event is registered until the system is read, cleared, and another event can be accepted. Since every EVENT and TRIGGER pulse are recorded by scalars, the ratio of these gives a direct measurement of the computer deadtime and is used in correcting measured yields. A schematic drawing of the EVENT and TRIGGER fast electronics circuits is shown in Fig. 2.9.

Particle identification (PID) is obtained using time-of-flight (TOF) and pulse height (PH) information derived from the event scintillators. A TRIGGER signal is used to start a

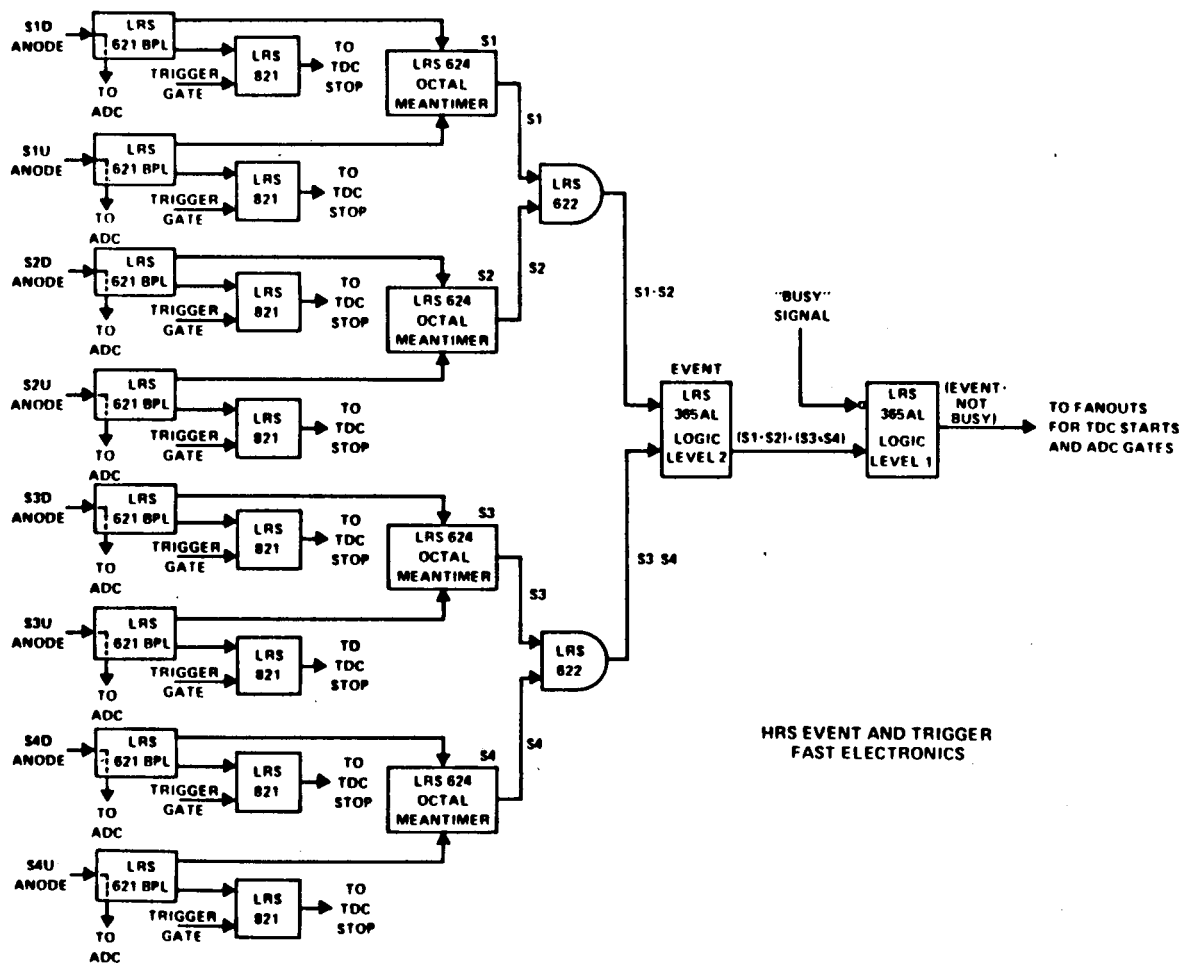


Figure 2.9: A schematic diagram of the EVENT and TRIGGER fast electronics for the HRS. The function and uses of the signals are discussed in the text.

multichannel CAMAC TDC and each end of scintillators S1 and S4 are used to provide stop signals to a TDC channel. This provides the crude TOF information necessary for particle identification. Similarly, pulse heights from each end of scintillator S4 are read into a multichannel CAMAC ADC which is gated by a TRIGGER signal, providing the necessary PH information. The software then calculates TOF between the scintillators as well as mean PH information for each event analyzed on-line. These data are used to create two-dimensional dotplot displays of TOF versus PH in which the groups of particles can clearly be distinguished. Software cuts are used to select the particles of interest. A typical PID dotplot is shown in Fig. 2.10.

The recoil detection system was used to identify the quasi-elastic $\vec{p} + n$ and $\vec{p} + p$ events from the LD₂ target by detecting the recoil proton or neutron in coincidence with the proton detected by the HRS. This was accomplished by positioning the recoil array at the appropriate conjugate angle to the HRS for quasi-elastic scattering kinematics. The recoil array spanned a solid angle of about 200 msr (as opposed to the HRS acceptance of about 3.6 msr) so precise positioning of the array was not required. Due to analyzer and CAMAC space limitations, only 24 of the 25 array detectors were used in Cycle 24 and only 23 of the 25 detectors were used in Cycle 26. During Cycle 24 a corner detector on the top row of the array was not used, while both corner detectors of the top row were unused in Cycle 26. Each array

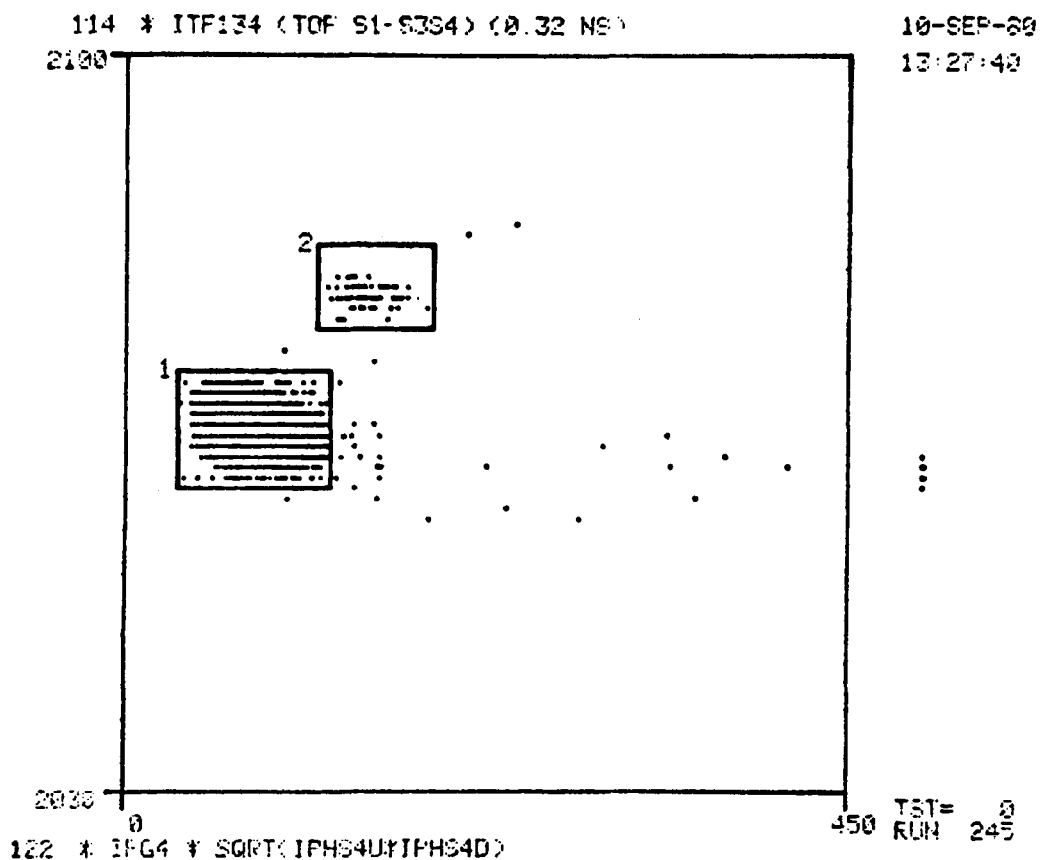


Figure 2.10: A typical particle identification (PID) dotplot. Software tests (Boxes) are used to select the particles of interest. In the Figure, BOX 1 surrounds the proton group while BOX 2 has been placed around the deuteron group.

detector's output served as an input to one channel of an eight channel discriminator. The array detector discriminator thresholds were set at -50 mV and the photomultiplier tube voltages adjusted until the Compton edge of the 1.17 and 1.33 MeV gamma decays of a Cobalt-60 source occurred just above the discriminator threshold setting. This setting corresponded to a discriminator threshold of about 3 MeV for neutrons.⁽²²⁾

Outputs from the array counter discriminators were delayed and used as stop signals for multichannel CAMAC TDC's which had been started by a TRIGGER signal. Modified ORTEC TD811 TDC's were used during Cycle 24 while standard ORTEC TD811 TDC's were used in Cycle 26. The modified TDC's timed out at about 400 ns and had resolving times of 0.2 ns per channel. The standard TDC's used during Cycle 26 timed out at 200 ns and had resolving times of about 0.1 ns per channel. In both Cycles, stop delays were adjusted to center the coincidence peaks at about channel 120 of the TDC for reasons which are explained in the next section of this chapter. The delays were periodically checked and adjusted as the recoil particle energy changed in order to maintain the positions of the coincidence peaks in the appropriate TDC channels.

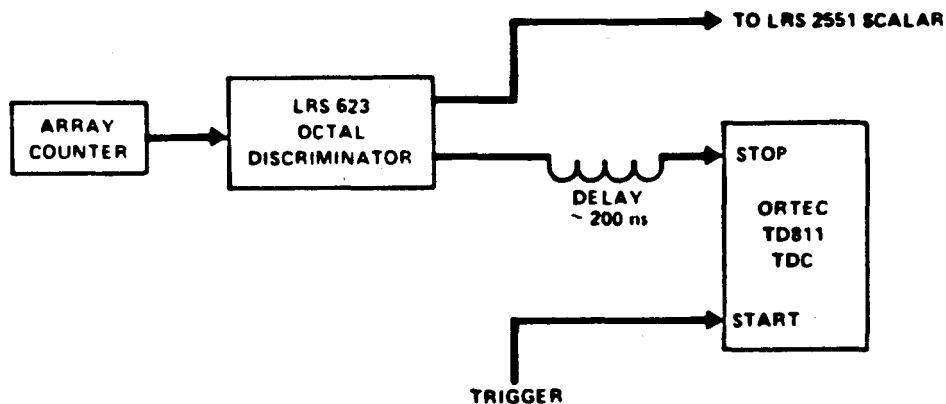
The charged particle paddle discriminator thresholds were set at -50 mV and the tube voltages set about 75 V above the knee on their relative efficiency curves. The discriminator outputs were meantimed with an LRS 624 octal meantimer and the output from the meantimer was then used as a TDC stop in the same fashion as

for the array detectors described above. The pulse widths to the TDC stops from both the array detectors and charged particle paddle were then set at 10 ns.

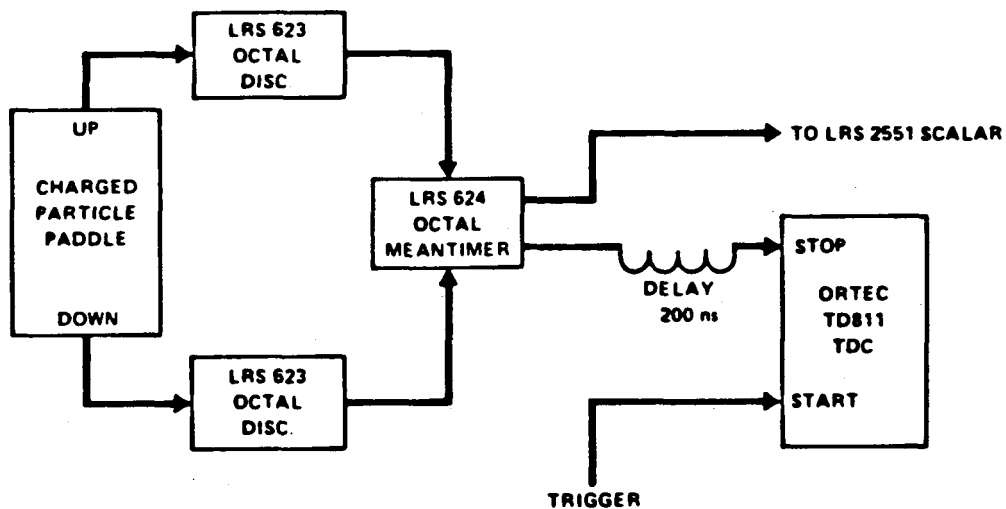
The signals from the array detectors and charged particle paddle were also read into CAMAC scalars. This provided a means of monitoring singles rates in the recoil detection system as the beam intensity was changed. A block diagram of the electronics associated with the recoil detection system is shown in Fig. 2.11.

The CAMAC electronics are interfaced to the PDP 11/45 computer through a Bi-Ra microprogrammable branch driver (MBD)⁽²³⁾. Each event written to tape consisted of 45 data words for Cycle 24 and 50 data words for Cycle 26. The data words for both Cycles are listed in Appendix I. In addition, cumulative scalar readings from the 124 CAMAC scalar channels were written to tape every 15 seconds. A listing of the scalars used in the experiment during Cycle 26 can also be found in Appendix I.

Gating signals for the multichannel CAMAC scalars were formed by combinations of logic pulses and logic levels. The RUN, NORMAL, REVERSE, and NOT BUSY signals were logic levels. The BEAM signal was a 500 μ s long logic pulse. The BEAM, NORMAL, and REVERSE signals are control signals from the accelerator which indicate a beam pulse, beam polarized with spin up, and beam polarized with spin down, respectively. The NOT BUSY logic level is the compliment of the BUSY signal generated by the Event Trigger Module. The RUN signal is a logic level which is generated



RECOIL ARRAY COUNTER ELECTRONICS



CHARGED PARTICLE PADDLE ELECTRONICS

Figure 2.11: A block diagram of the electronics associated with a recoil array detector and the charged particle paddle. The delays to the TDC stops were adjusted as discussed in the text.

whenever the PDP 11/45 computer is in a data-taking mode. These logic signals were combined to form the scalar gating signals in parentheses in the scalar listing of Appendix I. These gates enabled discrimination among signals which were generated in each of the two beam polarization modes.

SOFTWARE AND ON-LINE ANALYSIS

The software used during the experiment consisted of a variety of programs which were written to interface with the general data acquisition program "Q".⁽²⁴⁾ This software can be separated into three main groups: the ANALYZER, the ALLTEST package, and the DISPLAY package. The functions of each of these sets of software along with modifications to the general software packages which were made for the experiment are outlined below.

The ANALYZER is responsible for the disposition of the data associated with each TRIGGER. On-line data acquisition is performed in a "may-process" mode whereby the raw data words associated with each TRIGGER pulse are written to tape and if time permits, the data are analyzed on-line. The ANALYZER performs both of these functions. For each event which is analyzed, the ANALYZER calculates various quantities from the raw data words such as particle trajectories, averaged scintillator pulse heights, time-of-flights between scintillators, and a variety of calculated data words which are used in tests of the data and in determining various correction factors.

Certain modifications to the "standard" HRS ANALYZER were necessary in order to read in the additional raw data words associated with the recoil detection system. The ANALYZER was also rewritten to construct calculated data words associated with the array counters. The raw TDC word for each array counter was read and its value truncated at channel 256, thus explaining the need for the timing and peak positioning of each TDC stop explained in the previous section. The truncated data word was then further modified by using the raw NORMAL and REVERSE pulse heights and the TDC data word associated with the charged particle paddle. In this way a calculated data word was constructed for each array detector which contained both beam polarization (normal or reverse) and recoil particle charge (neutral or charged) information for each event analyzed. An explanation of how this was accomplished will be presented in the next chapter.

The ALLTEST package⁽²⁵⁾ is used to define conditions which raw or calculated data must satisfy in the processing of an event. The file which defines the tests is written in a straightforward manner which enables users to construct test files which suit their particular needs. The test file consists of a series of tests and gates on data words (known as microtests) and a series of logic tests on combinations of previously defined tests (known as macrotests). The tests used in analyzing the experimental data will be discussed in more detail in the next chapter.

Histograms of raw and calculated data may be viewed with the use of the DISPLAY⁽²⁶⁾ software. This software enables the experimenter to define histograms, view the histograms as data accumulates on-line, and store the histograms on a disk when the run is completed. The DISPLAY package also allows the user to create and display two-dimensional dotplots of on-line data such as the PID dotplot shown in Fig. 2.10.

As many as 40 histograms may be defined using the routine DSP.⁽²⁷⁾ Histograms are defined by specifying the raw or calculated quantity to be histogrammed, the upper and lower limits of the variable, a binning factor for the histogram, and a test which the histogrammed data must satisfy. Any test defined in the ALLTEST package may be used.

The software outlined above allows the experimenter great flexibility in the analysis and display of the on-line data. The versatility of the integrated HRS system facilitates studies of a broad spectrum of proton-initiated reactions as well as nuclear structure studies. In the next chapter, the off-line analysis of the data will be described and the experimental data will be presented.

CHAPTER 3

OFF-LINE ANALYSIS AND PRESENTATION OF RESULTS

INTRODUCTION

Experimental data were acquired in the "may process" mode in which raw data were written directly to magnetic tape, and if time permitted, analyzed on-line. The fraction of data which was analyzed on-line depended upon the event rate, and typically only 20-30% of the data were analyzed on-line. It was therefore necessary to replay the data tapes in order to analyze all of the data accumulated. This involved the analysis of about 110 tapes of data; each tape contained about 2.6×10^5 events.

In addition to enabling a complete analysis of all taped events, replay allows the experimenter to revise the software to provide additional information which was not determined on-line. In this chapter, the software and methods used in the off-line analysis of the data will be described and the results of the analysis will be presented. A discussion of the errors associated with the data and the analysis will also be given.

SOFTWARE FOR OFF-LINE ANALYSIS

The software packages used in replay are similar to those used for on-line data acquisition and analysis except that in

the ANALYZER operates in a "must process" mode thus ensuring that all taped data are analyzed. In this section a detailed description of the purposes and functions of the off-line software will be given, and modifications made to the software for replay will be described.

The ANALYZER used for replay was changed in two ways from that used on-line. The first modification consisted of rewriting the ANALYZER so that the Floating Point Systems AP-120B array processor⁽²⁸⁾ could be used for the off-line data reduction. The array processor performed many of the calculations in the event analysis and greatly reduced the time required for replay of the data tapes.

The ANALYZER was also modified to define and calculate an additional data word which was used in determining good events in the recoil counters. The data word was formed by examining the raw data words from each of the 24 (23 in Cycle 26) array counters and was defined to record how many of the array counters were triggered for a given HRS event. The use of this additional data word will be described later in this section.

As mentioned in the previous chapter, a calculated data word was also defined for each array counter which not only contained the timing information associated with a detected event in the array counter but also information concerning the beam polarization state for the event and the charge of the detected particle. For each event detected by the HRS, the raw data words

associated with the beam polarization (NORMAL and REVERSE pulse heights) and the charged particle paddle were tested to determine the beam polarization state and the type of recoil particle (proton or neutron). A data word for each array counter was then formed by adding 256 to the truncated TDC time for the counter if the beam polarization was reverse and 512 to the truncated TDC time if a charged particle was detected by the charged particle paddle. The truncated TDC time was formed by terminating the raw TDC word for each array counter at channel 256 as described in the previous chapter. Thus for each array counter a calculated TDC time was constructed for every HRS event which ranged from 1-256 for neutrons with beam polarization normal (NN), 257-512 for neutrons with beam polarization reverse (NR), 513-768 for protons with beam polarization normal (PN), and 769-1024 for protons with beam polarization reverse (PR).

The ALLTEST test file and the histogram file were also modified for the off-line analysis. An additional histogram and several associated tests were defined in order to determine which events registered in the recoil array counters were valid. Listings of the test and histogram files used in the off-line analysis of the data taken during Cycle 26 are given in Appendix I. Similar test and histogram files were used for the off-line analysis of the Cycle 24 data.

Certain tests were particularly important in defining acceptable events to be histogrammed. Several tests were combined

to create a GOOD EVENT test for gating HRS events. This test ensured that accepted HRS events satisfied the PID requirements and a series of wire chamber tests. The normal and reverse histograms of the calculated missing mass variable were gated by this GOOD EVENT test.

Additional tests were designated for determining valid coincidence events in the recoil array. Analogous to the GOOD EVENT test used in gating HRS events, the test used in gating array detector events was a combination of several tests. Each event detected in the recoil array was required to have a corresponding good event detected by the HRS. In addition, the HRS event was required to fall within a gate set on the missing mass histograms. This test was necessary at forward angles where both deuterium elastic and quasi-elastic events were detected by the HRS and ensured that there was a valid quasi-elastic event detected by the HRS in coincidence with the particle detected by the recoil array counters.

Along with the coincidence requirement, each event detected by the recoil array was required to have triggered only one array detector. This was accomplished by histogramming the data word that counted the number of array detector TDC's which did not time out for a given event. Gates were then set on this histogram in order to ensure that only one array detector recorded the event and only events which fell within these gates were accepted.

The elimination of events in which more than one array detector registered a particle for a given HRS event was necessary in order to avoid multiple counting of an event in the recoil array. The test eliminated two types of multiple hit events, one caused by a particle being detected in a given array counter and then scattering into a adjacent counter and triggering it and the other caused by a true coincidence particle being detected in one array counter and a background (random) particle being detected in another. More discussion of multiple hits in the array counters will be presented later in the chapter.

Finally, tests on the beam polarization state and the charge of the recoil particle were necessary in order to construct the data words described earlier in this section. The beam polarization state for each event was determined by requiring the NORMAL and REVERSE ADC values to fall within certain limits. The charge of the recoil particle was determined by a gate on the histogram of the charged particle paddle TDC spectrum. Events falling within this gate were identified as protons while events outside the gate were identified as neutrons. Additional details on the identification of the recoil particles are given in a later section of this chapter.

ANALYSIS OF LIQUID HYDROGEN RUNS

The first two days of the experiment were devoted to system checkout and calibration runs using a liquid hydrogen (LH₂) target.

Data were taken at laboratory scattering angles of 5° , 7° , 9° , 11° , and 14° using the HRS and at 17° , 18° , and 20° using both the HRS and the recoil detection system (set at about 65°). In this section, the results of the LH_2 runs will be discussed with regard to the measurements of the quasi-free $\vec{p} + n$ analyzing powers which followed this portion of the experiment.

The free $\vec{p} + p$ analyzing powers were measured at each of the above angles. This enabled a comparison of the analyzing powers measured by both the HRS and the recoil detection system with previously measured values of the $\vec{p} + p$ analyzing powers at 0.8 GeV.^(18,29) The results of the measurements indicated that the effective analyzing power of the polarimeter target was slightly larger than had previously been calculated so the polarimeter analyzing power was adjusted to 0.490 ± 0.020 from the previous value of 0.48 for use in the replay of the Cycle 24 data.

As part of a development run about two months after the LH_2 calibration runs were undertaken, a quench-ratio measurement of the effective analyzing power of the 32 mil CH_2 polarimeter target was performed. The measurement yielded an effective analyzing power of 0.477 ± 0.005 .⁽³⁰⁾ This decrease in the apparent analyzing power of the polarimeter target may be an indication of depletion of the hydrogen in the CH_2 target which has been estimated to occur at a rate which may be as high as 0.1% per nA-hour.⁽¹⁷⁾ Since the quasi-elastic events detected by the polarimeter detectors have an analyzing power which is about half that of the hydrogen, the

depletion of the hydrogen in the CH_2 lowers the effective analyzing power of the polarimeter target.

The results of the LH_2 calibration runs with the adjusted polarimeter analyzing power are shown in Fig. 3.1. Good agreement is seen with the previous analyzing power measurements, ^(18,29) particularly at the forward angles where geometric effects of scattering from an extended target are smallest. The analyzing power measurements using the recoil array also reproduce the previous measurements quite well and are much less sensitive to the effects of scattering from an extended target due to the large phase space acceptance of the recoil detection system.

In addition to being useful for calibration, the LH_2 runs were used to check the efficiency of the charged particle paddle. The assumption was first made that only protons impinged on the recoil detection system (this ignored the neutron sources such as the target flask, the scattering chamber rods, and the scattering chamber window) and the numbers of protons and neutrons as identified by the charged particle paddle and the array counters were recorded. Proton identification efficiencies of 99.3% and 99.4% were observed for HRS laboratory scattering angles of 20° and 17° respectively based on the above assumption. The recoil array was positioned at a laboratory angle of about 65° for these runs and recoil particle energies ranged from about 94 MeV to 127 MeV for HRS settings of 17° and 20° , respectively. Since target flask events contributed about a 1% background (as determined from empty

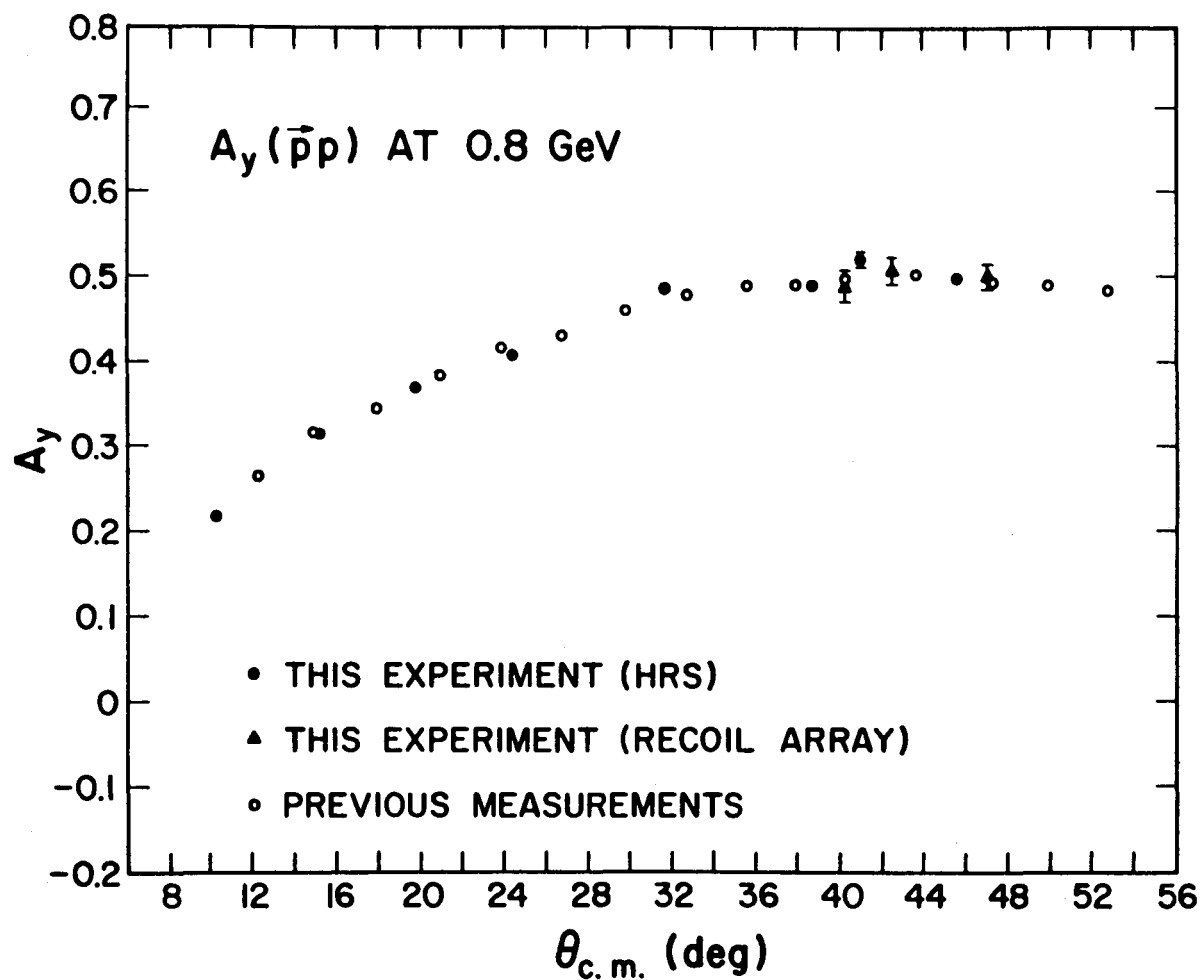


Figure 3.1: The results of the analyzing power measurements using the LH_2 target. The previous data are from references 18 and 29.

flask runs) to these measurements, and since the pp and pn total cross sections are roughly equivalent at 800 MeV, the true charged particle paddle efficiency obtained by considering the production of neutrons from the target flask, scattering chamber rods, and scattering chamber window was estimated to be 0.997%. The effects of the charged particle paddle efficiency on the analyzing power measurements which followed the LH₂ runs will be discussed in more detail in a later section of this chapter.

ANALYSIS OF LIQUID DEUTERIUM RUNS

After the LH₂ runs were completed, the remainder of the time allotted to the experiment in Cycles 24 and 26 was used to measure quasi-free $\vec{p} + n$ and $\vec{p} + p$ analyzing powers using a liquid deuterium (LD₂) target. Data were taken at HRS laboratory scattering angles of 6°, 8°, 10°, 12°, 14°, 16°, 18°, 20°, and 22° during Cycle 24 and at scattering angles of 18°, 20°, 22°, 24°, 26°, 28°, 31°, and 32.91° during Cycle 26. Both quasi-free $\vec{p} + p$ and $\vec{p} + n$ analyzing powers were obtained simultaneously at all angles except 6°, 8°, and 10° where only the quasi-free $\vec{p} + n$ analyzing powers were measured because the recoil protons were absorbed in the target and scattering chamber window. In addition, an empty flask measurement was made at each angle so that target empty backgrounds could be determined and subtracted from the target full runs. At each HRS setting the recoil detection system

was positioned at the appropriate conjugate angle for the quasi-elastic reaction.

The software used for the off-line analysis of the LD₂ data was identical to that used for the analysis of the LH₂ calibration runs described previously. However for the replay of the LD₂ runs, particular care was necessary in setting the software tests, since both protons and neutrons were detected by the recoil array. Six gates were set for the replay of each run, one on the missing mass histograms, one on the charged particle paddle TDC histogram, and four on the histogram which counted multiple hits in the recoil array.

The missing mass gate (IGAT1 in the test file of Appendix I) was set on the quasi-elastic portion of the histogram in order to ensure that events in coincidence with particles detected by the recoil array were indeed quasi-elastic scatterings. This gate was straightforward to set and was actually unnecessary except at the most forward angles where elastic events were also detected by the HRS.

The gate set on the TDC histogram of the charged particle paddle, IGAT2 of the test file, was used to determine whether the recoil particle was a proton or a neutron. An event which fell within this gate was identified as a proton. All other events were identified as neutrons. A typical TDC spectrum (the time difference between the HRS trigger and the paddle) and a typical

gate for proton identification are shown for the sum of the 18° runs during Cycle 26 in Fig. 3.2.

Since IGAT2 was instrumental in differentiating between $\vec{p} + p$ and $\vec{p} + n$ quasi-free scattering, a more detailed discussion is warranted concerning the placement of this gate. Four possibilities exist for determining recoil particle type using such a method: (1) a recoil proton may be identified as a proton if it is detected by the charged particle paddle and the event falls within the gate on the TDC histogram; (2) a recoil proton may be identified as a neutron if the charged particle paddle does not trigger or if the event lies outside the gate on the TDC histogram; (3) a recoiling neutron may be identified as a neutron if it does not trigger the charged particle paddle, or if the paddle is triggered but the event lies outside the gate on the TDC histogram; (4) the recoiling neutron may be identified as a proton if it triggers the charged particle paddle and lies within the gate, or if a random particle triggers the paddle while the neutron is passing through the paddle and the event falls within IGAT2.

Two of the above cases result in proper identification of the recoil particle while the other two result in misidentification of the recoil particle. Misidentifications can be minimized, although not completely eliminated, by proper placement of the gate on the charged particle paddle TDC histogram.

Improper identification of the recoil particle due to the charged particle paddle not triggering on a proton or triggering on

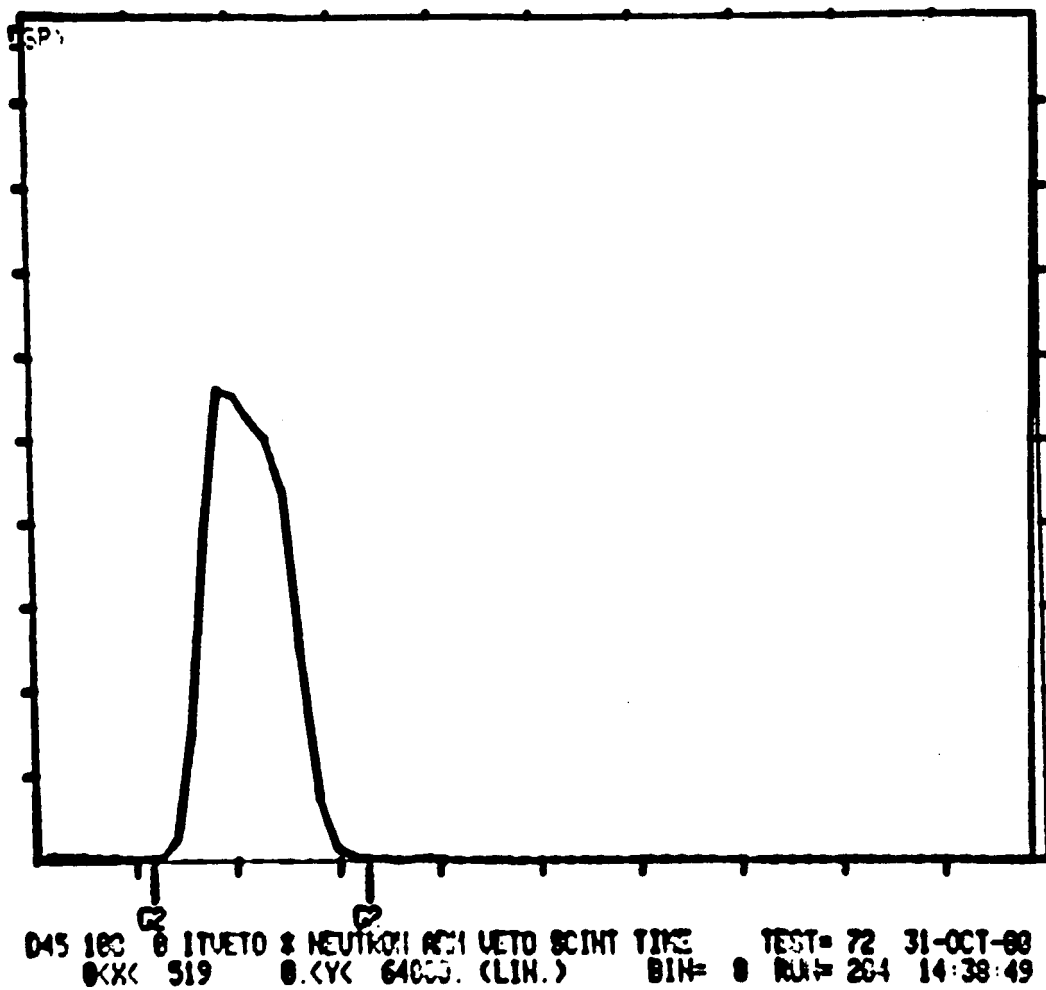


Figure 3.2: A typical charged particle paddle TDC spectrum illustrating the placement of the gate used to determine the recoil particle type. The histogram is from the Cycle 26 summed LD_2 runs at $\theta_L = 18^\circ$.

a neutron is related to the paddle's detection efficiencies for protons and neutrons. To minimize this effect it is necessary to have a detector which has a very high efficiency for detecting protons and a very low efficiency for detecting neutrons. It was not possible to distinguish misidentifications of this type in the experiment and this resulted in some systematic error in the data. Estimates of the effect of this type of systematic error on the measured analyzing powers will be given in a later section of this chapter.

The other processes described above which lead to misidentification of the recoil particle are related to the placement of the gate on the charged particle TDC histogram. Since true recoil particles are time-correlated with the proton detected by the HRS, events lying outside the peaks in the TDC histograms of the charged particle paddle and array detectors can be identified as random coincidences with the HRS. As can be seen in Fig. 3.2, the gate on the charged particle paddle TDC histogram was set around the peak. This ensured that only time-correlated events which triggered the paddle were identified as protons. As a result of this gate placement two classes of events were identified as neutrons: those which were not time-correlated with the HRS event in both the charged particle paddle and the array detectors, and those which were not time-correlated in the charged particle paddle but were time-correlated in the array detectors. The latter case represents true recoil neutrons which would be misidentified as

protons if all particles which triggered the charged particle paddle were identified as protons. The former case represents randoms which can be separated from the time-correlated neutrons by a background subtraction which will be described later in this section.

It was also necessary to eliminate events in which more than one array counter triggered. Two processes lead to multiple hit events. The first occurs when a recoil particle triggers one of the array counters, but is scattered into another detector and also triggers it. The other occurs when a recoil particle triggers one array counter and a random event triggers another counter. In principle the two processes can be distinguished to some extent but software limitations on the number of tests which may be defined to test an event made an attempt impossible. In addition it was not feasible to determine which of the triggered array counters contained the real time-correlated event. It was therefore necessary to reject all multiple hit events in order to prevent double counting of an event.

Four gates (IGAT3-IGAT6) were used to select the single hit events. These gates were set on a histogram of the data word that counted how many array detector TDC's did not time out for a given HRS event. This data word was incremented by 10 for each array detector TDC that did not time out. This value was then modified in the same manner as the truncated array counter TDC times (256 was added if the beam polarization was reverse and 512 was added if

the recoil particle was charged). This created distinct peaks in the histogram for single and multiple hits for each of the four recoil particle-beam polarization state types (NN,NR,PN,and PR). A gate was then set on the single hit peak of each of these types. Figure 3.3 shows a portion of this histogram for the sum of the runs at 18° during Cycle 26. The portion of the histogram shown is for recoil protons with normal beam polarization (PN) and the gate is set on the single hit peak.

One effect of eliminating all the multiple hits was a reduction in statistics since the true time-correlated events could not be identified and kept. The ratio of single hits to multiple hits as a function of center-of-mass scattering angle is shown in Fig. 3.4 for both protons and neutrons. The ratios were found to be independent of the beam polarization state in both cases. As can be seen from the Figure, the effect on the statistics is worse for neutrons than for protons and becomes worse with increasing angle, eliminating about 1 in every 3 events at the larger angles.

Besides lowering the statistical accuracy of the data, the elimination of multiple hit events also represented a possible source of error in the measurements through the introduction of a false asymmetry. The nature of this source of error and its effect on the analyzing powers will be addressed in a later section of this chapter.

Each of the array counter histograms was gated by the missing mass gate (IGAT1) and the four multiple hit gates

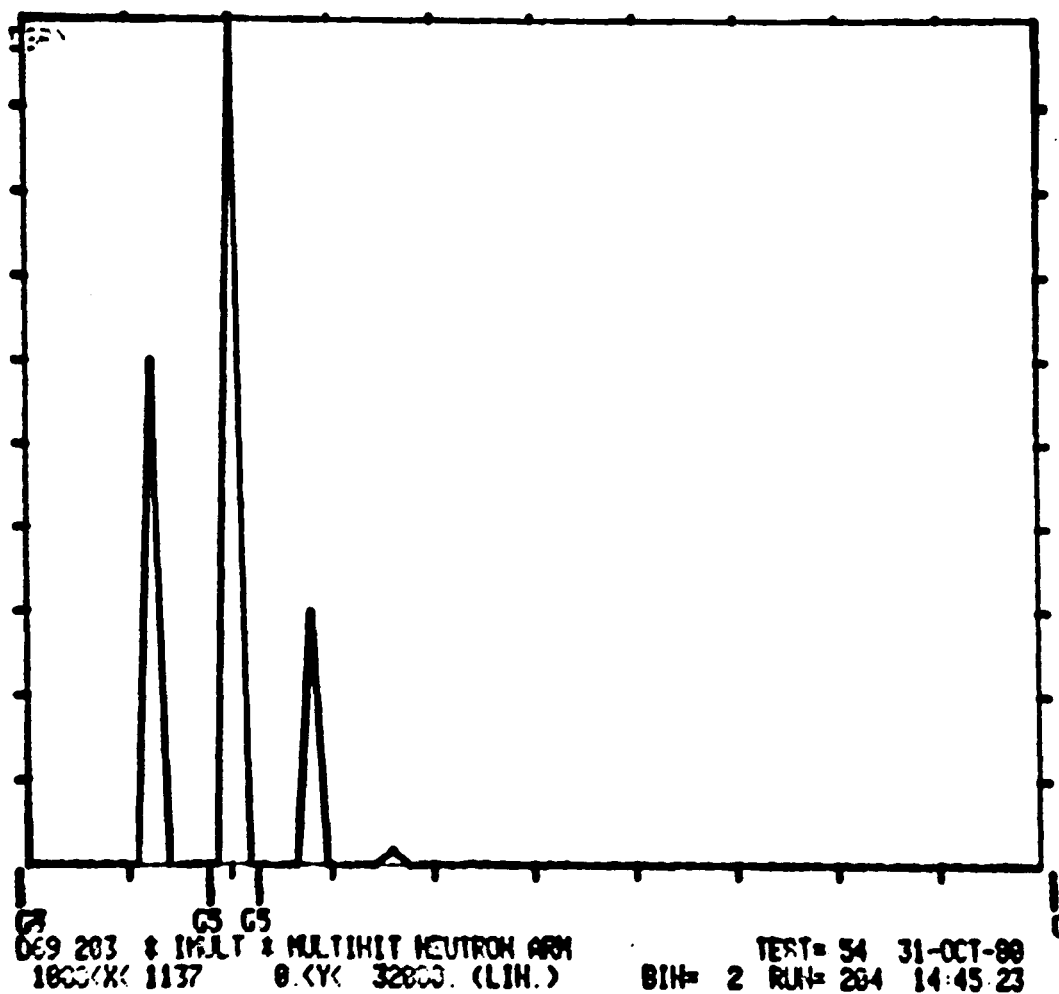


Figure 3.3: A portion of the histogram used to record multiple hit events in the recoil array. The portion shown is for recoil protons-beam spin up (PN) and is from the Cycle 26 summed LD₂ runs at $\theta_L = 18^\circ$. The gate is set on the single hit peak of the PN portion of the histogram.

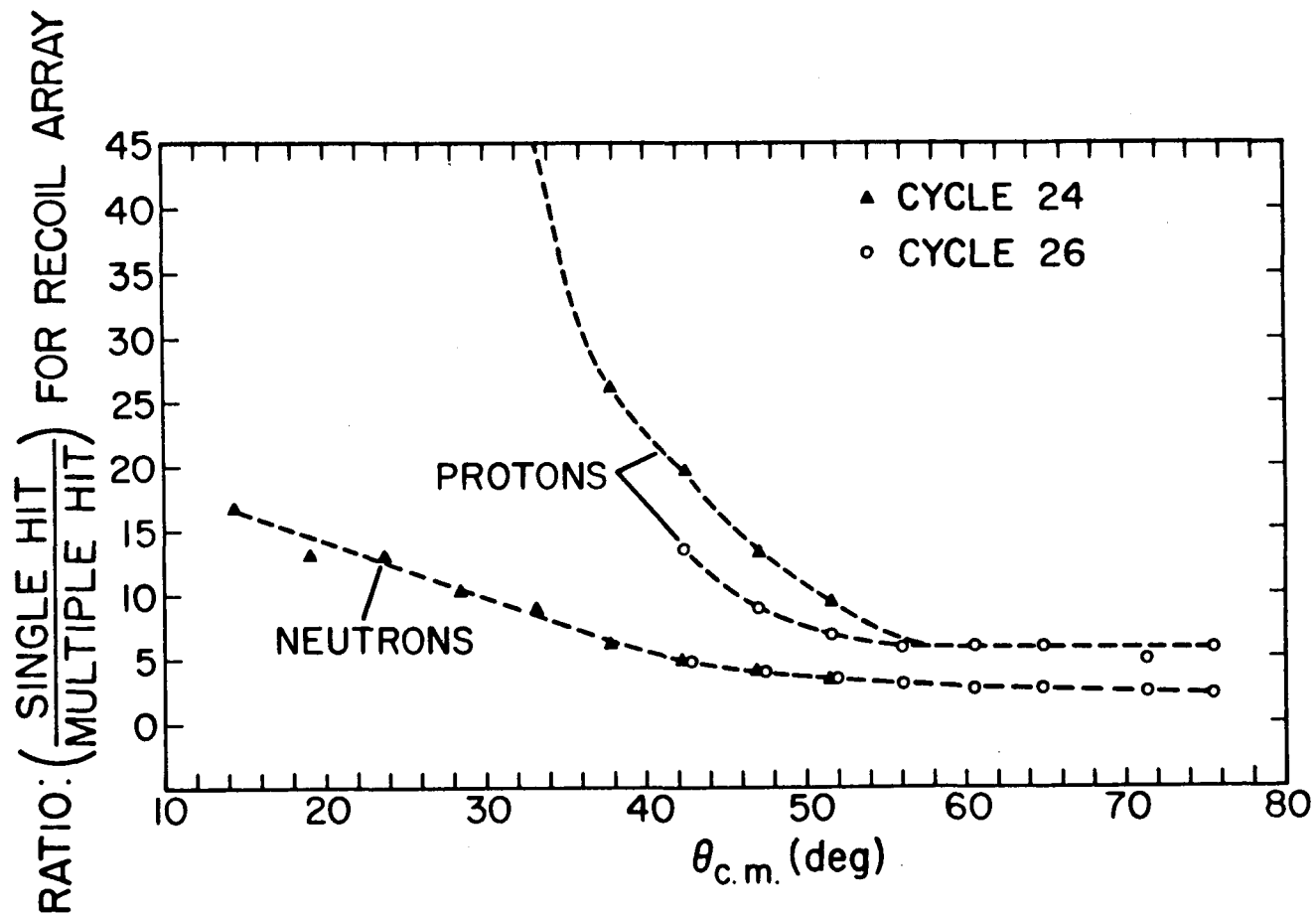
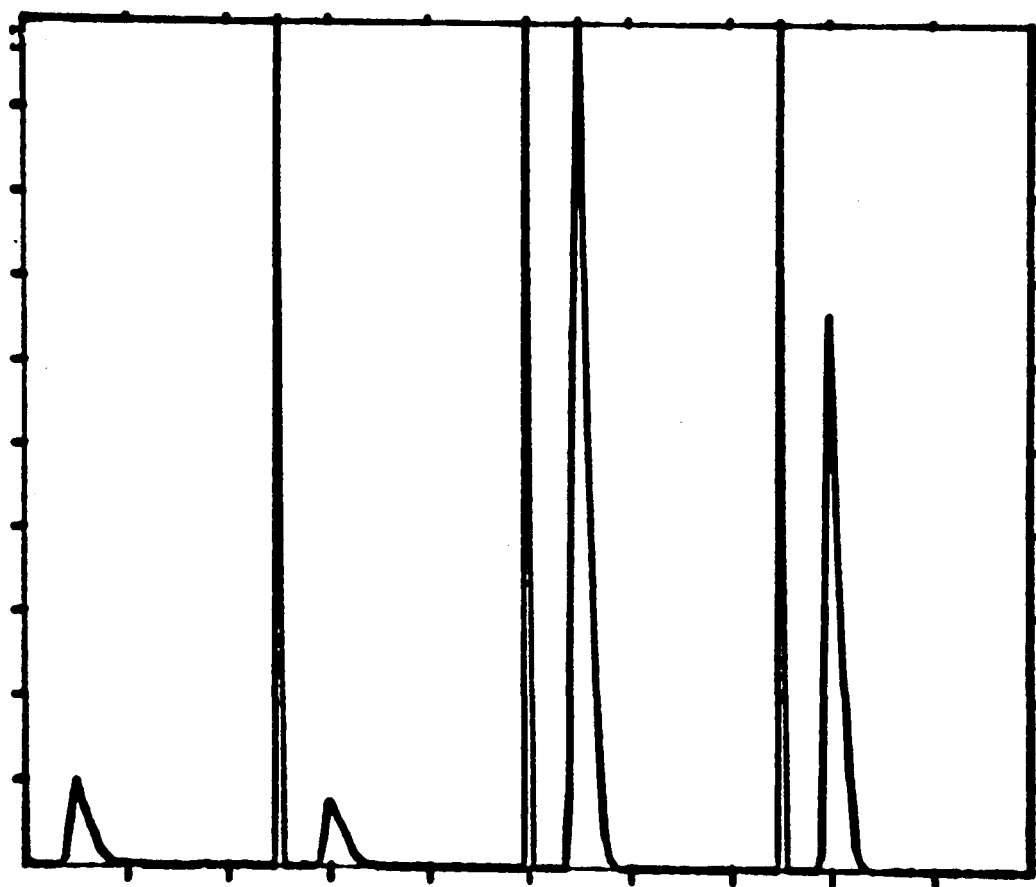


Figure 3.4: The single hit to multiple hit ratios of events registered in the recoil array during the quasi-free analyzing power measurements using the LD_2 target. The curves are to guide the eye and are not fits.

(IGAT3-IGAT6). This required each array counter event to occur in coincidence with the quasi-elastically scattered proton detected by the HRS and also eliminated multiple hits in the recoil array. In addition, the array counters were gated by the GOOD EVENT test which ensured that the corresponding event detected by the HRS satisfied the PID criteria and passed a series of wire chamber tests. The gate on the charged particle paddle histogram determined whether the array counter event was a proton or a neutron. A histogram of the modified TDC times of one of the array counters from the summed 18° runs of Cycle 26 is shown in Fig. 3.5.

Each of the data tapes was replayed in the manner described above using the PDP 11/60 computer and the Floating Point Systems AP-120B array processor located at CCH. The LD_2 runs at each angle were summed and the replayed histograms were stored on a disk for future data reduction.

After the replay of the data tapes was completed, the areas of the peaks in the array counter TDC histograms had to be extracted in order to calculate the analyzing powers. This was done using the peakfitting routine ⁽³¹⁾PEAKFIT. In this routine four markers are used to specify the background and peak channel limits. Markers 1 and 4 define the region of the histogram over which the background will be calculated. Markers 2 and 3, which are placed between the background markers, define the peak region. After the markers are set, the routine calculates the background using the information in the 1-2 and 3-4 regions and subtracts the background



DS6 87 8 ITHMOD)11 8 (MODIFIED) NEUTRON ARM TIME TEST= 74 31-OCT-88
 0(X< 2849 0(Y< 4655 (LIN.) BIN= 10 RUN= 284 14:41:47

Figure 3.5: A typical histogram of an array detector TDC spectrum. The four peaks correspond to neutrons-beam spin up (NN), neutrons-beam spin down (NR), protons-beam spin up (PN), and protons-beam spin down (PR), respectively. The histogram is from the Cycle 26 summed LD₂ runs at $\theta_L = 18^\circ$.

from region 2-3 to obtain the counts above background for this region. PEAKFIT then fits the resulting peak with a Gaussian lineshape. The routine also calculates the uncertainty in the corrected peak area by considering both the statistical uncertainty in the peak area and the uncertainty in the determination of the background. A typical fit to one of the peaks in an array counter TDC histogram is shown in Fig. 3.6:

The peak areas in each array counter TDC spectrum were determined in the manner described above for the summed runs for each laboratory scattering angle. The target empty runs were analyzed in a similar manner. The areas and the associated errors for the four peaks in each array counter TDC histogram were then stored in a data file for future use. Thus at each angle two data files were created, one which contained the peak areas and errors of each array counter TDC histogram for the summed LD₂ runs and one which contained the peak areas and errors associated with the empty flask run.

After the peak areas of both the LD₂ and empty flask runs at a given angle had been determined, the analyzing powers could be calculated. The actual calculations were done with the program ASYMM2. Before discussing ASYMM2, the method employed to obtain the analyzing powers will be presented.

The analyzing power is computed from the corrected yields for both beam polarization states and the beam polarization. The measured yields for each beam polarization state are a function of

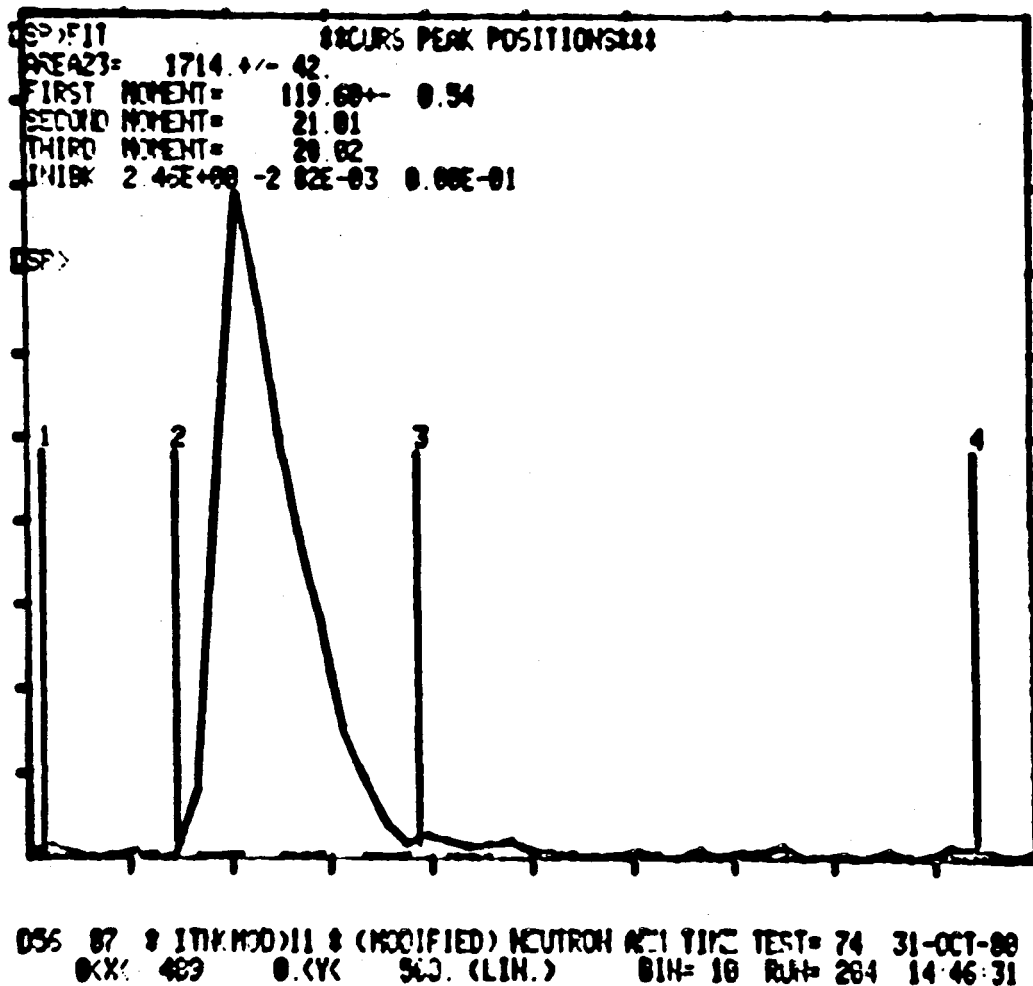


Figure 3.6: A sample fit to a peak in an array detector histogram using the routine PEAKFIT. The dashed line indicates the calculated background. The placement of the markers and their purpose are described in the text.

the integrated beam current, the computer deadtime, and various other factors. These raw yields must be normalized before the analyzing power can be computed. The corrected yield (for either beam polarization state) may be defined as

$$\text{CORRECTED YIELD} = \frac{\text{MEASURED YIELD} \cdot \text{CF}}{\text{IC}}, \quad (3.1)$$

where

$$\text{CF} = \text{CORR. FACTOR} = \frac{1}{\text{COMP. LIVE TIME} \cdot \text{CHMBR. EFF.}}$$

IC = RELATIVE INTEGRATED BEAM CURRENT.

The relative integrated beam currents corresponding to the two states of beam polarization were obtained from an ion chamber using an ORTEC 439 current integrator.

The beam polarization was determined for each run by measurements with the Line C beam line polarimeter as described in Chapter 2. The geometric mean of the beam polarizations with spin up and spin down was computed and used for the analyzing power calculations. Figure 3.7 shows the measured mean beam polarizations for both Cycle 24 and Cycle 26.

Once the corrected yields and beam polarization are determined the analyzing power may be computed. The analyzing power is defined as

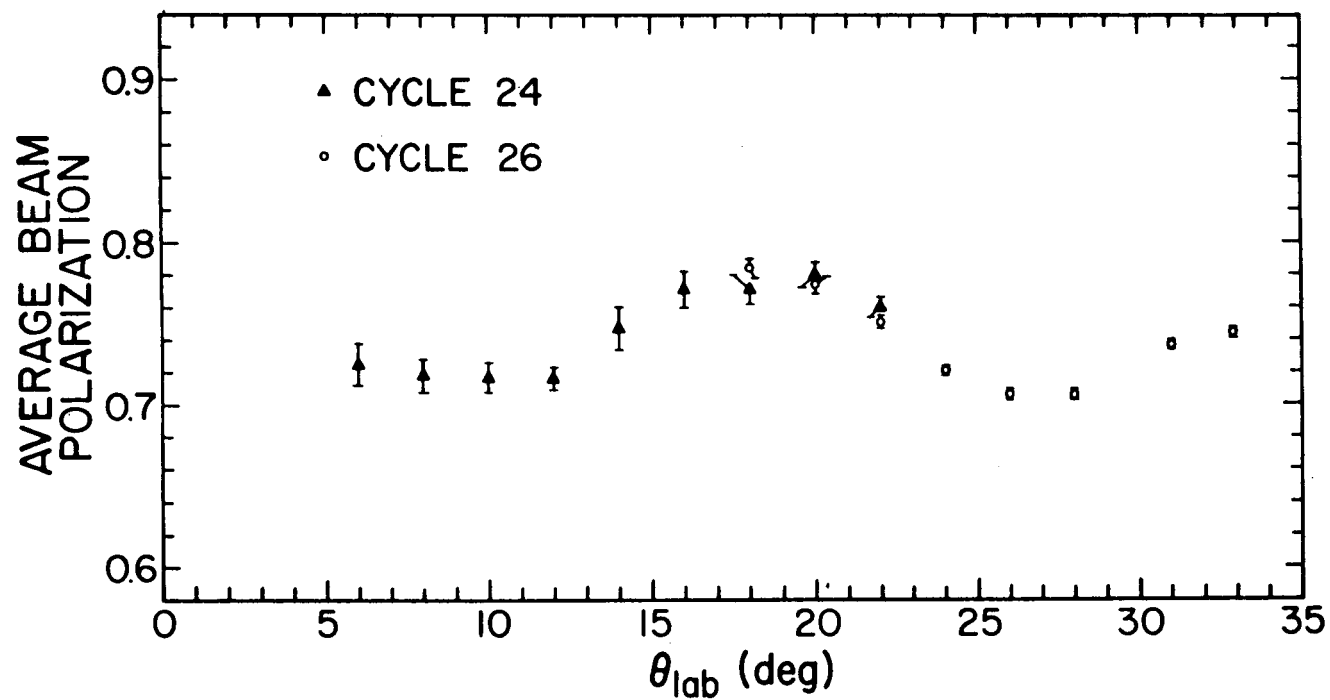


Figure 3.7: The average beam polarizations during the experiment as determined by the Line C beam line polarimeter. The polarizations are a function of time but are plotted in the Figure against the HRS angle setting at the time they were determined.

$$A_y = \frac{\epsilon}{P_B} , \quad (3.2)$$

where ϵ is the asymmetry defined in Equation (2.2) and P_B is the beam polarization. Since the HRS detects only particles scattered to the left of the beam, the asymmetry (ϵ) may be redefined as:

$$\epsilon = \frac{N - R}{N + R} . \quad (3.3)$$

Here N is defined as the normalized yield scattered left with beam polarization NORMAL (spin up) while R is defined as the normalized yield scattered left with beam polarization REVERSE (spin down). The R yield can be shown to be equivalent to the yield scattered right with beam polarization NORMAL by symmetry arguments. Thus the two definitions of the asymmetry, Equations 2.2 and 3.3, are equivalent and differ only in notation.

In actuality the simple formula given in Equation 3.2 for the analyzing power was not used because the target flask contributed to the measured yields of the LD_2 runs. It was necessary to correct the yields of the LD_2 runs by using the measured yields from the corresponding empty flask runs. When the flask background is taken into account, the analyzing power must be redefined and is given by

$$A_y = \frac{1}{P_T} \cdot \frac{(N_T - R_T) - \frac{P_T}{P_E}(N_E - R_E)}{(N_T + R_T) - (N_E + R_E)}, \quad (3.4)$$

where

P_T = Mean beam polarization, target (LD₂) in

P_E = Mean beam polarization, empty flask

N_T = Corrected yield, target in, NORMAL beam polarization

R_T = Corrected yield, target in, REVERSE beam polarization

N_E = Corrected yield, empty flask, NORMAL beam polarization

R_E = Corrected yield, empty flask, REVERSE beam polarization.

The computation of the error associated the the analyzing power is straightforward but tedious, and the equation used to compute this error will not be given here. A derivation of both the equation for the analyzing power and the equation for the corresponding error is given in Appendix II.

As mentioned previously, the actual calculation of the analyzing powers and associated errors was performed using the program ASYMM2. A listing of the program is given in Appendix III. The program was written to allow the calculation of both the pp and pn analyzing powers in a variety of ways. The program has an option to compute the analyzing power from specified individual

counters or the analyzing power may be computed by summing specified counters. In practice, the latter method was used in the data analysis.

The program reads five data files as input. Two data files contain the measured yields and errors for the LD_2 runs and empty flask run at a given angle. Two others contain the normal and reverse correction factors and integrated beam currents as well as the measured mean beam polarizations and the associated errors for the LD_2 and empty flask runs. The fifth data file specifies which counters of the recoil array are to be used in calculating the analyzing powers.

When the program ASYMM2 is executed, the user is prompted to specify several options built into the program such as whether array counter yields are to be summed for the specified counters and whether errors in the measured yields are to read from the data files or calculated from the measured yields. The program then asks for the names of the five data files described above. After the file names are specified, the program reads the files and calculates the analyzing power and error in the manner specified.

PRESENTATION OF EXPERIMENTAL RESULTS

The experiment simultaneously obtained both quasi-free $\vec{p} + n$ and $\vec{p} + p$ analyzing power data except at laboratory scattering angles of 6° , 8° , and 10° where only the $\vec{p}n$ analyzing power was determined since the recoil protons did not reach the

recoil detection system. In this section, the results of the analyzing power measurements will be presented.

The analyzing powers were calculated with the program ASYMM2 by summing the measured yields of the recoil array counters which spanned the maximum in the phase space distribution of the recoil particles. The sources of errors used in the calculation were specified in the data files for both the LD_2 and empty flask runs and included both statistical and fitting uncertainties. The mean beam polarization and error, the correction factors, and the integrated beam currents were calculated with the standard HRS program POLSHT which uses results from the ALLTEST tests and the scalars to calculate the above quantities. The calculation of the beam polarization and its error takes into account the statistical uncertainty in determining the left-right asymmetry and the specified uncertainty in the effective analyzing power of the polarimeter target.

The results of the quasi-free analyzing power measurements are shown in Fig. 3.8 for the $\vec{p} + n$ measurements and in Fig. 3.9 for the $\vec{p} + p$ measurements. The center-of-mass scattering angle, θ_{cm} , was determined from free nucleon-nucleon kinematics for the central angle of the HRS at each angle setting. Both the quasi-free $\vec{p} + n$ and $\vec{p} + p$ analyzing powers are tabulated in Table 3.1.

Two measurements of the quasi-free $\vec{p}n$ and $\vec{p}p$ analyzing powers were made at laboratory scattering angles of 18° , 20° , and

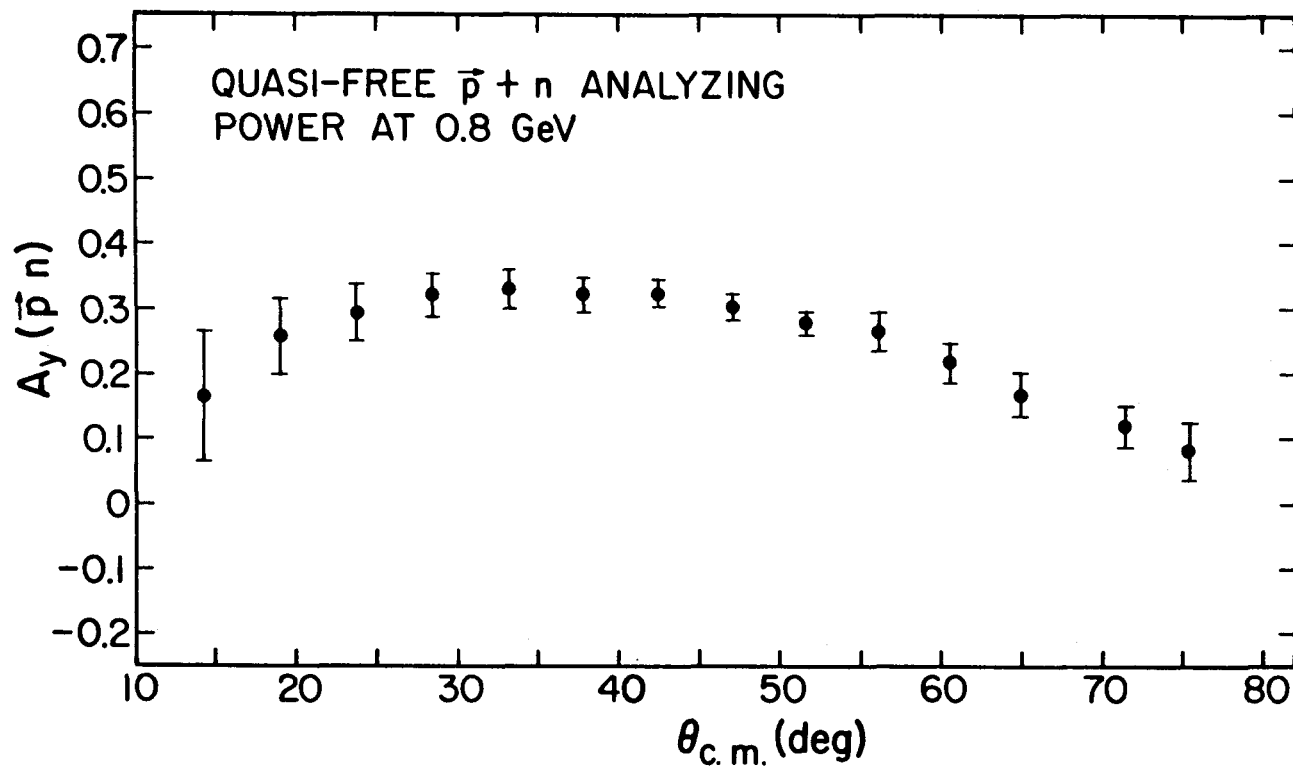


Figure 3.8: The results of the quasi-free $\bar{p} + n$ analyzing power measurements obtained from the off-line analysis of the data. The errors include the statistical uncertainties, the fitting uncertainties, and the uncertainty in the beam polarization.

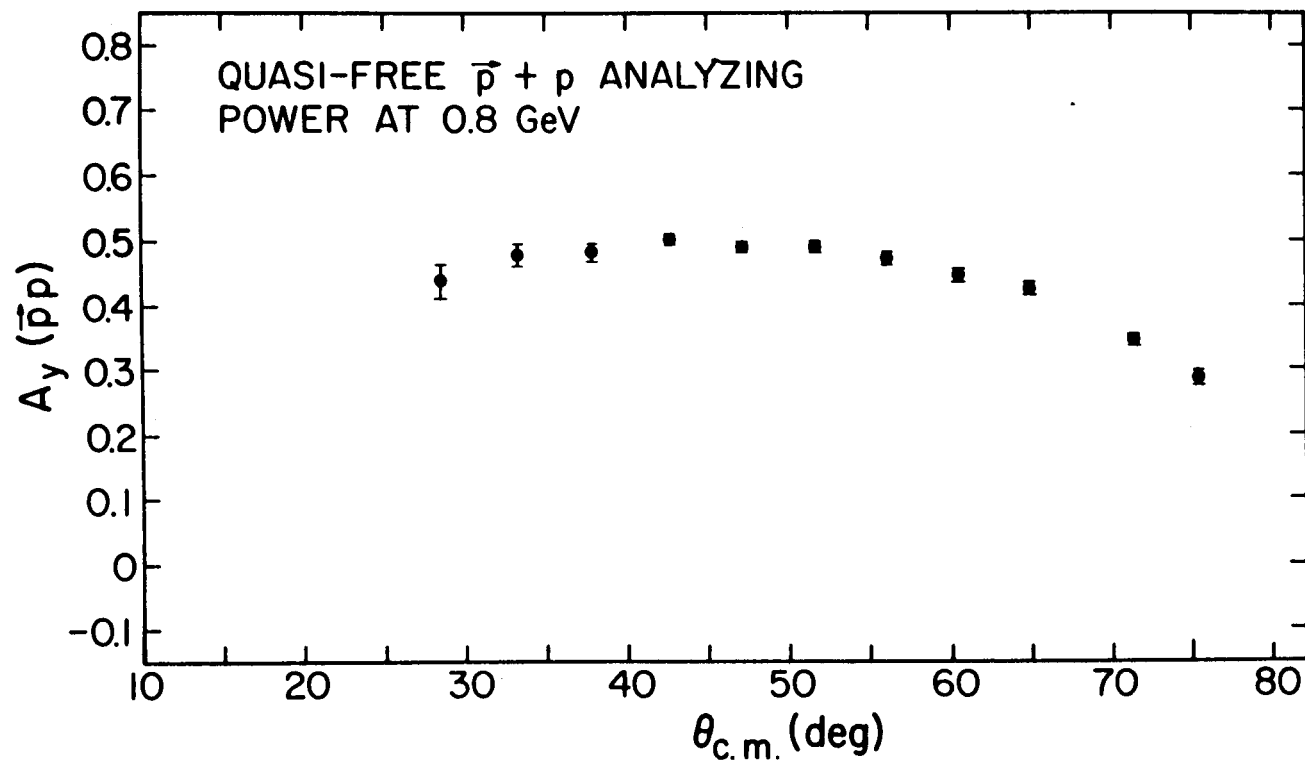


Figure 3.9: The results of the quasi-free $\bar{p} + p$ analyzing power measurements obtained from the off-line analysis of the data. The errors include the statistical uncertainties, the fitting uncertainties, and the uncertainty in the beam polarization.

22°. These angles were repeated in order to overlap the data obtained during the separate running cycles. The two measurements at each angle were combined by the weighted sums method⁽³²⁾ and the error bars reflect the improved statistics.

In the next section a more detailed discussion of the errors associated with the data points will be presented. Also, estimates of systematic errors in the results and a discussion of the sources of these errors will be given. The data will then be compared to existing free $\vec{p}p$ and $n\vec{p}$ data which overlap the present results.

DISCUSSION OF EXPERIMENTAL ERRORS

The errors associated with the analyzing power measurements shown in Figs. 3.8 and 3.9 are due to a combination of uncertainties in the measured recoil yields and absolute determination of the mean beam polarization. The uncertainties in the yields are due to both the statistical uncertainties of the measurements and the uncertainties in the corrected yields due to the subtraction of the randoms background under the peaks in the TDC spectra. The error in the determination of the beam polarization arises from a combination of statistical uncertainties in the yields measured by the beam line polarimeter detectors and the uncertainty in the effective analyzing power of the polarimeter target. These errors were combined in the manner described in Appendix II to produce the uncertainties in the

analyzing power measurements listed in Table 3.1 and shown in Figures 3.8 and 3.9.

In addition to the errors mentioned above, certain systematic errors exist which are not reflected in the quoted uncertainties of the results. Although these errors are believed to be small, they are possible sources of error which may become substantial when certain experimental conditions exist; they therefore warrant discussion. The remainder of this section will address these possible sources of systematic errors and estimate their effect on the quasi-free analyzing powers.

The first source of systematic error results from uncertainties in the relative integrated beam currents for the two beam polarization states. Absolute determinations of the integrated beam currents are not necessary for analyzing power measurements, but the determination of the relative integrated beam currents of the two beam polarization states is essential. It is for this reason that two relative beam current monitors were used during the experiment. By monitoring the ratios of the two current monitors for both beam polarization states, the ability to determine the relative integrated beam currents can be estimated. As mentioned in the previous chapter, the current monitors tracked to better than 1.5% in Cycle 24 and to better than 1% in Cycle 26. The systematic errors in the analyzing power results due to the uncertainties in the relative beam currents are therefore expected to be small.

Table 3.1

Quasi-free analyzing powers at 0.8 GeV obtained in the experiment

$\theta_L(\text{deg})$	$\theta_{\text{cm}}(\text{deg})$	$A_y(\vec{p}n)$	$\Delta A_y(\vec{p}n)$	$A_y(\vec{p}p)$	$\Delta A_y(\vec{p}p)$
6.0	14.3	0.165	0.099	-----	-----
8.0	19.1	0.258	0.057	-----	-----
10.0	23.8	0.293	0.042	-----	-----
12.0	28.5	0.321	0.033	0.437	0.025
14.0	33.2	0.329	0.029	0.478	0.017
16.0	37.8	0.320	0.026	0.482	0.014
18.0	42.4	0.322	0.020	0.499	0.008
20.0	47.0	0.302	0.019	0.489	0.007
22.0	51.5	0.278	0.017	0.490	0.006
24.0	56.0	0.266	0.029	0.473	0.009
26.0	60.4	0.217	0.029	0.445	0.009
28.0	64.8	0.170	0.033	0.426	0.010
31.0	71.3	0.120	0.031	0.344	0.009
32.9	75.4	0.084	0.044	0.288	0.011

Another source of systematic error is related to the ability to properly identify the type of recoil particle detected in the array counters. Since both recoil neutrons and protons are detected by the array counters, false asymmetries may be introduced into the results if the true quasi-free $\vec{p}p$ and $\vec{p}n$ analyzing powers differ and if misidentifications occur.

For the quasi-free $\vec{p}p$ results a false asymmetry may occur if the charged particle paddle is triggered by recoil neutrons. The magnitude of the false asymmetry is dependent upon the efficiency of the Pilot B charged particle paddle and array counters to detect recoil neutrons and on the relative differences in the quasi-free $\vec{p}p$ and $\vec{p}n$ analyzing powers. The efficiencies of the charged particle paddle and array counters to detect neutrons was not measured during the experiment but are estimated to be about 0.5% and 30% respectively, by extrapolation from previous neutron detection efficiency measurements using plastic scintillators, ^(22,33,34) over most of the energy range covered by the experiment. Based on these estimates, the error in the quasi-free $\vec{p}p$ analyzing power results due to the misidentification of detected recoil neutrons as protons is very small and can be neglected.

A false asymmetry may also be introduced into the quasi-free $\vec{p}n$ analyzing power measurements if improper identification of the recoil particles occurs. However, unlike the previous case, substantial errors in the $\vec{p}n$ analyzing power

measurements may result due to small inefficiencies in the charged particle paddle for detecting protons. This is due mainly to the near 100% efficiency of the array counters in detecting recoil protons which do not trigger the charged particle paddle. Estimates of this effect were made for charged particle paddle proton detection efficiencies of 99.3% and 99.7%. The former efficiency is the "measured" efficiency from the LH₂ calibration runs while the latter is the estimated actual efficiency of the charged particle paddle as discussed earlier in the chapter. The results of these calculations are shown in Table 3.2. In doing the calculations the assumption was made that 0.7% and 0.3% of the protons were misidentified as neutrons. The measured neutron yields were then corrected based on this assumption and the analyzing powers computed. As can be seen from the Table, the effects become more significant with increasing scattering angle and decreasing charged particle paddle efficiency. For all cases where simultaneous $\vec{p}_p$ and $\vec{p}_n$ analyzing power data were obtained, the corrections for the inefficiency in the charged particle paddle result in smaller $\vec{p}_n$ analyzing powers than the uncorrected results indicate. Although no absolute determination of the size of this systematic error can be made since the true efficiency of the charged particle paddle can only be estimated, the above calculations serve to illustrate the necessity for a very high charged particle paddle efficiency.

Table 3.2

Effects of the charged particle paddle efficiency
on the quasi-free $\vec{p} + n$ analyzing powers

$\theta_L(\text{deg})$	$A_y(\vec{pn})^{(1)}$	$A_y(\vec{pn})^{(2)}$	Percent Difference	$A_y(\vec{pn})^{(3)}$	Percent Difference
6.0	0.165	0.165	0.0	0.165	0.0
8.0	0.258	0.258	0.0	0.258	0.0
10.0	0.293	0.293	0.0	0.293	0.0
12.0	0.321	0.320	0.3	0.321	0.0
14.0	0.329	0.325	1.2	0.328	0.3
16.0	0.320	0.314	1.9	0.318	0.6
18.0	0.322	0.313	2.8	0.318	1.2
20.0	0.302	0.287	5.0	0.296	2.0
22.0	0.278	0.261	6.1	0.271	2.5
24.0	0.266	0.250	6.0	0.260	2.3
26.0	0.217	0.196	9.7	0.209	3.7
28.0	0.170	0.145	14.7	0.160	5.9
31.0	0.120	0.096	20.0	0.111	7.5
32.9	0.084	0.058	31.0	0.074	11.9

(1) Quasi-free analyzing powers as measured in the experiment (no corrections).

(2) "Corrected" quasi-free analyzing powers assuming a charged particle paddle efficiency of 99.3%.

(3) "Corrected" quasi-free analyzing powers assuming a charged particle paddle efficiency of 99.7%.

Systematic errors can also be introduced into the results during the analysis of the data. The elimination of all multiple hits in the off-line analysis of the data is one source of such an error. As discussed previously, two types of multiple hits are eliminated. One is due to the scattering of a recoil particle into a nearby counter, while the other is due to a coincidence between a real recoil event in one array counter and a random background event in another counter. Eliminating events in which a random coincidence was involved could lead to a false asymmetry if the beam currents were different in the two beam polarization states, since true coincidences scale with the beam current but random coincidences scale with the square of the beam current.

The magnitude of a false asymmetry of this type can be estimated by noting that differences in the normal and reverse ratios of the single to multiple hit events were not seen for either recoil protons or neutrons. If one assumes that the probability of a recoil particle scattering into a nearby detector is independent of the beam polarization state, then differences in the random coincidence rates due to unequal beam currents in the two beam polarization states would cause differences in the single to multiple hit ratios for normal and reverse beam polarizations. Since differences were not seen in these ratios, this systematic error is estimated to be small.

Finally, a comparison between the quasi-free $\vec{p}p$ and $\vec{p}n$ analyzing powers determined in this experiment and previously

measured free $\vec{p}p$ analyzing powers^(18,29) and free $n\vec{p}$ analyzing
 powers⁽³⁵⁾ is shown in Fig. 3.10. Excellent agreement is seen
 between the free $\vec{p}p$ data and the quasi-free $\vec{p}p$ data from this
 experiment suggesting that overall systematic errors are small.
 However, only fair agreement is seen in the $\vec{p}n$ case which suggests
 that in either the $n\vec{p}$ measurements or this $\vec{p}n$ experiment the quoted
 errors are unrealistic.

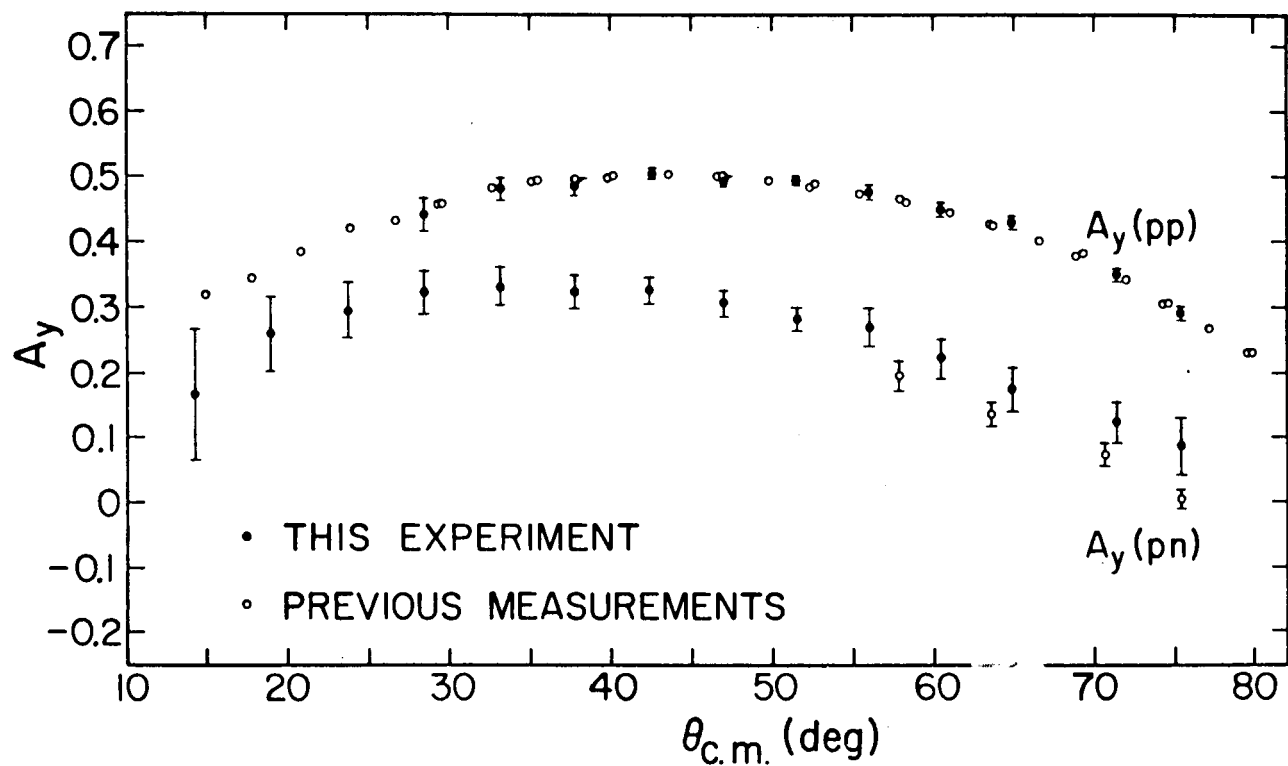


Figure 3.10: A comparison of the quasi-free analyzing powers obtained in this experiment with previous free analyzing power measurements. The free $\vec{p}p$ analyzing power data are from references 18 and 29. The free $n\vec{p}$ analyzing power data are from reference 35.

CHAPTER 4

PARAMETERIZATION OF THE DATA, IMPLICATIONS, AND CONCLUSIONS

INTRODUCTION

The determination of the 0.8 GeV quasi-free $\vec{p} + n$ analyzing powers at forward angles was the first of a set of experiments designed to help better determine the free nucleon-nucleon scattering amplitudes at this energy. In this chapter, the experimental results will be discussed and comparisons with phase shift predictions will be made. The usefulness of the new data in constraining the phase shifts will be shown by comparing the nucleon-nucleon amplitudes obtained with and without the new data. These amplitudes will then be used in a KMT analysis of previously reported $\vec{p} + {}^{40}\text{Ca}$ elastic scattering data⁽³⁶⁾ in order to provide an indication of the problems which still exist.

USE OF QUASI-FREE EXPERIMENTS TO DETERMINE FREE

NUCLEON-NUCLEON AMPLITUDES

Before the effects of the new experimental data on the nucleon-nucleon scattering amplitudes are described, some discussion is warranted concerning the validity of using quasi-free analyzing power measurements to aid in the determination of the free nucleon-nucleon amplitudes. As mentioned previously, the LD_2

target used in the experiment served as a source of "free" protons and neutrons. In actuality, the LD_2 target differs in two ways from a free proton target (i.e. an LH_2 target) or a hypothetical free neutron target: (1) the proton and neutron which comprise the deuteron are bound and, (2) the possibility of final-state interactions must be considered in quasi-free scattering using deuterons.

Quasi-elastic scattering is a process in which the projectile and a target nucleon scatter as if the target nucleon were free. If the energy of the projectile is large compared to the binding energy of the target nucleon and if the projectile is a nucleon, then the process essentially follows the free two-nucleon kinematics. Since the binding energy of the deuteron is about 2.23 MeV while the proton beam energy is 0.8 GeV, any kinematic effects due to the target nucleon being bound are expected to be quite small.

The interaction of the quasi-elastically scattered target nucleon with the spectator nucleon of the deuterium nucleus (final-state interaction) may also result in differences between free and quasi-free nucleon-nucleon scattering. Considerable theoretical attention has been given to final-state interactions in quasi-free scattering at lower incident energies,⁽³⁷⁻⁴⁰⁾ but detailed theoretical studies of the role of the final-state

interaction in quasi-free nucleon-nucleon scattering at energies near 1 GeV have not been made.

However, some qualitative statements can be made concerning the effects of final-state interactions. Final-state effects are thought to be small in the region of the quasi-free peak for momentum transfers which exceed 100 MeV/c.⁽⁴¹⁾ This is supported by the excellent agreement between the previously measured free $\vec{p}p$ analyzing powers and the quasi-free $\vec{p}p$ analyzing powers obtained in this experiment. Final-state interaction effects on the forward angle $\vec{p}n$ analyzing powers, where quasi-free $\vec{p}p$ analyzing powers were not obtained, are less certain. Previous quasi-free measurements at lower incident energies⁽⁴²⁻⁴⁴⁾ and subsequent reanalyses of the data^(37,39,45) indicate that, in general, final-state interaction corrections to quasi-free analyzing power measurements are small ($< 10\%$) and that good agreement is seen between free and quasi-free analyzing powers over a wide range of incident particle and recoil particle energies. Thus any differences between the quasi-free analyzing powers obtained in this experiment and the free nucleon-nucleon analyzing powers are expected to be small.

PHASE-SHIFT ANALYSES

In order to see if the new 0.8 GeV quasi-free $\vec{p} + n$ analyzing power data further constrain the neutron-proton

scattering amplitudes at 800 MeV, phase-shift analyses which incorporated these data were made. Three sets of proton-neutron amplitudes for 800 MeV were obtained using the program SAID⁽⁴⁶⁾ (Scattering Analyses Interactive Dial-In) which enables a dial-in user to obtain the phase-shift predictions, amplitudes, and observables of Arndt and collaborators using a variety of user-specified options in the program. In this section, the results of these phase-shift analyses will be described.

Amplitudes and observables may be obtained from the program SAID by specifying either an energy-dependent or "single-energy" solution. The single-energy solution C750 was used to compute the amplitudes and observables shown in this dissertation. This solution uses the nucleon-nucleon data from 670 to 820 MeV in the data base to calculate the phases, amplitudes, and observables. Using this solution, phase-shift predictions of the np scattering amplitudes and the free $\vec{n}p$ analyzing powers at 800 MeV were obtained before the present experimental data were entered into the data base. The resulting prediction for the analyzing power is shown as the dashed curve in Fig. 4.1 while the real and imaginary parts of the np amplitudes a, c, m, g, and h (defined in Equation 1.22 of Chapter 1) are represented by the dashed curves of Figs. 4.2 - 4.6. As seen in Fig. 4.1, the experimental angular distribution is inadequately reproduced by the phase-shift solution in both shape and magnitude.

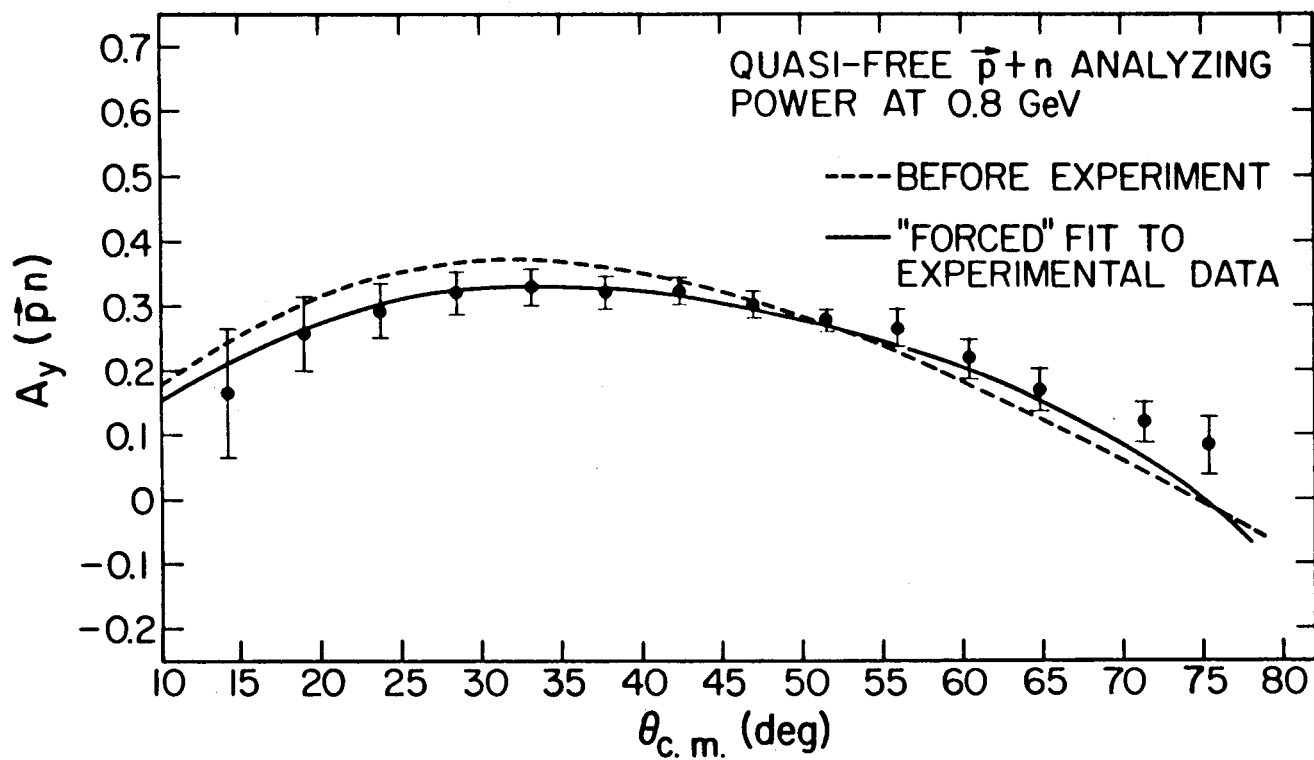


Figure 4.1: A comparison of the phase-shift predictions for the $\bar{p}n$ analyzing powers at 800 MeV with the quasi-free analyzing powers obtained in this experiment. The phase-shift results are from reference 46 and are described in the text.

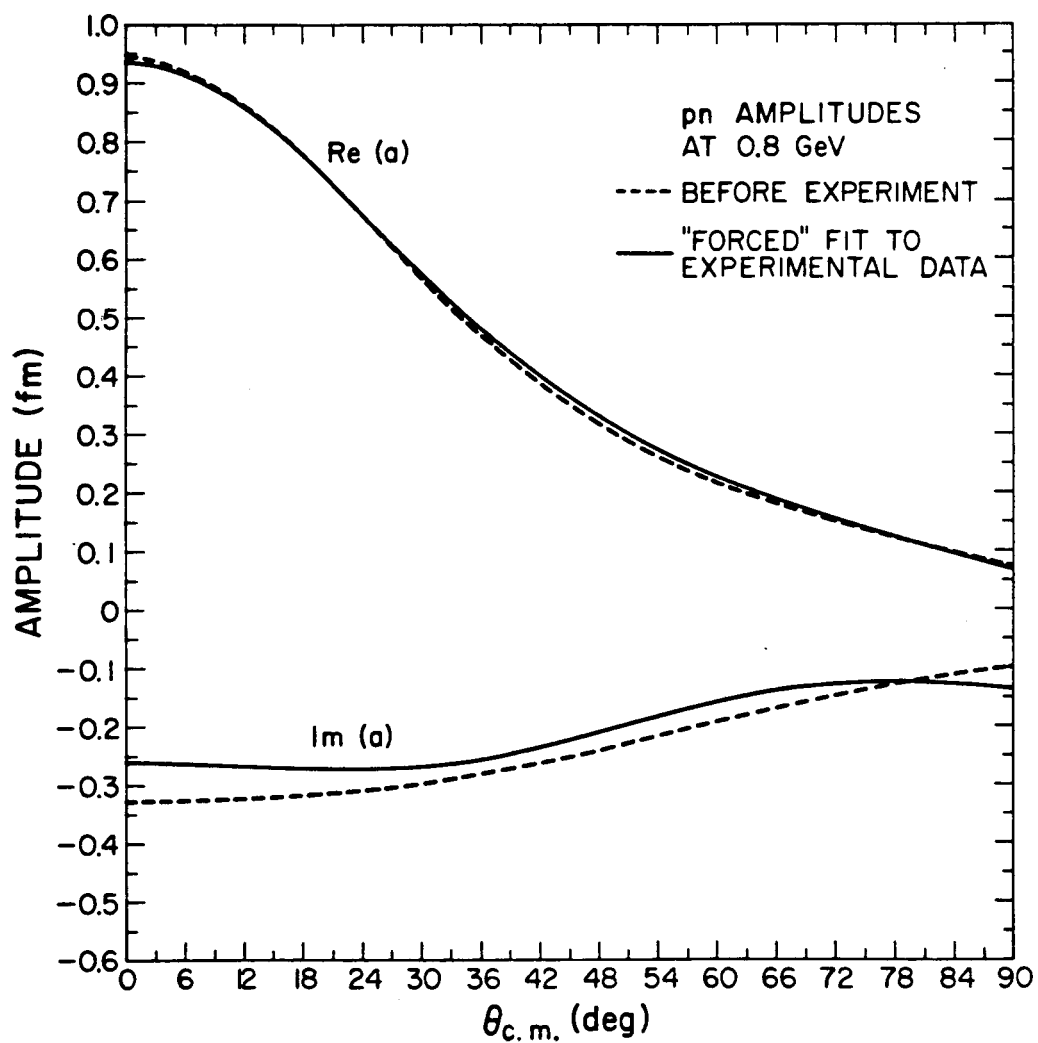


Figure 4.2: The real and imaginary parts of the spin-independent amplitude, a , for the proton-neutron system at 800 MeV. The phase-shift solutions used to obtain the amplitudes are discussed in the text.

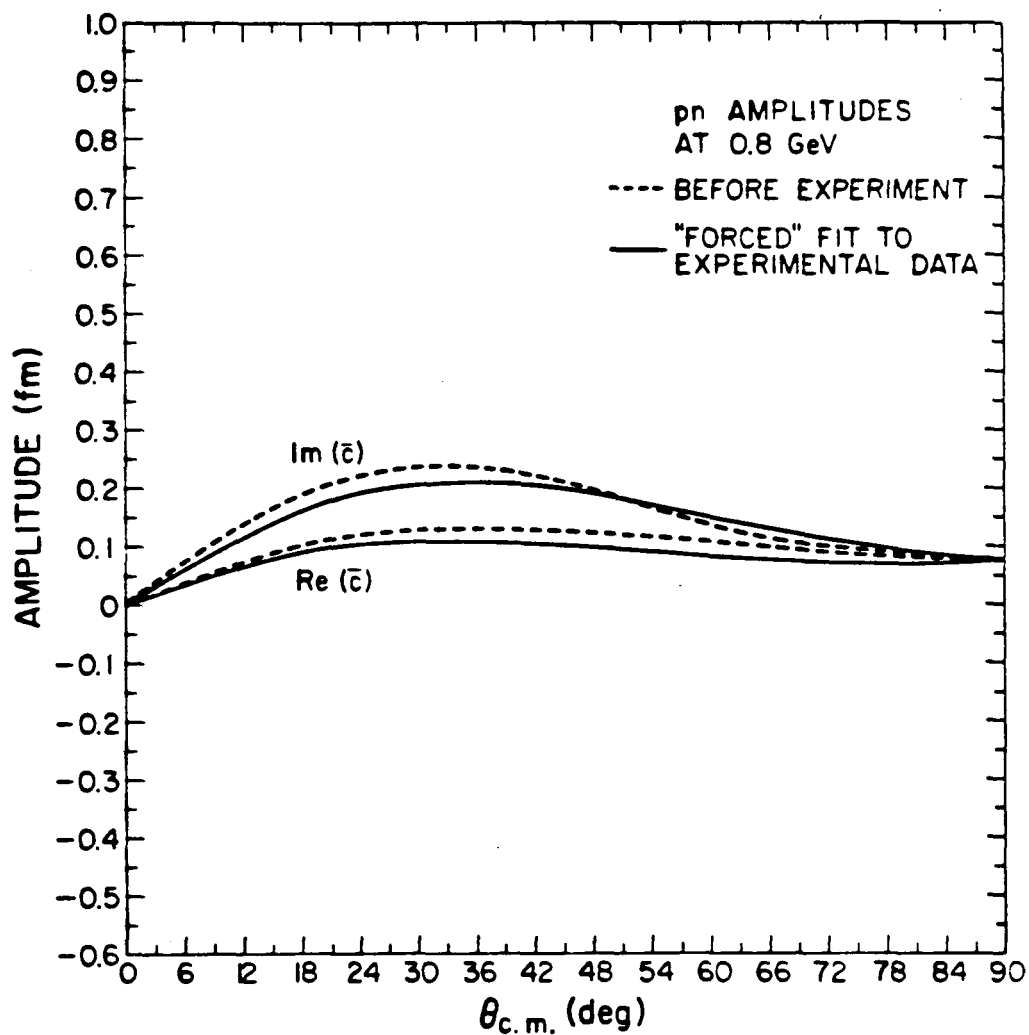


Figure 4.3: The real and imaginary parts of the spin-dependent amplitude, $\bar{c}$, where $\bar{c} = ic$ (see Equation 1.22) for the proton-neutron system at 800 MeV. The phase-shift solutions used to obtain the amplitudes are discussed in the text.

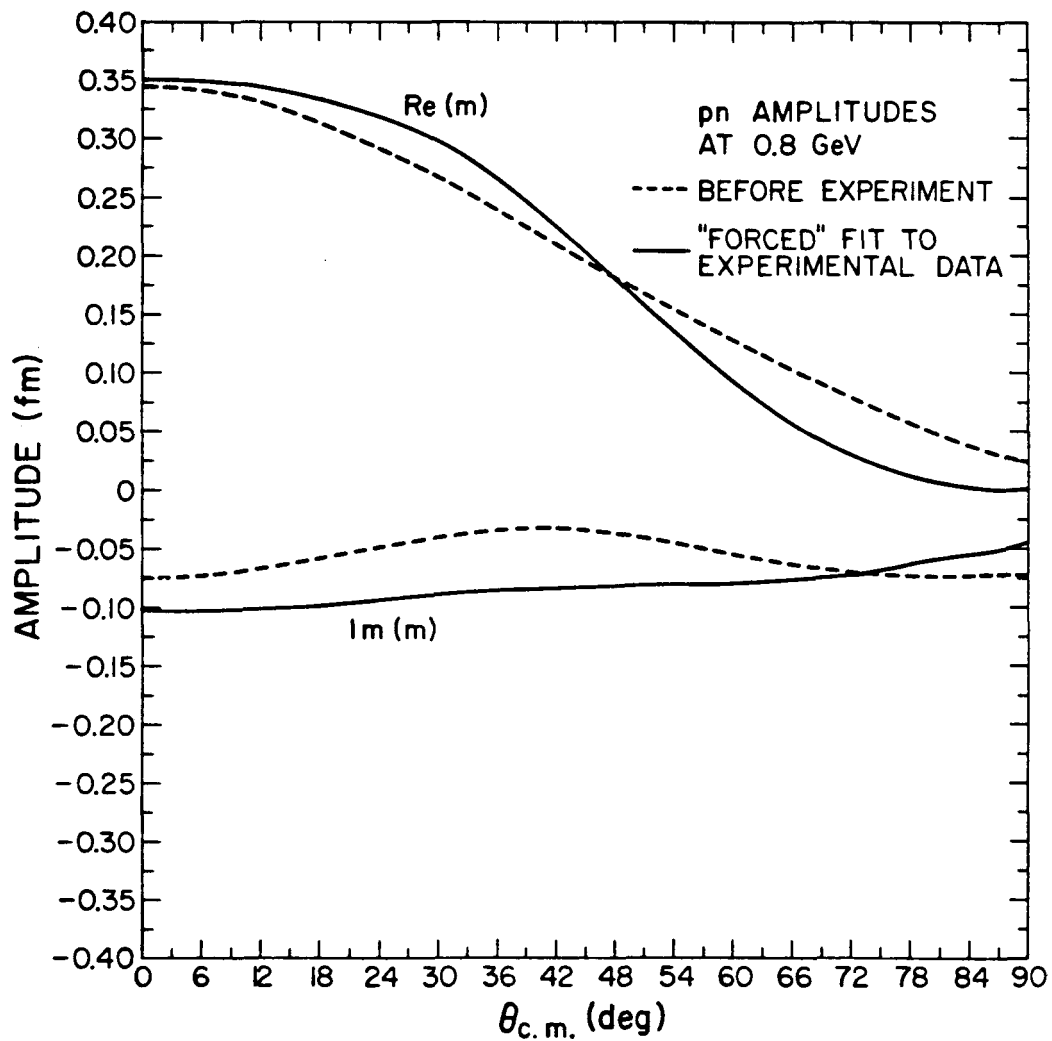


Figure 4.4: The real and imaginary parts of the double-spin-flip amplitude, m , for the proton-neutron system at 800 MeV. The phase-shift solutions used to obtain the amplitudes are discussed in the text.

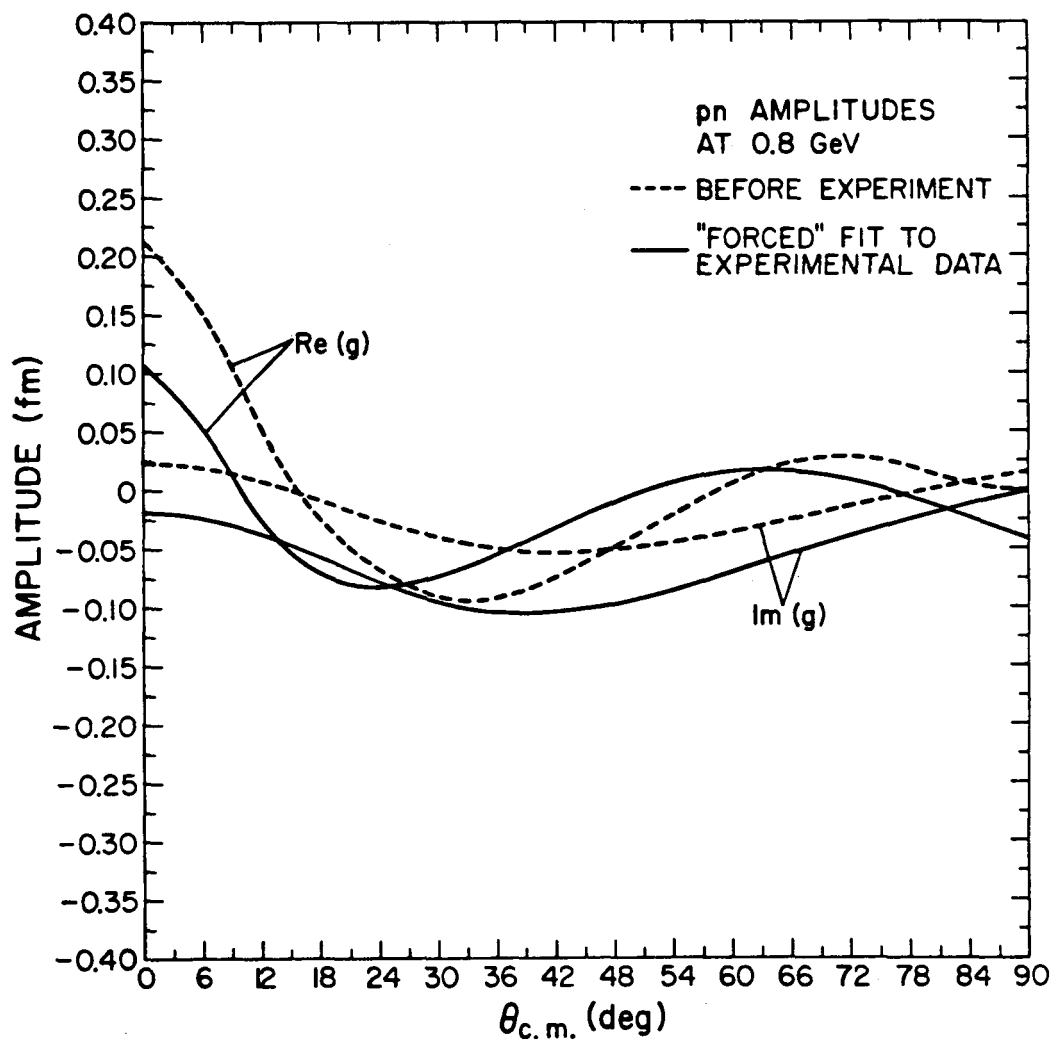


Figure 4.5: The real and imaginary parts of the double-spin-flip amplitude, g , for the proton-neutron system at 800 MeV. The phase-shift solutions used to obtain the amplitudes are discussed in the text.

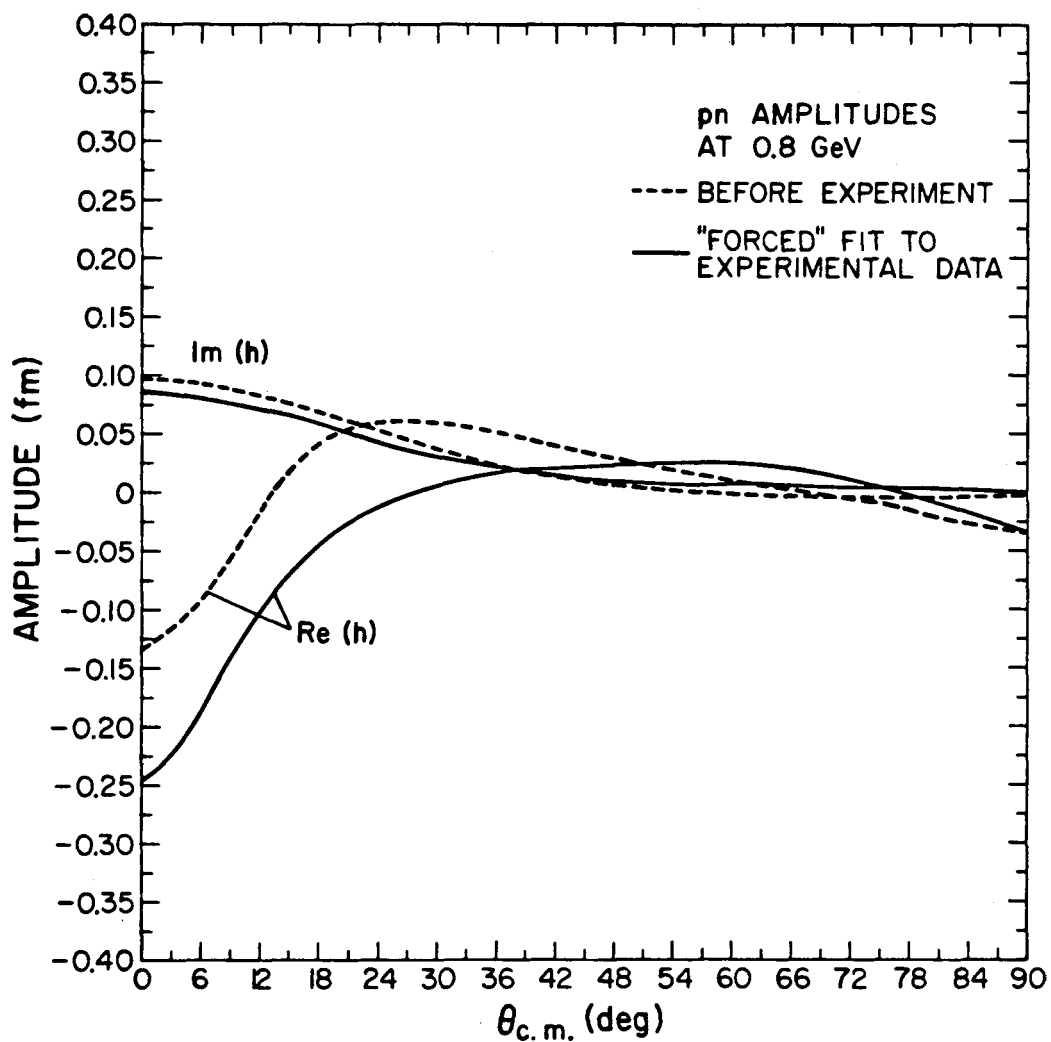


Figure 4.6: The real and imaginary parts of the double-spin-flip amplitude, h , for the proton-neutron system at 800 MeV. The phase-shift solutions used to obtain the amplitudes are discussed in the text.

The experimental data were then added to the data base and the amplitudes and analyzing power predictions were recomputed. The resulting pn analyzing power and scattering amplitudes changed insignificantly from the predictions made before the experimental data were included. For this reason, the predictions for the analyzing power and amplitudes which resulted when the experimental data were included in the data base are not shown in Figs. 4.1 - 4.6, since the curves would be indistinguishable from the previous results.

One naively expects some improvement in the fit to the experimental data when they are included in the data base; however, since the data base used in the computation of the observables and amplitudes contained 651 experimental data points before the data from this experiment were added, the phases were apparently constrained enough so that the inclusion of the additional 14 data points did little to alter the amplitudes and phases at 800 MeV.

In order to determine a phase-shift solution which reproduced the analyzing power data obtained in this experiment, an option in the program SAID was used to enter fictitious data into the data base. Emphasis was placed on reproducing fits to the forward angle pn data near 800 MeV which consist of the $\vec{p}n$ analyzing power measurements of this experiment and the forward angle differential cross section data of Carlini, et. al.⁽⁴⁷⁾ In order to accomplish this, smooth curves were drawn through the

forward angle data, and fictitious data which fell on these curves were added to the data base. The errors associated with the fictitious data were specified to be ± 0.01 , thus causing the new solution to bend toward the fictitious data. A total of 11 fictitious differential cross section points and 28 fictitious analyzing power points were included in this way. The resulting phase-shift predictions for the analyzing power and the pn scattering amplitudes are shown as the solid curves in Figs. 4.1 - 4.6. As expected, the forward angle analyzing powers are now adequately reproduced.

An additional routine in the program SAID was then used to compute the $|\chi|^2$ per degree of freedom for the data base points lying between 700 and 800 MeV for the phase-shift solutions before and after the "forced" fit to the forward angle data. The results are given in Table 4.1. As can be seen from the Table, the forced fit phase-shift solution provides somewhat poorer reproduction of the experimental data base than the "standard" phase-shift solution except at energies very close to 800 MeV where some overall improvement is seen. It is unclear whether these results reflect the unphysical nature of the forced-fit solution or whether these problems are a manifestation of the way in which the energy dependence of the phases are parameterized.

In the next section the results of KMT calculations, using the pn scattering amplitudes obtained from the phase-shift analyses

Table 4.1

Results of the $|\chi|^2$ analysis of the pn data base from 700 to 800 MeV⁽¹⁾ before and after the "forced" fit to the 800 MeV forward angle analyzing powers

<u>Observable</u> ⁽²⁾	<u># pts.</u>	<u>Energy(MeV)</u>	<u>$\chi ^2$/pt.</u> <u>before</u>	<u>$\chi ^2$/pt.</u> <u>after</u>
P	8	700.0	1.525	1.299
SGTR	1	700.0	0.268	0.268
DSG	85	709.3	0.939	1.529
P	18	725.0	1.906	2.288
SGTR	1	725.0	0.104	0.104
SGT	1	725.8	0.043	0.141
SGT	1	730.0	1.565	1.760
DSG	87	734.1	1.087	2.045
SGTR	1	750.0	0.883	0.884
SGT	1	767.3	0.094	0.098
DSG	98	770.6	1.775	3.244
P	18	775.0	1.192	2.079
SGTR	1	775.0	1.968	1.969
DSG	36	790.0	2.042	1.924
SGTR	1	800.0	2.661	2.662
P	14	800.0	1.342	0.722

(1) Number of points, energy, and $|\chi|^2$ are from reference 46.

(2) P = Polarization or analyzing power

DSG = Differential cross section

SGTR = Total reaction cross section

SGT = Total cross section

discussed in this section, will be presented. These calculations will demonstrate that either (1) the pn amplitudes are still very poorly determined, or (2) the standard applications of multiple scattering theories at 0.8 GeV are not, as yet, capable of providing such information as neutron-proton density differences.

NUCLEON-NUCLEON AMPLITUDES AND KMT ANALYSES

An analysis of recent $\vec{p} + {}^{40}\text{Ca}$ differential cross section and analyzing power data⁽³⁶⁾ obtained at HRS was performed using the KMT formalism discussed in Chapter 1. Inputs to the calculations consisted of three different sets of nucleon-nucleon amplitudes, discussed below, and the proton matter distribution obtained from electron scattering data. For a given calculation, the neutron matter distribution was varied to optimize the fit to the experimental differential cross section while keeping the proton matter distribution and the given set of nucleon-nucleon amplitudes fixed. In this way, the effects of a given set of scattering amplitudes on the predicted $\vec{p} + {}^{40}\text{Ca}$ analyzing power angular distribution and the root-mean-square difference in the neutron and proton matter distribution radii, Δr_{np} , of the ${}^{40}\text{Ca}$ nucleus could be studied.

Two of the KMT calculations were performed using nucleon-nucleon amplitudes obtained from phase-shift analyses. The pp scattering amplitudes were obtained from the SM80 phase-shift

solution⁽⁴⁶⁾ at 800 MeV, while two sets of pn scattering amplitudes were used in the calculations: (1) the amplitudes obtained using the C750 phase-shift solution before the quasi-free analyzing power measurements were added to the data base, and (2) the amplitudes obtained by forcing a fit to the forward angle data near 800 MeV, as discussed previously.

The third KMT calculation used a set of Gaussian scattering amplitudes as input. The amplitudes were obtained by fixing the double-spin-flip amplitudes, m , g , and h , at values predicted by phase-shift analyses and then fitting the available nucleon-nucleon data near 800 MeV with Gaussian parameterizations of the spin-independent and spin-dependent amplitudes, a and c . Four of the six parameters for either the pp or pn system may be determined using the available data and the remaining two parameters are the obtained by searching on the undetermined parameters and minimizing the $|\chi|^2$ of the fit to the nucleon-nucleon data. The procedure described here for obtaining the Gaussian amplitudes is very similar to a previously reported method⁽⁵⁾ used to obtain parameterized scattering amplitudes for KMT calculations, with the exception that here the double-spin-flip amplitudes are fixed at values predicted by phase-shift analyses enabling the determination of a unique set of scattering amplitudes.⁽⁴⁸⁾

The results of the KMT calculations using the pn amplitudes obtained from the phase-shift analysis before the quasi-free

analyzing power data were included in the data base are shown in Figure 4.7 and as Solution 1 in Figure 4.8. Also shown in Figure 4.8 are the results of the KMT calculations using the forced-fit amplitudes (Solution 2) and the Gaussian amplitudes (Solution 3). Since comparable fits to the $\vec{p} + {}^{40}\text{Ca}$ differential cross section data resulted for all three calculations, the results of the calculations for Solutions 2 and 3 have been omitted from Figure 4.7 for the sake of clarity.

As seen in Figure 4.8, the fits to the $\vec{p} + {}^{40}\text{Ca}$ analyzing power data differ only slightly for the calculations using either of the sets of scattering amplitudes obtained from the phase-shift analyses (Solution 1 or 2) and both calculations fail to reproduce the structure of the analyzing power angular distribution at forward angles. These results suggest that the allowable variation in the double-spin-flip amplitudes may offset any partial attempt to determine the spin-independent and spin-dependent amplitudes, a and c , used in the KMT calculations. The calculation using the Gaussian amplitudes (Solution 3) is more successful in reproducing the forward angle structure of the analyzing power data, but all three calculations fail to reproduce the experimental data quantitatively. In addition, the KMT calculations resulted in values for the neutron-proton root-mean-square radius difference, Δr_{np} , of -0.175 fm, -0.193 fm, and -0.142 fm for Solutions 1, 2, and 3, respectively. These values differ somewhat from results

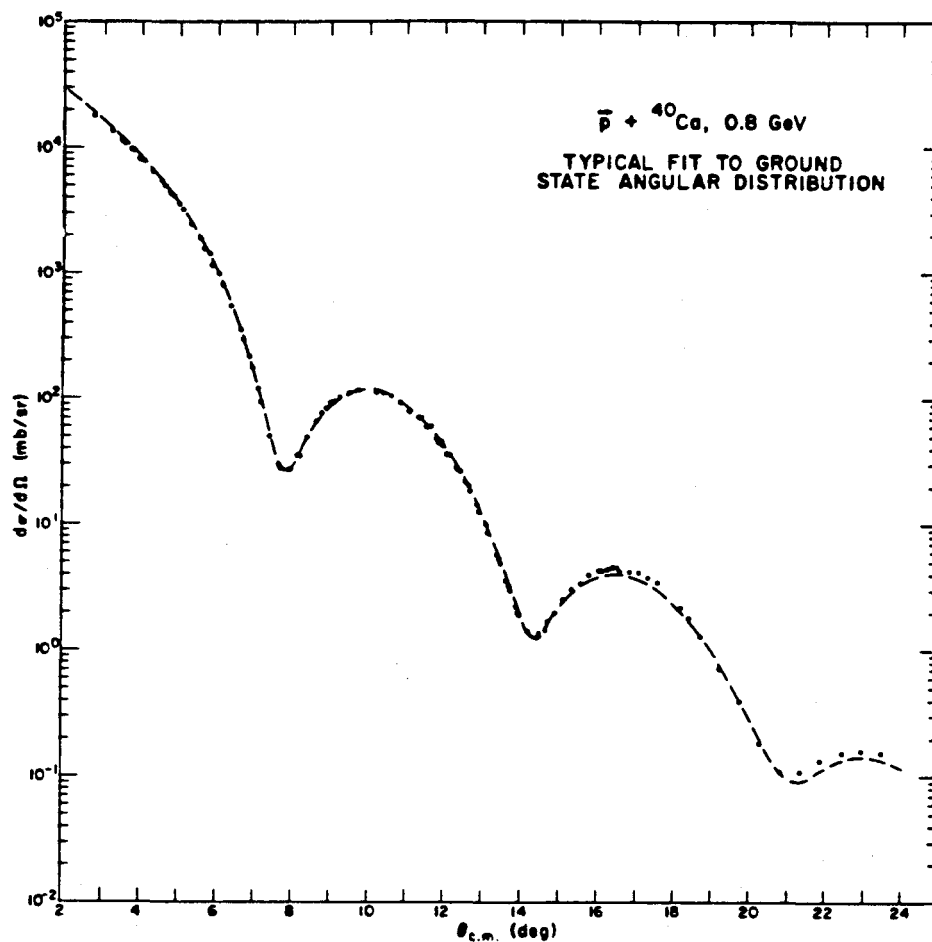


Figure 4.7: Fit to the 0.8 GeV $\bar{p} + {}^{40}\text{Ca}$ elastic differential cross section data of reference 36. The fit shown is the result of a KMT calculation using the proton-neutron amplitudes obtained before the data from the present experiment were included in the data base, as explained in the text. Similar fits resulted when the proton-neutron amplitudes obtained from other phase-shift solutions or the Gaussian amplitudes discussed in the text were used in the KMT calculations.

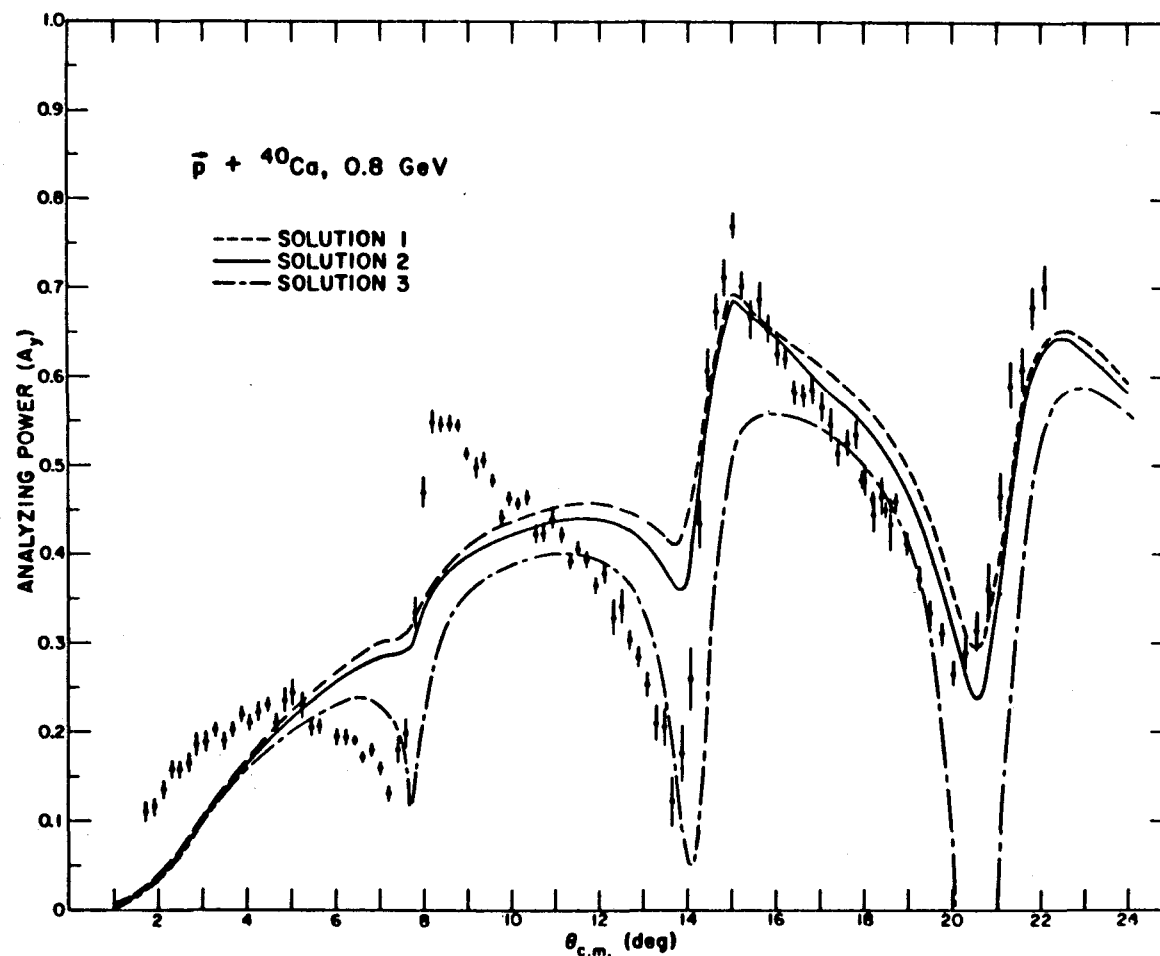


Figure 4.8: Predicted elastic analyzing powers for $\bar{p} + {}^{40}\text{Ca}$ at 0.8 GeV compared to the data of reference 36. Solution 1 results when the amplitudes, obtained before the data from the experiment were added to the data base, are used. Solution 2 is obtained by using the amplitudes from the forced-fit phase-shift solution. Solution 3 results when Gaussian amplitudes are used.

obtained in previous analyses of the $\vec{p} + {}^{40}\text{Ca}$ data^(5,36) and provide some indication of the sensitivity of the KMT analyses of p-nucleus scattering data to the nucleon-nucleon scattering amplitudes. A study to determine the origins of the differences encountered in KMT analyses as they relate to the scattering amplitudes will be undertaken in the near future.⁽⁴⁸⁾

CONCLUSIONS

The measurement of the forward angle quasi-free $\vec{p} + n$ analyzing powers at 800 MeV represents the first step in a better determination of the nucleon-nucleon scattering amplitudes at this energy. Phase-shift analyses of the data reported here have shown that the nucleon-nucleon phases and amplitudes are sensitive to the data. The results of KMT calculations using scattering amplitudes obtained from phase-shift analyses have suggested that the variations possible in the double-spin-flip amplitudes may prevent any partial determination of the spin-independent and spin-dependent amplitudes used in the KMT calculations. The KMT analysis has also provided an indication of the sensitivity of the proton-nucleus calculations to the nucleon-nucleon amplitudes. Additional nucleon-nucleon experiments are necessary to uniquely determine the nucleon-nucleon amplitudes at 0.8 GeV. Experiments designed to help determine the double-spin-flip amplitudes will be

undertaken in the near future and represent the next step in determining the scattering amplitudes.

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APPENDIX I

CAMAC DATA WORDS AND SAMPLE SCALAR, TEST FILE, AND HISTOGRAM FILE LISTINGS

The CAMAC data words associated with each HRS TRIGGER signal are listed for both Cycles 24 and 26. Sample listings of the scalars used for on-line data acquisition during Cycle 26 and the ALLTEST and histogram files used in the off-line analysis of the Cycle 26 data follow.

CAMAC Data Words

Cycle 24

ADC WORDS⁽¹⁾

Polar. NORMAL P.H.

Polar. REVERSE P.H.

S4 UP P.H.

S4 DOWN P.H.

TDC WORDS⁽²⁾

S1 UP TIME

S1 DOWN TIME

S4 UP TIME

S4 DOWN TIME

CHMBR 2 CATH(+)

CHMBR 3 CATH(+)

CHMBR 6 CATH(+)

CHMBR 2 CATH(-)

CHMBR 3 CATH(-)

CHMBR 6 CATH(-)

CHMBR 2 ANODE(+)

CHMBR 3 ANODE(+)

CHMBR 6 ANODE(+)

CHMBR 2 ANODE(-)

Cycle 26

ADC WORDS⁽¹⁾

Polar. NORMAL P.H.

Polar. REVERSE P.H.

S4 UP P.H.

S4 DOWN P.H.

TDC WORDS⁽³⁾

S1 UP TIME

S1 DOWN TIME

S3 UP TIME

S3 DOWN TIME

S4 UP TIME

S4 DOWN TIME

CHMBR 2 CN-CP

CHMBR 2 CATH(+)

CHMBR 2 AN-AP

CHMBR 2 ANODE(+)

CHMBR 3 CN-CP

CHMBR 3 CATH(+)

CHMBR 3 AN-AP

CHMBR 3 ANODE(+)

Cycle 24

CHMBR 3 ANODE(-)

CHMBR 6 ANODE(-)

NEUTRON 1 TOF

NEUTRON 2 TOF

NEUTRON 3 TOF

NEUTRON 4 TOF

NEUTRON 5 TOF

NEUTRON 6 TOF

NEUTRON 7 TOF

NEUTRON 8 TOF

NEUTRON 9 TOF

NEUTRON 10 TOF

NEUTRON 11 TOF

NEUTRON 12 TOF

NEUTRON 13 TOF

NEUTRON 14 TOF

NEUTRON 15 TOF

NEUTRON 16 TOF

NEUTRON 17 TOF

NEUTRON 18 TOF

NEUTRON 19 TOF

NEUTRON 20 TOF

NEUTRON 21 TOF

Cycle 26

CHMBR 4 CN-CP

CHMBR 4 CATH(+)

CHMBR 4 AN-AP

CHMBR 4 ANODE(+)

CHMBR 5 CN-CP

CHMBR 5 CATH(+)

CHMBR 5 AN-AP

CHMBR 5 ANODE(+)

NEUTRON 1 TOF

NEUTRON 2 TOF

NEUTRON 3 TOF

NEUTRON 4 TOF

NEUTRON 5 TOF

NEUTRON 6 TOF

NEUTRON 7 TOF

NEUTRON 8 TOF

NEUTRON 9 TOF

NEUTRON 10 TOF

NEUTRON 11 TOF

NEUTRON 12 TOF

NEUTRON 13 TOF

NEUTRON 14 TOF

NEUTRON 15 TOF

Cycle 24

NEUTRON 22 TOF
NEUTRON 23 TOF
NEUTRON 24 TOF
CHARGED PARTICLE TIME

Cycle 26

NEUTRON 16 TOF
NEUTRON 17 TOF
NEUTRON 18 TOF
NEUTRON 19 TOF
NEUTRON 20 TOF
NEUTRON 21 TOF
NEUTRON 22 TOF
NEUTRON 23 TOF
CHARGED PARTICLE TIME

- (1) The ADC's were gated by a TRIGGER signal.
- (2) The TDC's were started by a TRIGGER signal and stopped by a detector signal.
- (3) The TDC's were gated by a TRIGGER signal. All TDC channels except (CN-CP) and (AN-AP) were started by a TRIGGER signal and stopped by the detector signal. CN-CP and AN-AP channels were started by the signal from the (-) end of the chamber cathode or anode delay line and stopped by a signal from the (+) end of the delay line.

2-01-00 (RUN*NORM) TRIGGERS
 2-01-01 (RUN*NORM) EVENTS
 2-01-02 (RUN*NORM) 10 KHZ
 2-01-03 (RUN*NORM) SEM4
 2-01-04 (RUN*NORM) IC4
 2-01-05 (RUN*NORM) IC3
 2-01-06 (RUN*NORM) SEM3 (A+B)
 2-01-07 (RUN*NORM) PL1*PL2
 2-01-08 (RUN*NORM) PL1*DLDP12
 2-01-09 (RUN*NORM) PL3*PL4
 2-01-10 (RUN*NORM) PL3*DLDP14
 2-01-11 (RUN*NORM) BEAM GATES
 2-02-00 (RUN*REV) TRIGGERS
 2-02-01 (RUN*REV) EVENTS
 2-02-02 (RUN*REV) 10 KHZ
 2-02-03 (RUN*REV) SEM4
 2-02-04 (RUN*REV) IC4
 2-02-05 (RUN*REV) IC3
 2-02-06 (RUN*REV) SEM3 (A+B)
 2-02-07 (RUN*REV) PL1*PL2
 2-02-08 (RUN*REV) PL1*DLDP12
 2-02-09 (RUN*REV) PL3*PL4
 2-02-10 (RUN*REV) PL3*DLDP14
 2-02-11 (RUN*REV) BEAM GATES
 2-03-00 (RUN*BEAM*NORM) TRIGGERS
 2-03-01 (RUN*BEAM*NORM) EVENTS
 2-03-02 (RUN*BEAM*NORM) 10 KHZ
 2-03-03 (RUN*BEAM*NORM) SEM4
 2-03-04 (RUN*BEAM*NORM) SEM3
 2-03-05 (RUN*BEAM*NORM) VETO UP*DOWN
 2-03-06 (RUN*BEAM*NORM) PL1*PL2
 2-03-07 (RUN*BEAM*NORM) PL1*DLDP12
 2-03-08 (RUN*BEAM*NORM) PL3*PL4
 2-03-09 (RUN*BEAM*NORM) PL3*DLDP14
 2-03-10 (RUN*BEAM*NORM) NEUTRON #12
 2-04-00 (RUN*BEAM*REV) TRIGGERS
 2-04-01 (RUN*BEAM*REV) EVENTS
 2-04-02 (RUN*BEAM*REV) 10 KHZ
 2-04-03 (RUN*BEAM*REV) SEM4
 2-04-04 (RUN*BEAM*REV) SEM3
 2-04-05 (RUN*BEAM*REV) #1 TELE 1*2*3
 2-04-06 (RUN*BEAM*REV) #2 TELE 1*2*3
 2-04-07 (RUN*BEAM*REV) PL1*PL2
 2-04-08 (RUN*BEAM*REV) PL1*DLDP12
 2-04-09 (RUN*BEAM*REV) PL3*PL4
 2-04-10 (RUN*BEAM*REV) PL3*DLDP14
 2-04-11 (RUN*BEAM*REV) BEAM GATES
 2-05-00 (RUN*BEAM*BUSY*NORM) TRIGGERS
 2-05-01 (RUN*BEAM*BUSY*NORM) EVENTS
 2-05-02 (RUN*BEAM*BUSY*REV) 10 KHZ
 2-06-00 (RUN*BEAM*BUSY*REV) TRIGGERS
 2-06-01 (RUN*BEAM*BUSY*REV) EVENTS
 2-06-02 (RUN*BEAM*BUSY*REV) 10 KHZ

2-06-03 (RUN*BEAM*BUSY*REV) SEM4
 2-06-04 (RUN*BEAM*BUSY*REV) SEM3
 2-06-05 (RUN*BEAM*BUSY*REV) #1 TELE 1*2*3
 2-06-06 (RUN*BEAM*BUSY*REV) #2 TELE 1*2*3
 2-06-07 (RUN*BEAM*BUSY*REV) PL1*PL2*PL3
 2-06-08 (RUN*BEAM*BUSY*REV) PL1*DLDP12*PL3
 2-06-09 (RUN*BEAM*BUSY*REV) PL3*PL4*PL7
 2-06-10 (RUN*BEAM*BUSY*REV) PL3*DLDP14*PL7
 2-07-00 (RUN*BEAM) NEUTRON #1
 2-07-01 (RUN*BEAM) NEUTRON #2
 2-07-02 (RUN*BEAM) NEUTRON #3
 2-07-03 (RUN*BEAM) NEUTRON #4
 2-07-04 (RUN*BEAM) NEUTRON #5
 2-07-05 (RUN*BEAM) NEUTRON #6
 2-07-06 (RUN*BEAM) NEUTRON #7
 2-07-07 (RUN*BEAM) NEUTRON #8
 2-07-08 (RUN*BEAM) NEUTRON #9
 2-07-09 (RUN*BEAM) NEUTRON #10
 2-07-10 (RUN*BEAM) NEUTRON #11
 2-07-11 (RUN*BEAM) SEM4
 2-08-01 (RUN*NORM) IC4
 2-08-02 (RUN*NORM) IC3
 2-08-03 (RUN*NORM) SEM3 (A+B)
 2-08-04 (RUN*NORM) PL1 SINGLES
 2-08-05 (RUN*NORM) PL2 SINGLES
 2-08-06 (RUN*NORM) PL3 SINGLES
 2-08-07 (RUN*NORM) PL4 SINGLES
 2-08-08 (RUN*NORM) SEM4
 2-08-09 (RUN*NORM) SEM3
 2-08-10 (RUN*NORM) #1 TELE 1*2*3
 2-08-11 (RUN*NORM) #2 TELE 1*2*3
 2-09-01 (RUN*REV) IC4
 2-09-02 (RUN*REV) IC3
 2-09-03 (RUN*REV) SEM3 (A+B)
 2-09-04 (RUN*REV) PL1 SINGLES
 2-09-05 (RUN*REV) PL2 SINGLES
 2-09-06 (RUN*REV) PL3 SINGLES
 2-09-07 (RUN*REV) PL4 SINGLES
 2-09-08 (RUN*REV) SEM4
 2-09-09 (RUN*REV) SEM3
 2-09-10 (RUN*REV) #1 TELE 1*2*3
 2-09-11 (RUN*REV) #2 TELE 1*2*3
 2-10-01 (RUN*BEAM*NORM) T1*DLDP12
 2-10-02 (RUN*BEAM*NORM) T1*T2
 2-11-00 (RUN*BEAM*REV) T1*T2
 2-11-01 (RUN*BEAM*REV) T1*DLDP12
 2-11-02 (RUN*BEAM*REV) T1*T2*EVENT
 2-12-00 (RUN*BEAM) NEUTRON #13
 2-12-01 (RUN*BEAM) NEUTRON #14
 2-12-02 (RUN*BEAM) NEUTRON #15
 2-12-03 (RUN*BEAM) NEUTRON #16
 2-12-04 (RUN*BEAM) NEUTRON #17
 2-12-05 (RUN*BEAM) NEUTRON #18
 2-12-06 (RUN*BEAM) NEUTRON #19
 2-12-07 (RUN*BEAM) NEUTRON #20
 2-12-08 (RUN*BEAM) NEUTRON #21
 2-12-09 (RUN*BEAM) NEUTRON #22

```

601.65,55.4,
BOX 1,
BOX 2,
BOX 3,
GATE 1,1,-1,
GATE 1,1,-1,
GATE 1,1,-1,
GATE 1,1,-1,
GATE 12,20,600,
GATE 13,20,600,
IOR,-1,1,
AND,-9,8,
AND,-8,9,
END,
CA,141,9900,10100,
CA,142,9900,10100,
CA,143,9900,10100,
CA,144,9900,10100,
CA,145,9900,10100,
CA,146,9900,10100,
BOX 4,
CA,239,9980,10020,
CA,240,9980,10020,
CA,181,13000,7000,
CA,181,13000,7000,
ICAT 1,
ICAT 2,
CA,160,7500,12500,
CA,148,9800,10200,
CA,162,7500,12500,
CA,150,9800,10200,
CA,193,9868,9956,
CA,193,9956,10044,
CA,193,10044,10132,
CA,193,9868,10132,
CA,193,9846,10153,
CA,193,9840,10254,
AND,1,8,
AND,1,9,
AND,14,15,16,17,36,
AND,14,15,16,17,37,
AND,20,21,38,
AND,20,21,39,
AND,40,19,
AND,41,19,
AND,15,16,17,36,
AND,14,16,17,36,
AND,14,15,17,36,
AND,14,15,16,36,
AND,15,16,17,37,
AND,14,16,17,37,
AND,14,15,17,37,
AND,14,15,16,37,
AND,42,24,
AND,43,24,
IOR,42,43,
END,
ICAT 3,
ICAT 4,
ICAT 5,
ICAT 6,
CA,203,7,87,
CA,203,263,343,
CA,203,519,599,
CA,203,765,845,
IOR,55,56,
IOR,57,58,
IOR,63,64,
AND,42,65,
AND,43,65,
AND,59,-55,
AND,60,-56,
AND,61,-57,
AND,62,-58,
IOR,52,53,
IOR,66,67,
AND,73,24,
END,
FINISH,

1165,1701EXP183POL.TST (MODIFIED FOR PFNBUT)
11 INSIDE BOX -- 1, PID
12 2
13 3
14 DUMMY
15 DUMMY
16 DUMMY
17 DUMMY
18 NORM P.H. SIGNAL
19 REV P.H. SIGNAL
110 LOOP 1 COUNTER
111 LOOP 1 COUNTER NORM
112 REV
113 CHMBR 1 CKSUM
114 2
115 3
116 4
117 5
118 6
119 ANGLE CUT==> X(185) VS ROTATED ANGLE (196)
120 DIFF. OF DRIFT CORR. POS. CH2,3
121 DRF DIFF 45 (+/- 2MM)
122 SPARE
123 SPARE
124 PEAK 1
125 2
126 CH2X
127 CH2Y
128 CH4X
129 CH4Y
130 SCATT ANGLE 1
131 2
132 3
133 4
134 5
135 FULL SCT ANGLE REGION 2 DEGREES
136 GOOD PID, NORM
137 GOOD PID, REV
138 PID, 2,3,4,5 CKSUMS, NORM
139 PID, 2,3,4,5 CKSUMS, REV
140 PID, 2-5 CKSMS 8DRIFT DIFF, NORM
141 PID, 2-5 CKSMS 8DRIFT DIFF, REV
142 GOOD EVENT ==> GOOD PID, CHMBRS, XANGLE, NORM
143 REV
144 ALL CHMBRS BUT 2, GOOD PID, NORM
145 3
146 ALL CHMBRS BUT 4, GOOD PID, NORM
147 ALL CHMBRS BUT 5, GOOD PID, NORM
148 ALL CHMBRS BUT 2, GOOD PID, REV
149 3
150 ALL CHMBRS BUT 4, GOOD PID, REV
151 ALL CHMBRS BUT 5, GOOD PID, REV
152 GOOD EVENT, PEAK 1, NORM
153 GOOD EVENT, PEAK 1, REV
154 GOOD EVENT, OR OF NORM AND REV
155 SINGLE HIT NEUTRON NORMAL
156 SINGLE HIT NEUTRON REV
157 SINGLE HIT PROTON NORMAL
158 SINGLE HIT PROTON REVERSE
159 NEUTRON COUNTER (NEUTRON NORMAL)
160 NEUTRON COUNTER (NEUTRON REVERSE)
161 NEUTRON COUNTER (PROTON NORMAL)
162 NEUTRON COUNTER (PROTON REVERSE)
163 NEUTRON SINGLE HIT
164 PROTON SINGLE HIT
165 SINGLE HIT (NEUTRON COUNTER)
166 GOOD EVENT, 1 HIT, NORM
167 GOOD EVENT, 1 HIT, REVERSE
168 MULTIPLE HIT (NEUTRON NORMAL)
169 MULTIPLE HIT (NEUTRON REVERSE)
170 MULTIPLE HIT (PROTON NORMAL)
171 MULTIPLE HIT (PROTON REVERSE)
172 GOOD EVENT, PEAK 1, NORM OR REV
173 GOOD EVENT, 1 HIT NORM OR REV
174 GOOD EVENT, PEAK 1, 1 HIT NORM OR REV

```

FILE=PPMBUFF2.DSP
 FRIE ALL
 H1=194,8500,11500,4
 T1=42
 H2=194,8500,11500,4
 T2=43
 H3=193,9500,10500,20
 T3=42
 H4=193,9500,10500,20
 T4=43
 H5=100,0,512,8
 T5=72
 H6=77,0,2048,10
 T6=74
 H7=78,0,2048,10
 T7=74
 H8=79,0,2048,10
 T8=74
 H9=80,0,2048,10
 T9=74
 H10=81,0,2048,10
 T10=74
 H11=82,0,2048,10
 T11=74
 H12=83,0,2048,10
 T12=74
 H13=84,0,2048,10
 T13=74
 H14=85,0,2048,10
 T14=74
 H15=86,0,2048,10
 T15=74
 H16=87,0,2048,10
 T16=74
 H17=88,0,2048,10
 T17=74
 H18=89,0,2048,10
 T18=74
 H19=90,0,2048,10
 T19=74
 H20=91,0,2048,10
 T20=74
 H21=92,0,2048,10
 T21=74
 H22=93,0,2048,10
 T22=74
 H23=94,0,2048,10
 T23=74
 H24=95,0,2048,10
 T24=74
 H25=96,0,2048,10
 T25=74
 H26=97,0,2048,10
 T26=74
 H27=98,0,2048,10
 T27=74
 H28=99,0,2048,10
 T28=74
 H29=203,0,2048,2
 T29=54

APPENDIX II

A DERIVATION OF THE EQUATIONS USED TO COMPUTE THE ANALYZING POWER AND ERROR WITH CORRECTIONS FOR A TARGET FLASK BACKGROUND

A derivation of the equations used to compute the analyzing power and error with background corrections is presented. The corrections to the analyzing power and error take into account empty target (target flask) backgrounds and errors associated with the measured beam polarization. The derived equations are used in the program ASYM12, listed in APPENDIX III.

Derivation of the Analyzing Power with Corrections for a Background
Generated by a Target Flask

The experimental cross sections with beam spin up (σ_+) and beam spin down (σ_-) for a target with analyzing power A_y are given by

$$\sigma_+ = (1 + A_y P_B) \frac{\sigma}{2} \quad (\text{II.1})$$

and

$$\sigma_- = (1 - A_y P_B) \frac{\sigma}{2} , \quad (\text{II.2})$$

where P_B is the beam polarization and σ is the total cross section. This may be written in terms of the normalized yield for beam spin up (N) and the normalized yield for beam spin down (R) as

$$N = (1 + A_y P_B) \frac{Y}{2} \quad (\text{II.3})$$

and

$$R = (1 - A_y P_B) \frac{Y}{2} , \quad (\text{II.4})$$

where Y is the total ($N + R$) normalized yield and is independent of

the beam polarization, P_B . By subtracting Equations II.3 and II.4, the difference in the normalized yields may be written as

$$N - R = A_y P_B Y . \quad (\text{II.5})$$

Similarly, if the yields for an empty flask run are measured, the analyzing power of the empty flask may be written in terms of the normalized yields as

$$A_{yE} = \frac{1}{P_E} \left(\frac{N_E - R_E}{N_E + R_E} \right) , \quad (\text{II.6})$$

where P_E is the beam polarization for the empty flask run and N_E and R_E are the normalized yields of the empty flask with beam spin up and beam spin down, respectively.

For an empty flask run in which the beam polarization is the same as that for the flask full run ($P_B = P_E$), the analyzing power of the flask may be written as

$$A_{yE} = \frac{1}{P_B} \frac{N'_E - R'_E}{N'_E + R'_E} , \quad (\text{II.7})$$

where $(N'_E + R'_E) = (N_E + R_E) = Y_E$. By equating Equations II.6 and II.7 we find that

$$N'_E - R'_E = \frac{P_B}{P_E} (N_E - R_E) , \quad (\text{II.8})$$

since the total normalized yields are equal. The analyzing power of the target may be obtained by subtracting the flask background yields as follows:

$$A_y = \frac{1}{P_B} \left(\frac{(N_T - N'_E) - (R_T - R'_E)}{(N_T + N'_E) + (R_T - R'_E)} \right) , \quad (\text{II.9})$$

or equivalently,

$$A_y = \frac{1}{P_B} \left(\frac{(N_T - R_T) - (N'_E - R'_E)}{(N_T + R_T) - (N'_E + R'_E)} \right) . \quad (\text{II.10})$$

This may be written in terms of the measured empty target yields N_E and R_E (i.e. no longer assuming that the beam polarizations of the target full and empty flask runs are equal) as

$$A_y = \frac{1}{P_T} \left(\frac{(N_T - R_T) - \frac{P_T}{P_E} (N_E - R_E)}{(N_T + R_T) - (N_E + R_E)} \right) , \quad (\text{II.11})$$

by using Equation II.8 and the identity $N_E + R_E = N'_E + R'_E$. Here P_T

is the beam polarization for the target full run. This then gives the analyzing power with the flask background subtracted.

The error in the background-corrected analyzing power given by Equation II.11 may be obtained by differentiating the equation to obtain the errors associated with each term and adding the errors in quadrature. If Equation II.11 is rewritten as

$$A_y = \frac{F}{P_T G} , \quad (\text{II.12})$$

then the error associated with the corrected analyzing power is given by

$$\Delta A_y = \text{SQRT} \left(\left(\frac{\Delta F}{P_T G} \right)^2 + \left(\frac{F \Delta G}{P_T G^2} \right)^2 + \left(\frac{F \Delta P_T}{P_T^2 G} \right)^2 \right) , \quad (\text{II.13})$$

where

$$F = (N_T - R_T) - \frac{P_T}{P_E} (N_E - R_E) ,$$

and

$$G = (N_T + R_T) - (N_E + R_E) .$$

Here ΔP_T is the uncertainty in the beam polarization for the target full run and ΔF and ΔG remain to be determined.

The uncertainties associated with F and G may be determined by calculating the uncertainties associated with each term in the expressions for F and G and then adding the errors in quadrature. The errors associated with each term are given by

$$\Delta(N_T + R_T) = \Delta(N_T - R_T) = \text{SQRT}((\Delta N_T)^2 + (\Delta R_T)^2) , \quad (\text{II.14a})$$

$$\Delta(N_E + R_E) = \Delta(N_E - R_E) = \text{SQRT}((\Delta N_E)^2 + (\Delta R_E)^2) , \quad (\text{II.14b})$$

and

$$\Delta\left(\frac{P_T}{P_E}\right) = \text{SQRT}\left(\left(\frac{\Delta P_T}{P_E}\right)^2 + \left(\frac{P_T \Delta P_E}{P_E^2}\right)^2\right) , \quad (\text{II.14c})$$

where

ΔN_T = Error in the normalized yield, target full, beam spin up,

ΔR_T = Error in the normalized yield, target full, beam spin down,

ΔN_E = Error in the normalized yield, empty flask, beam spin up,

ΔR_E = Error in the normalized yield, empty flask, beam spin down,

ΔP_T = Error in the beam polarization, target full,

ΔP_E = Error in the beam polarization, empty flask .

The errors associated with the variables F and G may now be written in terms of Equations II.14a-II.14c:

$$\Delta F = \text{SQRT}((\Delta N_T^2 + \Delta R_T^2) + (N_E - R_E)^2 \Delta \left(\frac{P_T}{P_E}\right)^2 + \left(\frac{P_T}{P_E}\right)^2 (\Delta N_E^2 + \Delta R_E^2)) \quad (\text{II.15a})$$

and

$$\Delta G = \text{SQRT}((\Delta N_T^2 + \Delta R_T^2) + (\Delta N_E^2 + \Delta R_E^2)) . \quad (\text{II.15b})$$

These expressions (Equations II.15a and II.15b), together with the expressions for F and G may now be substituted into Equation II.13 to obtain the expression for the error associated with the corrected analyzing power in terms of the uncertainties in the normalized yields and the uncertainties in the beam polarizations for the target full and empty flask runs.

APPENDIX III

A LISTING OF ASYMM2

A listing of the program ASYMM2 and the associated subroutines follows. The program was used to calculate the analyzing power and error using yields obtained from the recoil detection system.


```

150  FORMAT(12)
    IF (ICYC.EQ.24) ZZZ=-1.0
159  WRITE (3,160)
160  FORMAT (45H DO YOU WISH TO INPUT YIELD ERRORS? (Y/N) )
    READ (3,170,ERR=159,END=159)IYYY
170  FORMAT (A1)
    IF (IYYY.EQ.IY)XXX=1.0
179  WRITE (3,180)
180  FORMAT (45H DO YOU WISH TO SUM COUNTER YIELDS? (Y/N) )
    READ (3,190,ERR=179,END=179)IWWW
190  FORMAT(A1)
    IF (IWWW.EQ.IY)VVV=1.0
    IF (XXX.EQ.1.0) GO TO 340
195  WRITE (3,200)
200  FORMAT (49H TGT. IN FILE THAT CONTAINS YIELDS. IN FORMAT: )
    WRITE (3,210)
210  FORMAT (25H NNORM,NREV,PNORM,PREV )
    READ (3,220,ERR=195,END=195) NCHARB,(BFILE(1),I=1,NCHARB)
220  FORMAT (Q,80A1)
    OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=BFILE)
    J=1
230  READ (1,240,END=250) TGT(J,1),TGT(J,3),TGT(J,5),TGT(J,7)
240  FORMAT (4F10.0)
    J=J+1
    GO TO 230
250  CLOSE (UNIT=1)
    JMAX=J-1
255  WRITE (3,260)
260  FORMAT (50H TGT. OUT FILE THAT CONTAINS YIELDS. IN FORMAT: )
    WRITE (3,270)
270  FORMAT (25H NNORM,NREV,PNORM,PREV )
    READ (3,280,ERR=255,END=255) NCHARC,(CFILE(1),I=1,NCHARC)
280  FORMAT (Q,80A1)
    OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=CFILE)
    DO 300 J=1,JMAX
    READ (1,290,END=310) EMP(J,1),EMP(J,3),EMP(J,5),EMP(J,7)
290  FORMAT (4F10.0)
300  CONTINUE
310  CLOSE (UNIT=1)
    DO 330 I=1,JMAX
    DO 320 J=1,4
    K=(2*J)-1
    L=(2*J)
    TGT(I,L)=SQRT(TGT(I,K))
    EMP(I,L)=SQRT(EMP(I,K))
320  CONTINUE
330  CONTINUE
    GO TO 470
340  WRITE (3,350)
350  FORMAT (49H TGT. IN FILE THAT CONTAINS YIELDS. IN FORMAT: )
    WRITE (3,360)
360  FORMAT (39H NN,NNERR,NR,NRERR,PN,PNERR,PR,PRERR )
    READ (3,370,ERR=340,END=340) NCHARB,(BFILE(1),I=1,NCHARB)
370  FORMAT (Q,80A1)
    OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=BFILE)
    J=1
380  READ (1,390,END=400) TGT(J,1),TGT(J,2),TGT(J,3),TGT(J,4),TGT(J,5)
    1,TGT(J,6),TGT(J,7),TGT(J,8)
390  FORMAT (8F10.0)
    J=J+1
    GO TO 380
400  CLOSE (UNIT=1)
    JMAX=J-1

```

```

405 WRITE (3,410)
410 FORMAT (50H TGT. OUT FILE THAT CONTAINS YIELDS, IN FORMAT: )
WRITE (3,420)
420 FORMAT (39H NN,NNERR,NR,NRERR,PN,PNERR,PR,PRERR )
READ (3,430,ERR=405,END=405) NCHARC,(CFILE(1),I=1,NCHARC)
430 FORMAT (Q,80A1)
OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=CFILE)
DO 450 J=1,JMAX
READ (1,440, END=460) EMP(J,1),EMP(J,2),EMP(J,3),EMP(J,4)
1,EMP(J,5),EMP(J,6),EMP(J,7),EMP(J,8)
440 FORMAT (8F10.0)
450 CONTINUE
460 CLOSE (UNIT=1)
C
C
C ALL NEUTRON COUNTER YIELDS HAVE NOW BEEN READ IN
C
C
470 WRITE (3,480)
480 FORMAT (39H TGT. IN FILE THAT CONTAINS RUN DATA )
WRITE (3,490)
490 FORMAT (32H NCF,RCF,POL,POLERR,IC3N,IC3R )
READ (3,500,ERR=470,END=470) NCHAR,(FILE(1),I=1,NCHAR)
500 FORMAT (Q,80A1)
OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=FILE)
DO 520 I=1,6
READ (1,510, END=530)TCTFAC(I)
510 FORMAT (F11.4)
520 CONTINUE
530 CLOSE (UNIT=1)
535 WRITE (3,540)
540 FORMAT (40H TGT. OUT FILE THAT CONTAINS RUN DATA )
WRITE (3,550)
550 FORMAT (32H NCF,RCF,POL,POLERR,IC3N,IC3R )
READ (3,560,ERR=535,END=535) NCHAR,(FILE(1),I=1,NCHAR)
560 FORMAT (Q,80A1)
OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=FILE)
DO 580 I=1,6
READ (1,570, END=590) EMPFAC(I)
570 FORMAT (F11.4)
580 CONTINUE
590 CLOSE (UNIT=1)
C
C
C ALL DATA HAVE NOW BEEN READ IN AND WILL NOW DETERMINE WHICH
C DETECTORS ARE TO BE USED IN THE ASYMMETRY CALCULATIONS
C
C
595 WRITE (3,600)
600 FORMAT (46H FILE THAT CONTAINS DETECTOR #'S TO BE USED? )
READ (3,610,ERR=595,END=595) NCHAR,(AFILE(1),I=1,NCHAR)
610 FORMAT (Q,80A1)
OPEN (UNIT=1,TYPE='OLD',ACCESS='SEQUENTIAL',NAME=AFILE)
L=1
620 READ (1,630, END=640) KARRAY(L)
630 FORMAT (I2)
L=L+1
GO TO 620
640 CLOSE (UNIT=1)
LMAX=L-1
IF (VVV.EQ.0.0) GO TO 670
C
C IF TEST NOT PASSED, FOLLOWING ROUTINE SUMS SPECIFIED COUNTERS

```

```

C
DO 660 I=1,LMAX
J=KARRAY(I)
DO 650 L=1,8
STGT(I,L)=STGT(I,L)+TGT(J,L)
SEMP(I,L)=SEMP(I,L)+EMP(J,L)
650 CONTINUE
660 CONTINUE
C
C
C DETECTOR YIELDS HAVE NOW BEEN SUMMED
C
C CALL TO SUBROUTINE WHICH NORMALIZES YIELDS
C
C
N=1
CALL CORRECT (STGT,SEMP,TGTFAC,EMPFAC,N,CTGT,CEMP)
GO TO 690
670 DO 680 N=1,JMAX
CALL CORRECT (TGT,EMP,TGTFAC,EMPFAC,N,CTGT,CEMP)
680 CONTINUE
GO TO 700
C
C ALL YIELDS HAVE NOW BEEN NORMALIZED TO ION CHAMBER #3
C AND CORRECTED FOR DEAD TIMES,ETC.
C
C
N=1
690 CALL ASY (CTGT,CEMP,TGTFAC,EMPFAC,N,ZZZ,AY)
GO TO 720
700 DO 710 M=1,LMAX
N=KARRAY(M)
CALL ASY (CTGT,CEMP,TGTFAC,EMPFAC,N,ZZZ,AY)
710 CONTINUE
GO TO 730
720 CALL ASYE (CTGT,CEMP,TGTFAC,EMPFAC,N,AYERR)
GO TO 741
730 DO 740 M=1,LMAX
N=KARRAY(M)
CALL ASYE (CTGT,CEMP,TGTFAC,EMPFAC,N,AYERR)
740 CONTINUE
GO TO 861
741 WRITE (2,742) ICYC
742 FORMAT (T5,'CYCLE=',T13,I2,/)
L=NCNARB-4
WRITE (2,743) (BFILE(I), I=1,L)
743 FORMAT (T5,'TARGET IN RUN=',T21,<L>A1,/)
L=NCNARC-4
WRITE (2,744) (CFILE(I), I=1,L)
744 FORMAT (T5,'EMPTY FLASK RUN=',T23,<L>A1,///)
750 WRITE (2,755)
755 FORMAT (53H ASYMMETRY CALCULATION FOR THE SUM OF COUNTER #'S: )
WRITE (2,760) (KARRAY(I), I=1,LMAX)
760 FORMAT (<LMAX>I3,/)
WRITE (2,765)
765 FORMAT (T30,'TARGET IN',T55,'EMPTY FLASK',/)
WRITE (2,770) TGTFAC(1),EMPFAC(1)
770 FORMAT (T3,'NORM CORR FACTOR',T31,F6.4,T57,F6.4)
WRITE (2,775) TGTFAC(2),EMPFAC(2)
775 FORMAT (T3,'REV CORR FACTOR',T31,F6.4,T57,F6.4)
WRITE (2,780) TGTFAC(3),TGTFAC(4),EMPFAC(3),EMPFAC(4)
780 FORMAT (T3,'BEAM POLARIZATION',T27,F5.4,'+/-',F5.4,T53,F5.4,'+
1/-',F5.4)

```

```

      WRITE (2,785) TGTFC(5),EMPFAC(5)
785   FORMAT (T3,'RUN*NORM IC3',T30,F8.0,T55,F8.0)
      WRITE (2,790) TGTFC(6),EMPFAC(6)
790   FORMAT (T3,'RUN*REV IC3',T30,F8.0,T55,F8.0,/)
      WRITE (2,795)
795   FORMAT (T21,'TARGET IN COUNTER YIELDS',/)
      WRITE (2,800)
800   FORMAT (T2,'COUNTER',T15,'NEUTRON(NOR)',T29,'NEUTRON(REV)',T43
1,'PROTON(NOR)',T56,'PROTON(REV)')
      DO 820 I=1,JMAX
      WRITE (2,810) I,TGT(1,1),TGT(1,3),TGT(1,5),TGT(1,7)
810   FORMAT (T5,12,T13,F10.0,T27,F10.0,T41,F10.0,T54,F10.0)
820   CONTINUE
      WRITE (2,828)
828   FORMAT(/)
      WRITE (2,830)
830   FORMAT (T21,'EMPTY FLASK COUNTER YIELDS',/)
      WRITE (2,800)
      DO 840 I=1,JMAX
      WRITE (2,810) I,EMP(1,1),EMP(1,3),EMP(1,5),EMP(1,7)
840   CONTINUE
      WRITE (2,828)
      WRITE (2,850)
850   FORMAT (T25,'CORRECTED ASYMMETRIES')
      WRITE (2,855)
855   FORMAT (T15,'NEUTRON',T40,'PROTON')
      WRITE (2,860) AY(1,1),AYERR(1,1),AY(1,2),AYERR(1,2)
860   FORMAT (T11,F6.4,'+/-',F6.4,T37,F6.4,'+/-',F6.4)
      GO TO 900
861   WRITE (2,862) ICYC
862   FORMAT (T5,'CYCLE=',T13,12,/)
      L=NCHARB-4
      WRITE (2,863) (BFILE(I), I=1,L)
863   FORMAT (T5,'TARGET IN RUN=',T21,<L>A1,/)
      L=NCHARC-4
      WRITE (2,864) (CFILE(I), I=1,L)
864   FORMAT (T5,'EMPTY FLASK RUN=',T23,<L>A1,/)
865   WRITE (2,870)
870   FORMAT (T3,'ASYMMETRY CALCULATION FOR COUNTER #S:')
      WRITE (2,875) (KARRAY(I), I=1,LMAX)
875   FORMAT (<LMAX>13,/)
      WRITE (2,765)
      WRITE (2,770) TGTFC(1),EMPFAC(1)
      WRITE (2,775) TGTFC(2),EMPFAC(2)
      WRITE (2,780) TGTFC(3),TGTFC(4),EMPFAC(3),EMPFAC(4)
      WRITE (2,785) TGTFC(5),EMPFAC(5)
      WRITE (2,790) TGTFC(6),EMPFAC(6)
      WRITE (2,795)
      WRITE (2,800)
      DO 880 I=1,JMAX
      WRITE (2,810) I,TGT(1,1),TGT(1,3),TGT(1,5),TGT(1,7)
880   CONTINUE
      WRITE (2,828)
      WRITE (2,830)
      WRITE (2,800)
      DO 885 I=1,JMAX
      WRITE (2,810) I,EMP(1,1),EMP(1,3),EMP(1,5),EMP(1,7)
885   CONTINUE
      WRITE (2,828)
      WRITE (2,850)
      WRITE (2,887)
887   FORMAT (T2,'COUNTER',T25,'NEUTRON',T45,'PROTON')

```