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POLARIZATION TRANSFER COEFFICIENTS AT E(D) = 6 MEV FOR THE CHARGE SYMMETRIC TRITON (POLARIZED DEUTERON, POLARIZED NEUTRON) HELIUM-4 AND HELIUM-3 (POLARIZED DEUTERON, POLARIZED PROTON) HELIUM-4 REACTIONS

The Ohio State University

Ph.D. 1981

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POLARIZATION TRANSFER COEFFICIENTS AT $E_d = 6$ MeV FOR THE
CHARGE SYMMETRIC $^2\text{H}(\vec{d},\vec{n})^4\text{He}$ and $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ REACTIONS

DISSERTATION

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

By
Rocco Detomo, Jr., B.S., M.S.

The Ohio State University
1981

Reading Committee:
Professor T. R. Donoghue
Professor H. J. Hausman
Professor R. N. Boyd
Professor R. G. Seyler

Approved by

Advisor
Department of Physics
To my parents
Rocco and Barbara Detomo, Sr.
Whose example and confidence
have been my motivation.
ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my advisor, Dr. T. R. Donoghue, for his guidance and assistance in the completion of this dissertation. The contributions of time and effort by my fellow students, H.W. Clark, T. Rinckel, J. Brown and K. Sale in the maintenance and operation of the polarized ion source and in the acquisition of the data for this experiment are also deeply appreciated.

I would also like to thank the entire staff of the Van de Graaff Accelerator Laboratory for their assistance and numerous helpful suggestions. Special thanks are extended to Mr. R.L. Johnson, Mr. H. Dyke and Mr. B. Samuels for their personal interest and support during the experiment's course.

I would like to express a special appreciation to my parents whose encouragement was paramount throughout the period of my education. Finally, the greatest of praise and thanks go to my wife, Julie, whose understanding, assistance and love allowed this work to be completed.
VITA

September 13, 1952 ...... Born - Syracuse, New York

June, 1970 ............... Graduated with honors, Satellite
Beach H.S., Satellite Beach, Florida

December, 1973 .......... B.S. cum laude in Physics, The Ohio
State University, Columbus, Ohio

1974 - 1976 ............. Graduate Teaching Associate., De-
partment of Physics, The Ohio State
University, Columbus, Ohio

March, 1976 ............. M.S. (Physics), The Ohio State
University, Columbus, Ohio

1976 - 1981 ............. Graduate Research Associate, De-
partment of Physics, The Ohio State
University, Columbus, Ohio

June, 1981 .............. Ph.D. (Nuclear Physics), The Ohio
State University, Columbus, Ohio

PUBLICATIONS

"Analyzing Power Measurement for the 4-nucleon System below

"Analyzing Power Measurement for p-\(^3\)He Elastic Scattering
from 1.75 to 4.50 MeV," R. Detomo, Jr., H.W. Clark, L.J.
Dries, J.L. Regner and T.R. Donoghue, Nuclear Physics A313,
269 (1979).

"Comparison of Analyzing Powers for the Charge Symmetric
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I. INTRODUCTION

A complete investigation of a nuclear reaction would involve measurements of cross sections and all polarization observables, including polarization, analyzing powers, polarization transfer coefficients, and spin correlation parameters. Cross sections, involving only a single scattering, are the least difficult of these measurements and are usually the first process by which one explores the nuclear interaction. However, nuclear systems which exhibit more complicated behavior, such as when states overlap or when several reaction mechanisms are present, require more detailed information such as can be provided by "double-scattering like" experiments, (i.e. polarization and analyzing powers), or even "triple-scattering like" experiments, (i.e. polarization transfer coefficients and spin correlation parameters). While these "triple-scattering like" experiments would be expected to provide unique information, very few of these measurements have as yet been made due to their experimental difficulty.

The $A=5$ system exhibits broad and overlapping states in the energy region $E_x=18$ to $25$ MeV and has already been explored at this laboratory through "double-scattering like"
measurements, (Dr 79c). These measurements, together with the results of previous work on the A=4 system participated in by this author, (Dr 78a, De 79a, Do 79b) motivated the measurement of polarization transfer coefficients for the charge symmetric reactions $^3\text{He}(^3\text{He},^3\text{He})^4\text{He}$ and $^3\text{H}(^3\text{He},^3\text{He})^4\text{He}$.\(^1\) Observed differences between observables of these reactions are discussed within the context of charge symmetry of the nuclear force.

Charge symmetry in mirror nuclei was first investigated through beta decay by Fowler et al. (Fo 36a). Mirror nuclei offer a particularly attractive testing ground for an investigation of charge symmetry of the nuclear force. When exact charge symmetry holds, the differential cross section and polarization observables of the mirror reactions will be identical; however charge symmetry can only be expected for the hadronic force in the absence of all electromagnetic effects, (He 66a, He 69b). Of these, coulomb effects can only be taken into account theoretically, and therefore charge symmetry can only be tested to the extent that this consideration can be carried out in a suitable model, (Ja 50a, Fo55a, He 60a, He 67a). Because coulomb effects are reduced in light nuclear systems, these systems can provide an interesting way to explore charge symmetry.

1) The arrow notation indicates that the polarization of that particular nucleus is determined in the reaction.
One attempt to investigate charge symmetry in light nuclear systems was a recent study of the A=4 system at this laboratory by Dries et al. (Dr 78a) who measured analyzing powers for the D(d,n)^3He and D(d,p)^3H reactions from 1.5 to 4.0 MeV. While the vector $A_y$, and tensor, $1/2(A_{xx} - A_{yy})$, analyzing powers of the two reactions were nearly identical from 2 to 4 MeV, the tensor analyzing powers $A_{zz}$ and $A_{xz}$ differed substantially in the two reactions over the entire energy range. Although some differences are explored in the two reaction's observables due to coulomb effects, the observed differences were so large as to raise the question whether coulomb effects would be sufficient to account for the differences. Hardekopf et al. (Ha 72a) proposed an ad-hoc way of taking these coulomb effects into consideration by comparing polarization observables at equal exit channel energies. The measurements of Dries et al. (Dr 78a), however, showed conclusively that this ad-hoc method is not correct. To further determine whether the differences in these charge symmetric reactions merely arise from coulomb effects requires a complete charge-independent R-matrix analysis of the mass 4 system such as has been undertaken by Dodder and Hale, (Do 75h) at Los Alamos.

Because of these interesting effects in the A=4 system, particularly in the tensor analyzing powers, a similar comparison was begun in the A=5 system. This work began
with the comparisons of $A_{zz}(0^\circ)$ in the mirror reactions $^3\text{H}(^3\text{He},n)^4\text{He}$ and $^3\text{He}(^3\text{He},p)^4\text{He}$ between 1 and 6 MeV by Dries et al. (Dr 79c). The energy dependence of $A_{zz}(0^\circ)$ was similar in both reactions showing large differences at energies below 1.65 MeV, but identical magnitudes, (as would be anticipated from charge symmetry) above that energy. However, in the energy region from 4 to 8 MeV large differences surprisingly reappear. Although differences at low energies may be attributed to coulomb effects associated with the very low energy $J^\pi = 3/2^+$ resonance which occurs at slightly different energies in the two reactions and which dominates these reactions here, there are no simple explanations yet at hand for the reappearance of the observed differences at higher energies. These large differences prompted the development of a more detailed investigation of these reactions through both analyzing power measurements and the present polarization transfer coefficient measurements. Clark et al. (Cl 80b) recently completed measurements of angular distributions of vector and tensor analyzing powers over the energy range 3-6 MeV. Although he observed differences in the analyzing powers between the charge symmetric reactions at many energies and angles, these differences were found to be considerably smaller than those anticipated from the zero degree $A_{zz}$ measurement of Dries et al. (Dr 79c).
Beyond the interesting aspects of charge symmetry in the mirror reactions, the 5 nucleon system is beset by uncertainties in its level structure. The latest energy tabulation (Aj 79d) shows systems with positive parity states near 17 MeV and 20 MeV excitation, with $J^\pi$ assignments of $3/2^+$ and $(3/2^+ \text{ or } 5/2^+)$ respectively, (Figure I-1). However, theoretical models suggest more complicated structure here, and recent experimental work, (see Aj 79d), has indicated both additional positive and negative parity states in the region 18 to 25 MeV excitation; but because the levels are broad and overlapping, their existence, identification and properties are still very unclear.

The shell model for the mass 5 system has systematically predicted a large number of positive parity states of the 1p-1h (1 particle - 1 hole) type in this energy range, (Go 6&c, Ra 70e, Wa 71q). Although this model is useful in predicting spins, parities and possible configurations of excited states in the mass 5 system, the meaningfulness of these predictions are sometimes questioned because of the unbound character of these states. The shell model does however describe the character of the observed normal parity states in this energy range, i.e. $3/2^+$, $1/2^+$, and $(3/2^+ \text{ or } 5/2^+)$; and, in addition, predicts the existence of four to six other states, (Figure I-2). Although the non-normal-parity of the ground state ($J^{\pi}=3/2^-$) and first excited state ($J^{\pi}=1/2^-$) are obtained with particle-hole interactions, the
Figure I-1  Energy level structure of $^5$Li and $^5$He,
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<td>$\frac{1}{2}^+$</td>
</tr>
</tbody>
</table>

**Figure I-2**
usual shell model configurations do not predict other negative parity states in the region 18 to 25 MeV excitation. However, usual shell model calculations suffer from a basic restriction in that the test-function space is truncated to configurations with at most two clusters, one of which is constrained to be an elementary particle, and thus states with more complicated configurations may not be predicted, (Ma 69d).

More recently, microscopic cluster model calculations using resonating group theory have been applied to study scattering and reactions involving very light nuclei, (Fi 78d). In the resonating group method, choice of the proper cluster structure of the system leads to wave functions which correctly predict measured observables. Recent calculations using this model applied to the mass 5 system, have been performed by Heiss and Hackenbroich, (He 70d, He 71a) and Chwieroth et al. (Ch 73l, Ch 74g). The earlier calculations by Heiss and Hackenbroich, (He 71a) suggest a quartet of $L=2$, $S=3/2$ states at about 20 MeV, with two ($L=1$, $S=1/2$, 3/2) negative parity states from three-body break-up via an intermediate $\alpha^*-p$ structure, (where $\alpha^*$ is the first excited state, $J^\pi = 0^+$, of $^4$He).

However, the more recent calculations by Chwieroth et al. (Ch 73l, Ch 74g) predict that above the well known 3/2$^+$ resonance at 16.7 MeV, there should be a quartet of $S=1/2$ states ($L=0,1,2,3$) but only a single $L=2$, $S=3/2$ state.
Calculations indicating these negative parity states were prompted by measurements of the d-\(^3\)H elastic scattering of Killian et al. (Ki 71b), and were later given support by the three-body break-up measurements of \(^3\)He + \(^2\)H \to p + p + t from 18.6 to 22.4 MeV by Schröder, et al. (Sc 76a). A re-evaluation of the data, (Po 63b) of the \(^3\)H(d,n)pt reaction by Fick (Fi 78d) showed evidence for the analogous resonance in \(^5\)He. The negative parity level can be regarded as a replication of the ground state built upon the \(\alpha^*\) cluster instead of the \(\alpha\) cluster. Since one of the main components of the \(\alpha^*\) (\(J^\pi=0^+\)) wave function has to be a 2p-2h, (2 particle - 2 hole) component, the configuration of these states may be regarded as having partly two holes in the 1s shell. Furthermore, Schröder et al. (Sc 76a) and Fick (Fi 78d) have tentatively identified at least one state at around \(E_x \approx 20\) MeV as having \(J^\pi = 3/2^-\) from examining results of three-body break-up interactions.

Therefore, to further explore charge symmetry and complex structures in the mass 5 system, we have undertaken to measure polarization transfer coefficients for the \(^3\)He(\(\vec{d},\vec{p}\))\(^4\)He and \(^3\)H(\(\vec{d},\vec{n}\))\(^4\)He reactions. The connection between models and experiment is represented by the reaction matrix elements that can only be practically determined by polarization and correlation experiments for nuclei with spin. Polarization transfer coefficients should be most useful in exploring these systems because a
description of them involves different and somewhat more selective combinations of matrix elements than do usual polarization observables. These "triple-scattering" observables should provide increased sensitivity to any symmetry breaking interactions which could be present, and may also offer a more sensitive test for model calculations.

The formalism for describing polarization transfer coefficients $K_{j}^{k'}(\Theta)$ in nucleon-nucleon scattering was first used by Schumacher and Bethe (Sc 61d) and was greatly expanded to reactions of $1/2 + \uparrow \rightarrow 1/2 + 0$ spin structure by Ohlsen (Oh 72e) and Keaton et al. (Ke 74e). For the latter reaction, the subscript "j" represents the vector or tensor component of incident deuteron polarization, and the superscript "k" represents the vector component of the outgoing particle polarization. The measurement of a polarization transfer coefficient involves a classic triple-scattering experiment determining the effect of initial polarization on final polarization in a given scattering process. The initial polarization is generated by either a scattering or by a polarized ion source; the second scattering, which is the one of interest, explores how that spin is affected by the interaction; and the third scattering analyzes the outgoing nucleon polarization. Although the equations which describe the reaction process are discussed thoroughly in section II, it is instructive here to tabulate all the transfer coefficients which describe a
reaction with the above spins, and define their value in terms of the elements of the relevant 6 x 2 dimensional $M$ (scattering) matrix. Figure I-3 defines the appropriate $M$ matrix and tabulates the twenty different possible observables, including one cross section, five analyzing powers, one polarization, and thirteen polarization transfer coefficients.

Because measuring a polarization transfer coefficient at our facility involves the use of an incident polarized beam whose intensity seldom exceeds 250 nA, followed by two scatterings, count rates for this type of experiment are low, ranging from 10 to 100 counts per hour depending upon the reaction cross section. Consequently the measurement of a data point with a reasonable statistical uncertainty ($\leq 0.05$) requires one to four days of beam time. Because each data point requires such a long period of measurement time, an evaluation of which coefficients might return the greatest amount of new information was made. We considered which coefficients, together with existing measurements, would yield independent information and could be done with available facilities. For these reasons, and others detailed in sections II and III, two vector polarization transfer coefficients, $(K^x_L, K^y_L)$, and one tensor polarization transfer coefficient, $(K^y_{zz})$, were selected. Practical considerations with respect to the reaction cross section restricted the measurements to the forward quadrant, and
The appropriate M matrix for the $1/2^+(1/2)0$ reaction. The twenty different observables are expressed in terms of six complex numbers $A, B, C, D, E, F$. For convenience, the factor that enters as a multiplier of each term when the cross section or polarization expressions are written is entered as the last row of the table (taken from Ke 74e).
Observables for $\gamma(d,\delta)d$

<table>
<thead>
<tr>
<th>Outgoing Beam Spin of particle</th>
<th>$I$</th>
<th>$P_x$</th>
<th>$P_y$</th>
<th>$P_z$</th>
<th>$P_{xy}$</th>
<th>$P_{xz}$</th>
<th>$P_{yz}$</th>
<th>$P_{xx}$</th>
<th>$P_{yy}$</th>
<th>$P_{zz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I(0)$</td>
<td></td>
<td>$-4\Im CE^*$</td>
<td>$-4\Im DF^*$</td>
<td>$-5\Re CE^*$</td>
<td>$2(AA^<em>BB^</em>+CC^<em>PP^</em>+EE^<em>FF^</em>)$</td>
<td>$6I_A$</td>
<td>$6I_Ay$</td>
<td>$6I_Az$</td>
<td>$6I_Ax$</td>
<td>$6I_Ay$</td>
</tr>
<tr>
<td>$P_x I(0)$</td>
<td></td>
<td>$4\Re BF^*$</td>
<td>$-4\Re BD^*$</td>
<td>$-5\Re AC^*$</td>
<td>$-6\Re AE^*$</td>
<td>$6I_sx^y$</td>
<td>$6I_sx^z$</td>
<td>$6I_sy^x$</td>
<td>$6I_sy^z$</td>
<td>$6I_sz^x$</td>
</tr>
<tr>
<td>$P_y I(0)$</td>
<td></td>
<td>$4\Re AB^*$</td>
<td>$+4\Im CD^*$</td>
<td>$-5\Im CE^*$</td>
<td>$-6\Im EF^*$</td>
<td>$+4\Re BF^*$</td>
<td>$+4\Im CF^*$</td>
<td>$+4\Re AE^*$</td>
<td>$+4\Im BF^*$</td>
<td>$+4\Re AB^*$</td>
</tr>
<tr>
<td>$P_z I(0)$</td>
<td></td>
<td>$-4\Re BE^*$</td>
<td>$+4\Im AF^*$</td>
<td>$-5\Re AD^*$</td>
<td>$-6\Re AF^*$</td>
<td>$-6\Re BE^*$</td>
<td>$-6\Im CD^*$</td>
<td>$-6\Im EF^*$</td>
<td>$-6\Re BF^*$</td>
<td>$-6\Re AD^*$</td>
</tr>
<tr>
<td>Factor</td>
<td>1</td>
<td>$3/2$</td>
<td>$3/2$</td>
<td>$3/2$</td>
<td>$2/3$</td>
<td>$2/3$</td>
<td>$1/3$</td>
<td>$1/3$</td>
<td>$1/3$</td>
<td>$1/3$</td>
</tr>
</tbody>
</table>
all data were measured at $E_d = 6.0$ MeV, within the energy region of comparisons and proposed level structures discussed above. Predictions of observables made available by Dodder and Hale (Ha 80e) from their calculations with a charge independent $R$-matrix were of great assistance in selecting the most promising angles of measurement.
II. POLARIZATION TRANSFER COEFFICIENTS: THEORY

The formalism for polarization transfer coefficients for the special case of $^3$He($d,p)^4$He and $^5$H($d,n)^4$He is discussed in general by Ohlsen (Oh 72e) and in detail by Keaton et al. (Ke 74e). From their equations, the method of measurement most suitable for the determination of each polarization transfer coefficient can be determined. The important results of rather tedious calculations derived from the work of Keaton et al. (Ke 74e) will be summarized below.

II-A. Polarization Transfer Equations

In general, three vector quantities are necessary to describe the coordinates of a nuclear process. These are commonly taken to be $\vec{k}_{\text{in}}$, $\vec{k}_{\text{out}}$ and their cross product ($\vec{k}_{\text{in}} \times \vec{k}_{\text{out}}$). As shown in Figure II-1, the $\hat{y}$ axis is chosen parallel to the normal vector ($\vec{k}_{\text{in}} \times \vec{k}_{\text{out}}$) and the $\hat{z}$ axis is chosen along $\vec{k}_{\text{in}}$, when describing the polarization of outgoing particles. The unprimed coordinate system in Figure II-1 is commonly referred to as the projectile helicity frame, and the primed system is the outgoing particle helicity frame. The spin quantization axis of the beam is the unit vector $\hat{S}$. Then the angle between $\hat{S}$ and $\vec{k}_{\text{in}}$ is defined to be $\beta$ and the angle between
Figure II-1  Polarization transfer coefficient measurement; projectile and outgoing particle helicity coordinate frames.
Figure II-1
The example in Figure II-1 shows scattering left as it was in this experiment.

Relations for the cross section $I(\theta, \phi)$ and outgoing nucleon polarization in the projectile helicity frame are then given by (Ke 74e):

\begin{equation}
I(\theta, \phi) = I_c(\theta) \left[ 1 + \frac{3}{2} p_y A_y(\theta) + \frac{2}{3} p_{xz} A_{xz}(\theta) \\
+ \frac{1}{3} p_{xx} A_{xx}(\theta) + \frac{1}{3} p_{yy} A_{yy}(\theta) + \frac{1}{3} p_{zz} A_{zz}(\theta) \right]
\end{equation}

\begin{align*}
p_x I(\theta, \phi) &= I_c(\theta) \left[ \frac{3}{2} p_x K^x_x(\theta) + \frac{3}{2} p_z K^z_z(\theta) \\
&\quad + \frac{2}{3} p_{xy} K^x_{xy}(\theta) \right] \\
p_y I(\theta, \phi) &= I_c(\theta) \left[ \frac{3}{2} p_y K^y_y(\theta) + \frac{2}{3} p_{yz} K^y_{yz}(\theta) \\
&\quad + \frac{1}{3} p_{xx} K^y_{xx}(\theta) \right] \\
p_z I(\theta, \phi) &= I_c(\theta) \left[ \frac{3}{2} p_x K^z_x(\theta) + \frac{3}{2} p_z K^z_z(\theta) \\
&\quad + \frac{2}{3} p_{xy} K^z_{xy}(\theta) \right]
\end{align*}

where

\begin{align*}
p_x &= -p_s \sin \beta \sin \phi \\
p_y &= p_s \sin \beta \cos \phi \\
p_z &= p_s \cos \beta
\end{align*}
\[ p_{xx} = \frac{1}{2} (3 \sin^2 \varphi \sin^2 \phi - 1)p_{ss} \]
\[ p_{yy} = \frac{1}{2} (3 \sin^2 \varphi \cos^2 \phi - 1)p_{ss} \]
\[ p_{zz} = \frac{1}{2} (3 \cos^2 \varphi - 1)p_{ss} \]
\[ p_{xy} = -\frac{3}{4} \sin^2 \varphi \sin 2\phi \ p_{ss} \]
\[ p_{yz} = \frac{3}{4} \sin 2\varphi \cos \phi \ p_{ss} \]
\[ p_{xz} = -\frac{3}{4} \sin 2\varphi \sin \phi \ p_{ss} \] 

Above, \( I_o(\Theta) \) is the unpolarized cross section; \( A_i(\Theta) \) are the analyzing powers; \( P^Y(\Theta) \) is the outgoing polarization function; and \( K_{ij}^{k}(\Theta) \) are the polarization transfer coefficients. \( p_s \) and \( p_{ss} \) are the respective vector and tensor beam polarizations produced in the polarized ion source. Three additional constraint equations can be used to reduce the equations to other forms:

\[ p_{xx} + p_{yy} + p_{zz} = 0 \]
\[ A_{xx}(\Theta) + A_{yy}(\Theta) + A_{zz}(\Theta) = 0 \]
\[ K_{xx}^{Y}(\Theta) + K_{yy}^{Y}(\Theta) + K_{zz}^{Y}(\Theta) = 0 \] 

If \( N_x, N_y, \) and \( N_z \) are defined to be the number of times \( x, y, \) and \( z \) respectively appear in a coefficient, then a term is parity even (odd) if \( N_x + N_y \) is even (odd). Any term in equation (1) will go to zero at \( \Theta = \Theta^0 \) if its parity is odd.

For some particular combinations of \( \varphi \) and \( \phi \), these equations simplify considerably:
[[(\Theta)_{\mathcal{A}}^{xx,k}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

[[(\Theta)_{\mathcal{A}}^{xx,k}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

[[(\Theta)^{xx,v}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

\[\bar{\mathcal{R}} = \* \bar{\mathcal{R}} = \bar{\mathcal{R}}^*\]

Case III

\[0 = (0,^*\Theta)I^{\mathcal{A}d}\]

[(\Theta)_{\mathcal{A}}^{xx,k}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

[[(\Theta)^{xx,v}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

\[\bar{\mathcal{R}} = \* \bar{\mathcal{R}} = \bar{\mathcal{R}}^*\]

Case II

\[0 = (0,^*\Theta)I^{\mathcal{A}d}\]

[(\Theta)_{\mathcal{A}}^{xx,k}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

[[(\Theta)^{xx,v}SSdZ/\mathcal{I} + (\Theta)_{\mathcal{A}}^d] (\Theta)^{\circ}I = (0,^*\Theta)I^{\mathcal{A}d}]

\[\bar{\mathcal{R}} = \* \bar{\mathcal{R}} = \bar{\mathcal{R}}^*\]

Case I

\[0 = (0,^*\Theta)I^{\mathcal{A}d}\]
\[
\left[ (\Theta)_{\varepsilon}^{\varepsilon} \right]_{x}^{s_{d}} z/I + \\
(\Theta)_{\varepsilon}^{s_{d}} \eta/\varepsilon \Theta^0 I = (\varepsilon^{0 \varepsilon} \Theta) I_{x}^{z_{d}}
\]

\[
\left[ (\Theta)^{s_{d}} V^{s_{d}} \eta/I - \\
(\Theta)^{x_{d}} V^{s_{d}} \eta/\varepsilon + I \right] (\Theta)^0 I = (\varepsilon^{0 \varepsilon} \Theta) I
\]

\[
\frac{\varepsilon}{\varepsilon} = \phi^{0 \varepsilon} = \varepsilon
\]

Case V

\[
\left[ (\Theta)^{x_{d}} V^{s_{d}} z/I - \\
(\Theta)^{x_{d}} V^{s_{d}} \eta/\varepsilon + (\Theta)^{x_{d}} \right] (\Theta)^0 I = (\varepsilon^{0 \varepsilon} \Theta) I_{x}^{z_{d}}
\]

\[
\left[ (\Theta)^{s_{d}} V^{s_{d}} z/I - \\
(\Theta)^{x_{d}} V^{s_{d}} \eta/\varepsilon \right] (\Theta)^0 I = (\varepsilon^{0 \varepsilon} \Theta) I_{x}^{z_{d}}
\]

\[
\left[ (\Theta)^{s_{d}} V^{s_{d}} \eta/I + \\
(\Theta)^{x_{d}} V^{s_{d}} \eta/\varepsilon + I \right] (\Theta)^0 I = (\varepsilon^{0 \varepsilon} \Theta) I
\]

\[
\frac{\varepsilon}{\varepsilon} = \phi^{0 \varepsilon} = \varepsilon
\]

Case IV

\[
\left[ (\Theta)^{x_{d}} V^{s_{d}} z/\varepsilon \right] (\Theta)^0 I = (0 \varepsilon \Theta) I_{x}^{z_{d}}
\]
\[ p_y, I(\theta, 0^\circ) = I_o(\theta)[P^V(\theta) + 3\sqrt{2}/4 \, p_S K_y^{y'}(\theta) - 1/4 \, p_{SS} K_{xx}^{y'}(\theta)] \]

\[ p_z, I(\theta, 0^\circ) = I_c(\theta)[3\sqrt{2}/4 \, p_S K_z^{z'}(\theta) + 1/2 \, p_{SS} K_{yz}^{z'}(\theta)] \] (8)

Case VI. \( \beta = 45^\circ, \Phi = 90^\circ \)

\[ I(\theta, 90^\circ) = I_o(\theta)[1 - 1/2 \, p_{SS} A_{xz}(\theta) - 1/4 \, p_{SS} A_{yy}(\theta)] \]

\[ p_x, I(\theta, 90^\circ) = I_o(\theta)[-3\sqrt{2}/4 \, p_S K_x^{x'}(\theta) + 3\sqrt{2}/4 \, p_b K_z^{x'}(\theta)] \]

\[ p_y, I(\theta, 90^\circ) = I_o(\theta)[P^V(\theta) - 1/2 \, p_S K_x^{y'} - 1/4 \, p_{SS} K_{yx}^{y'}(\theta)] \]

\[ p_z, I(\theta, 90^\circ) = I_o(\theta)[3\sqrt{2}/4 \, p_b K_x^{z'}(\theta) - 3\sqrt{2} \, p_S K_z^{z'}(\theta)] \] (9)

Each case above serves to help isolate one or more polarization observables. Those observables that are best measured for each case above are summarized in Table II-1.
TABLE II-1

<table>
<thead>
<tr>
<th>Case</th>
<th>Isolated Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>$A_{zz}(\theta)$, $P_y^x(\theta)$, $K_x^{xx}(\theta)$, $K_y^{yy}(\theta)$, $K_z^{zz}(\theta)$</td>
</tr>
<tr>
<td>Case II</td>
<td>$A_y(\theta)$, $A_{yy}(\theta)$, $K_y^{yy}(\theta)$, $K_y^{yy}(\theta)$</td>
</tr>
<tr>
<td>Case III</td>
<td>$A_{xx}(\theta)$, $K_x^{xx}(\theta)$, $K_x^{xx}(\theta)$, $K_z^{zz}(\theta)$</td>
</tr>
<tr>
<td>Case IV</td>
<td>$K_{xy}(\theta)$, $K_{xy}(\theta)$</td>
</tr>
<tr>
<td>Case V</td>
<td>$K_{yz}(\theta)$, $K_{yz}(\theta)$</td>
</tr>
<tr>
<td>Case VI</td>
<td>$A_{xz}(\theta)$, $K_y^{xz}(\theta)$</td>
</tr>
</tbody>
</table>

Measuring a $p_z$, component of polarization, (underlined terms in Table II-1), would require a dipole magnet which is currently not available at this laboratory, hence, further discussion will be limited to measurements involving only $I(\Theta, \phi)$, $p_x(\Theta, \phi)$, and $p_y(\Theta, \phi)$. For the reasons discussed in Chapter I and later in this chapter, only cases I and II were explored in this experiment.

A secondary beam made up of spin 1/2 particles with a transverse polarization $p$ has a cross section for scattering from a target nucleus (2) given by

$$I_\alpha(\Theta, \phi) = I_{e\alpha}(\Theta, \phi)[1 + A_\alpha(\Theta)^2 \cdot \mathbf{p} \cdot \mathbf{n}]$$ (10)
where $I_{c_\alpha}(\Theta_\alpha)$ is the unpolarized cross section at angle $\Theta_\alpha$, $A_{\alpha}(\Theta_\alpha)$ is the analyzing power of the target, and $\hat{n}$ is a unit vector along $(\vec{k}_{in_\alpha} \times \vec{k}_{out_\alpha})$. The angle $\phi_\alpha$ is the angle between $\vec{p}$ and $\hat{n}$; i.e., $p \cdot n = |p| \cos \phi_\alpha$.

If the particle "side" detectors are located at $\phi_\alpha$ with respect to the secondary beam momentum direction, then $\vec{p} \cdot \hat{n} = -p_x$, for scattering up; $\vec{p} \cdot \hat{n} = +p_x$, for scattering down; and $\vec{p} \cdot \hat{n} = +p_y$, for scattering left and $\vec{p} \cdot \hat{n} = -p_y$, for scattering right. The yield in a given "side" detector is then:

\[
top \quad U(\Theta) = N \xi_{\alpha} I_{\alpha}(\Theta) \left[ 1 - \frac{p_x \cdot I(\Theta, \phi)A_{\alpha}(\Theta)}{I(\Theta, \phi)} \right]
\]

\[
bottom \quad D(\Theta) = N \xi_{\beta} I_{\alpha}(\Theta) \left[ 1 + \frac{p_x \cdot I(\Theta, \phi)A_{\alpha}(\Theta)}{I(\Theta, \phi)} \right]
\]

\[
left \quad L(\Theta) = N \xi_{\xi} I_{\alpha}(\Theta) \left[ 1 + \frac{p_y \cdot I(\Theta, \phi)A_{\alpha}(\Theta)}{I(\Theta, \phi)} \right]
\]

\[
right \quad R(\Theta) = N \xi_{\delta} I_{\alpha}(\Theta) \left[ 1 - \frac{p_y \cdot I(\Theta, \phi)A_{\alpha}(\Theta)}{I(\Theta, \phi)} \right]
\]

(11)

where $N$ is a constant depending upon charge integration only, and the $\xi$'s include associated detector efficiencies, solid angles and other constants which will remain the same during a measurement provided the detector remains stationary. One can then combine equations (1), (2) and
(3) with (11) to calculate the yields in the detectors as a function of incident deuteron spin.

For the spin system $1/2 + \uparrow \rightarrow 1/2 + 0$, as we have for the reactions of interest here, the scattering matrix takes a rather simple form, (dimension $6 \times 2$) and clearly involves 11 independent numbers, i.e. six complex numbers but the overall phase is irrelevant. Therefore, measurement of 11 independent observables would be required to completely describe the reaction. The problem of determining which experiments are necessary for a complete determination of the scattering amplitudes has been discussed by Simonius, (Si 70f). He states that, "If the particles in the reaction (incoming and outgoing taken separately) can be divided into two sets such that no polarization correlation is known between a particle from the first and one from the second set, then the measurements are not complete." Thus, for experiments such as $^3\text{He}(d,p)^4\text{He}$ or $^3\text{H}(d,n)^4\text{He}$, where three particles have nonzero spin, one cannot completely determine the scattering matrix from measurements of the $^3\text{He}(d,p)^4\text{He}$ reaction alone, (i.e., connecting $\vec{d}$ and $\vec{p}$); one must make a measurement connecting $^3\text{He}$ and $\vec{d}$ or $^3\text{He}$ and $\vec{p}$. Therefore one must use additionally either: a) a polarized deuteron beam incident on a polarized $^3\text{He}$ target and measure appropriate cross section ratios, (i.e. $^3\text{He}(d,p)^4\text{He}$).
or b) an unpolarized deuteron beam on a polarized $^3\text{He}$ target and measure the outgoing proton polarization, (i.e. $^3\text{He}(d,p)^4\text{He}$). However, the problem then remains as to which measurements in the $1/2 + \uparrow \rightarrow 1/2 + 0$ system, though not complete, form an independent set. By extensive algebraic manipulation of the quadratic relations which relate observables involved in this system, one may determine up to ten independent observables. Which ten one chooses to form the independent set is somewhat at one's discretion, subject to various restrictions; these details are discussed in Appendix A. One particularly attractive set consists of:

$$I_0, p_y', A_y, A_{xz}, (A_{xx} - A_{yy})/2, A_{zz},$$

$$K_x', K_y', (K_{xx} - K_{yy})/2, K_{zz}'.$$

This set is particularly useful because it involves relatively simple combinations of $B$ and $\phi$, and makes use of the more commonly measured vector and tensor analyzing powers which were measured at this laboratory by Clark (Cl 80c). This set of ten observables, though not complete, represents the maximum information available from the polarization transfer reaction $1/2 + \uparrow \rightarrow 1/2 + 0$, and involves now only four additional explicit measurements.
Although extensive measurement of these four transfer coefficients would have been desirable, the set of measured observables was reduced further to $K^x_z(\Theta)$, $K^y_y(\Theta)$ and $K^y_{zz}(\Theta)$ by time and experimental restrictions delineated in Chapter III. While these measurements will not completely determine the scattering matrix for these reactions, they can be expected to provide important information not available from analyzing power measurements alone.

II-B. Method of Measurement

Measurement of each transfer coefficient dictates an optimum method for the experimental apparatus available. Because of reasons discussed above, measurements were made of three polarization transfer coefficients; specifically, $K^x_z(\Theta)$, $K^y_y(\Theta)$, $K^y_{zz}(\Theta)$. The procedure used to measure each of these is described below.

1. Measurement of $K^x_z(\Theta)$

For the measurement of $K^x_z(\Theta)$ one fixes $\beta = \phi = 0^\circ$, and since the coefficient of $K^x_z(\Theta)$ is a vector polarization, it was convenient to measure this transfer coefficient with a beam which is vector polarized only. Then equation...
(11) reduces to
\[ U_+ (\Theta) = N_1 \varepsilon_u I_2 (\Theta_a) \left[ 1 - 1.5 p_s K_Z^X (\Theta) A_2 (\Theta_a) \right] \]
\[ D_+ (\Theta) = N_1 \varepsilon_d I_2 (\Theta_a) \left[ 1 + 1.5 p_s K_Z^Y (\Theta) A_2 (\Theta_a) \right] \] (12)

If one also makes the same measurements with the polarization off, then
\[ U_0 (\Theta) = N_2 \varepsilon_u I_2 (\Theta_a) \]
\[ D_0 (\Theta) = N_2 \varepsilon_d I_2 (\Theta_a) \] (13)

By forming the ratio defined by
\[ R_1 \equiv \frac{U_0 D_+ - D_0 U_+}{U_0 D_+ + D_0 U_+} \] (14)

one observes that \( R_1 \) is charge integration, (N's), and detector characteristics, (\( \varepsilon \)'s), independent, and
\[ R_1 = 1.5 p_s K_Z^X (\Theta) A_2 (\Theta_a). \]

The uncertainty in \( R_1 \) is given by
\[ \Delta R_1 = \frac{4 (U_0 D_0 U_+ D_+)}{(1/U_0 + 1/D_0 + 1/U_+ + 1/D_+)^{1/2}} \]
\[ (U_0 D_+ + D_0 U_+)^2 \] (15)

One particular advantage of this method is that the detectors remain fixed in position and require no exchange of identities, which eliminates geometrical errors that can arise if not done with a high degree of accuracy. The disadvantages relate directly to the uncertainties associated with the measurement. In particular, \( \approx 40\% \) more counts need to be collected in this type of measurement than one where a proper spin flip (i.e., rotation of the proton
polarimeter about $k_{in}$ could be executed, for an equivalent uncertainty.

The usual experimental procedure typically involves collecting data for $K_{x}^{*}(\Theta)$ for small amounts of charge, interspersed with beam polarization measurements every couple of hours. The $K_{z}^{*}(\Theta)$ spectra were resummed during an off-line analysis. The stability of the polarization could also be monitored by analysis of the transmission detector spectra for the $^3\text{He}(d,p)^4\text{He}$ experiment, by the ungated neutron spectra for $^3\text{H}(d,n)^4\text{He}$. A data point would take anywhere from 25 to 100 continuous hours of collection.

2. Measurement of $K_{y}^{*}(\Theta)$

For the measurement of $K_{y}^{*}(\Theta)$ fixes $\phi = -90^\circ$, $\phi = 0^\circ$, and again since the coefficient of $K_{y}^{*}(\Theta)$ is a vector polarization, it was convenient to measure this transfer coefficient with an only vector polarized beam. Then equation (11) reduces to

$$L_{+}^{*}(\Theta) = N_{1}\epsilon_{L}I_{a}(\Theta)\left[1 + (P_{y}^{*}(\Theta) - 1.5p_{S}K_{y}^{*}(\Theta))A_{a}(\Theta)\right]/(1 - 1.5p_{S}A_{y}(\Theta))$$

$$R_{+}^{*}(\Theta) = N_{1}\epsilon_{R}I_{a}(\Theta)\left[1 - (P_{y}^{*}(\Theta) - 1.5p_{S}K_{y}^{*}(\Theta))A_{a}(\Theta)\right]/(1 - 1.5p_{S}A_{y}(\Theta))$$

A similar measurement with an unpolarized beam yields

$$L_{0}^{*}(\Theta) = N_{2}\epsilon_{L}I_{a}(\Theta)\left[1 + P_{y}^{*}(\Theta)A_{a}(\Theta)\right]$$
\[ R_0(\Theta) = N_\alpha \varepsilon_{R_\alpha}(\Theta_\alpha)(1 - p^{Y'}(\Theta)A^{(0)}(\Theta_\alpha)) \]  

(17)

Then forming the same ratios as one did for \( K_z^{Y'}(\Theta) \) gives

\[ R_\alpha \equiv (R_0L_+ - L_0R_+)/R_0L_+ + L_0R_+ \]  

(18)

then

\[ R_\alpha = (G^{Y'}(\Theta) - p^{Y'}(\Theta))A_\alpha(\Theta_\alpha)/(1 - p^{Y'}(\Theta)A_\alpha(\Theta_\alpha)) \]

\[ \Delta R_\alpha = 4(L_0R_0L_+R_+)(1/R_0 + 1/R_0 + 1/L_+ + 1/R_+)/ \]

\[ (R_0L_+ + L_0R_+) \]

(19)

where

\[ G^{Y'}(\Theta) = (p^{Y'}(\Theta) - 1.5p^S_k^{Y'}(\Theta))/(1 - 1.5p^S_k^{Y'}(\Theta)) \]  

(20)

then one may solve for

\[ -1.5p^S_k^{Y'}(\Theta)A_\alpha(\Theta_\alpha) = (1 - 1.5p^S_k^{Y'}(\Theta))R_\alpha + p^{Y'}(\Theta)A_\alpha(\Theta_\alpha)/(1 + R_\alpha p^{Y'}(\Theta)A_\alpha(\Theta_\alpha)) - p^{Y'}(\Theta)A_\alpha(\Theta_\alpha) \]  

(21)

and also solve for the corresponding uncertainty.

3. Measurement of \( K_z^{Y'}(\Theta) \)

For the measurement of \( K_z^{Y'}(\Theta) \) one fixes \( \beta = \phi = 0^\circ \) and since the coefficient of \( K_z^{Y'}(\Theta) \) is a tensor polarization, one uses a tensor polarized beam. Although there exists a vector polarized component to the beam as well, at \( \beta = 0^\circ \)
it does not contribute to the yield here. Then equation (11) reduces to

\[
L_+ (\Theta) = N_1 \xi L A_\alpha (\Theta) \left[ 1 + \left( p^y (\Theta) + 0.5 p_{ss} K_{zz}^y (\Theta) \right) A_\alpha (\Theta) \right] / \\
\left( 1 + 0.5 p_{ss} A_{zz} (\Theta) \right)
\]

\[
R_+ (\Theta) = N_1 \xi R A_\alpha (\Theta) \left[ 1 - \left( p^y (\Theta) + 0.5 p_{ss} K_{zz}^y (\Theta) \right) A_\alpha (\Theta) \right] / \\
\left( 1 + 0.5 p_{ss} A_{zz} (\Theta) \right)
\]  \hspace{1cm} (22)

One may also measure yields with an unpolarized beam 
\((L_o (\Theta), R_o (\Theta))\); and with the tensor polarization reversed 
\((L_-(\Theta), R_- (\Theta))\). These measurements give

\[
L_o (\Theta) = N_2 \xi L A_\alpha (\Theta) \left[ 1 + p^y (\Theta) A_\alpha (\Theta) \right]
\]

\[
R_o (\Theta) = N_2 \xi R A_\alpha (\Theta) \left[ 1 - p^y (\Theta) A_\alpha (\Theta) \right]
\]  \hspace{1cm} (23)

\[
L_- (\Theta) = N_3 \xi L A_\alpha (\Theta) \left[ 1 + \left( p^y (\Theta) - 0.5 p_{ss} K_{zz}^y (\Theta) \right) A_\alpha (\Theta) \right] / \\
\left( 1 - 0.5 p_{zz} A_{zz} (\Theta) \right)
\]

\[
R_- (\Theta) = N_3 \xi R A_\alpha (\Theta) \left[ 1 - \left( p^y (\Theta) - 0.5 p_{ss} K_{zz}^y (\Theta) \right) A_\alpha (\Theta) \right] / \\
\left( 1 - 0.5 p_{ss} A_{zz} (\Theta) \right)
\]  \hspace{1cm} (24)

Then forming the ratio \(R_3\) defined by

\[
R_3 = 2R_+ R_- / (R_- - R_+)
\]  \hspace{1cm} (25)

where

\[
R_\pm = (L_\pm R_o - R_\pm L_o) / (L_\pm R_o + R_\pm L_o)
\]  \hspace{1cm} (26)
gives rise to the expressions

\[ R_3 = \frac{0.5p_{ss}A_z(\theta_a)(k_{zz}^Y(\theta) - p^Y(\theta)A_{zz}(\theta))}{(1 - (p^Y(\theta)A_z(\theta_a))^2)} \]

\[ \Delta R_3 = 2R_-R_+((R_-\Delta R_+/R_+)^2 + (R_+\Delta R_-/R_-)^2)\sqrt{2}/(R_- - R_+)^2 \]  \hspace{1cm} (27)

4. Measurement of \( A_{zz}(0^\circ) \)

For the measurement of \( A_{zz}(0^\circ) \) one fixes \( \Theta = \Phi = 0^\circ \). A series of three runs is made with the following states of polarization giving the yield at \( \Theta = 0^\circ \), (from equation (1)), listed below:

<table>
<thead>
<tr>
<th>TABLE II-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 MHz</td>
</tr>
<tr>
<td>ON</td>
</tr>
<tr>
<td>OFF</td>
</tr>
<tr>
<td>OFF</td>
</tr>
</tbody>
</table>

From these three measurements, one can now calculate \( p_{ss}A_{zz}(0^\circ) \) three different ways, any two of which are independent.

\[ p_{ss}A_{zz}(0^\circ) = 2\left[\frac{Y_+}{Y_0} - 1\right] \]

\[ p_{ss}A_{zz}(0^\circ) = -2\left[\frac{Y_-}{Y_0} - 1\right] \]

\[ p_{ss}A_{zz}(0^\circ) = 2\left[\frac{(Y_+ - Y_-)}{(Y_+ + Y_-)}\right] \]  \hspace{1cm} (28)
After each measurement, consistency among the results was a requirement, (agreement within statistical error bars), before the measurement of a polarization transfer coefficient would resume. The beam tensor polarization over the length of the experiment was typically $p_{ss} = 0.78$, and never varied more than $\Delta p_{ss} = \pm 0.005$ during any particular measurement.
III. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment was performed using a primary deuteron beam produced from the Ohio State University polarized ion source in conjunction with the Super-CN model 7MV Van de Graaff accelerator. This deuteron beam was then magnetically focused, analyzed and directed either to a rotatable scattering chamber, where charge particle work could be done, or to an experimental neutron area. Data were collected using an IBM 1800 computer, (in conjunction with a nuclear data ND100 multichannel analyzer), and a Tennelec eight-stretcher ADC system, and stored on magnetic disk. The beam polarization was monitored using $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)^4\text{He}$ reaction previously calibrated by the isospin forbidden $^1\omega 0(d,\alpha)^7\text{He}$ reaction at this laboratory.

III-A Polarized Ion Source

The Ohio State University polarized ion source has been described in detail earlier by Donoghue et al. (Do 75b) and Regner (Re 76f), with most recent modifications described by Dries (Dr 78c). The polarized ion source is unique in that it produces beams of polarized protons and deuterons and operates within the pressurized...
high voltage terminal of the 7MV Van de Graaff accelerator. This location limits the size and power that the source can consume, and requires many custom designed mechanical and electrical components for functional operation. The physical dimensions of the source and its accompanying electronics are limited by the 1.7 meter high by 0.9 meter diameter high voltage dome; and the total power available is provided by the belt driven 4kW 400 Hz alternator within the high voltage dome.

The basic components of the source are depicted in Figure III-1 and consist briefly of:

1. A free running, 20-30 MHz dissociator oscillator inductively coupled to a freon-cooled double jacketed dissociator bottle to produce an atomic deuteron (hydrogen) beam.

2. A 13.3 cm long sextupole magnet which produces a Stern-Gerlach separation of the hyperfine states of the atomic beam. This short sextupole is not long enough to complete the separation of these states, but in fact leaves a mixture of approximately 10% of the particles in unwanted states. This is currently the longest permissible size due to our space limitations, and the limiting factor on our polarization magnitude.
Figure III-1  Diagram of the Ohio State University
Polarized Ion Source.
Figure III-1
3. The rf transitions unit, (Bu 71f) is housed external to the vacuum system, (Dr 78c) and operates on the beam through a quartz tube (8 mm ID x 12mm OD x 20 cm long) which is relatively transparent to our operating frequencies. The unit is made up of the following:

i) A 348 MHz oscillator loop in a medium permanent magnetic field of uniform gradient (97-113 gauss) which inverts the populations of state 3 and 5, (Figure III-2), in the hyperfine structure of deuterium. Our measurements indicates that this transition is $\approx 100\%$ effective.

ii) An 8 MHz oscillator loop in a weak permanent magnetic field of uniform gradient (7.8-9.8 gauss) which follows the 348 MHz transition unit and will interchange populations of states with equal $F$ and opposite $m_f$ quantum numbers. When used alone the 8 MHz unit produces purely vector polarized deuterons and when used in conjunction with the 348 MHz unit, it will reverse the sign of both the tensor and vector deuteron polarization.

4. A strong solenoidal field (~1000 gauss) ionizer, based on the concept of Glavish et al. (Gl 68a)
Figure III-2  Zeeman hyperfine splitting of Atomic Deuterium through the sextupole magnet.
Figure III-2

\[ \Delta E = 1.34 \times 10^{-6} \, \text{eV} \]

\[ m_I \quad m_J \quad m_F \]

\begin{align*}
(1) & \quad +1 \quad +\frac{1}{2} \quad +\frac{3}{2} \\
(2) & \quad 0 \quad +\frac{1}{2} \quad +\frac{1}{2} \\
(3) & \quad -1 \quad +\frac{1}{2} \quad -\frac{1}{2} \\
(4) & \quad -1 \quad -\frac{1}{2} \quad -\frac{3}{2} \\
(5) & \quad 0 \quad -\frac{1}{2} \quad -\frac{1}{2} \\
(6) & \quad +1 \quad -\frac{1}{2} \quad +\frac{1}{2} \\
\end{align*}
which contains an electron cloud that ionizes the atomic deuterium beam leaving the polarization intact. Since this ionizer is one of our prime limiting factors concerning beam intensity, many variations and combinations of fields and extraction voltages were tried in an attempt to increase its efficiency. The extraction voltage is applied to the entire ionizer assembly. This voltage accelerates the ion beam from the ionization volume into a three element einzel lens which focuses the beam in the center of the spin precession unit which follows. Some increase in beam intensity was noted as the extractor voltage was increased. Currently the extractor is set at 6 kV.

5. A spin precession unit, or Wien filter, which consists of crossed E and B fields and is capable of precessing the spin vector of 6 keV deuterons by \( \geq 100^\circ \). In addition, the entire assembly can be rotated about the beam direction to aid in varying the azimuthal spin angle \( \phi \) at the target (see section III-B).
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6. An electrostatic main lens element (0-80 kV) to match the ion optics to the accelerator optics.

The polarized source is physically divided into four isolated vacuum chambers, each cylindrical for ease in self-alignment. Chamber 1 houses the dissociator bottle assembly and operates at vacuums approaching $\sim 1 \times 10^{-4}$ torr when a gas load of 300-500 microns is kept in the dissociator bottle. This relatively large gas flow (0.1 g/sec) is pumped by a titanium sublimation pump (TSP) which is affixed to Chamber 1 via a 14 cm diameter port. This pump, which was developed at this lab and is described by McEver et al. (Me 75d), consumes only $\sim 400-500$ watts and pumps $\sim 3000-4000$ liters/sec. Tests at this lab have shown that vacuums worse than $10^{-4}$ torr in Chamber 1 shorten the mean free path of the atomic beam enough to significantly affect the intensity of the beam.

Chamber 2 is isolated from Chamber 1 by a 8mm diameter hole which isolates the two vacuum systems. Chamber 2 houses the 6-pole Stern-Gerlach separation magnet. This chamber is also pumped by a TSP in combination with an ion pump through a 10 cm diameter port, and maintains a vacuum of about $\sim 1 \times 10^{-6}$ torr. This chamber is connected via a 20 cm long quartz tube to Chamber 3.

Chamber 3 houses the ionizer assembly. The quartz tube isolates Chamber 3 from the large gas loads of the top
portion of the source. A combination TSP and ion pump identical to that on Chamber 2 maintains this region at vacuums typically \( \sim 5 \times 10^{-8} \) torr, although vacuums approaching \( 5 \times 10^{-10} \) torr may be reached after a few weeks. This high vacuum is required because any background gases (hydrogen) that exist in this chamber will be ionized and become an unpolarized component to the ion beam, thus diluting the effective beam polarization. In addition, poorer vacuums affect the operational characteristics of the ionizer seriously enough to significantly reduce the intensity of the beam.

Chamber 4 contains the extractor and einzel lens assembly and Wien filter. It is pumped by a TSP and ion pump combination similar to 2 and 3 but about half the physical size. Tests showed that this TSP was necessary to help isolate Chamber 3 from the poorer vacuum in the accelerator tube (\( \sim 3 \times 10^{-7} \) torr) and minimize background beams. This is followed by the main lens assembly which protrudes into the accelerator tube and is connected to the first three electrodes of the accelerator tube.

III-B. Magnitude and Orientation of Spin Vector

The polarized ion source is operated to produce tensor and vector polarized beams or vector only polarized beams
whose polarization vectors are oriented for optimum measurement of a particular coefficient at the target. In order to determine which components of the spin vector are present at the target, a detailed examination of the origin and orientation of the polarization of the deuterium beam is necessary. The beam's vector and tensor polarization magnitude is determined by the sextupole magnet and rf transitions. The spin vector's orientation at the target is adjusted with the Wien filter in the polarized ion source taking into consideration the precession of the spin vector whenever the beam's momentum direction is changed. A more detailed discussion of these facts is presented below.

1. The magnitude of the deuterium beam's vector and tensor polarization produced within the source depends upon the relative population of the hyperfine states shown in Figure III-2. The sextupole magnet "focuses" states of \( m_J = \frac{1}{2} \) and "defocuses" states of \( m_J = -\frac{1}{2} \). Ideally, only states 1, 2, and 3 remain populated, but due to the non-optimum length of the magnet, states 4, 5, and 6 retain \( \sim 10\% \) of their original population. The vector and tensor polarization of the deuterium beam are defined by:
where \( N(M_\| = +1) \) is the number of atoms in the \( M_\| = +1 \) state and so forth for \( M_\| = -1 \) and \( M_\| = 0 \).

To produce a polarization, we must invert populations between the populated and relatively unpopulated states. The 348 MHz medium field transition inverts the populations of states 3 and 5, the 8 MHz weak field transition inverts populations of pairs of states; 1 and 4, 2 and 3, and 5 and 6. With the following definitions,

\[ \alpha \equiv \% \text{ deuterons remaining in states 4, 5, and 6} \]
\[ \Delta \equiv \% \text{ efficiency of weak field transition} \]
\[ \Gamma \equiv \% \text{ efficiency of medium field transition} \]
\[ \eta \equiv (1 - \alpha)/(1 + \alpha) \]

the following table of source polarization versus rf transitions used may be derived:

\[
\begin{align*}
\text{p}_s &= \frac{N(M_\| = +1) - N(M_\| = -1)}{N(M_\| = +1) + N(M_\| = 0) + N(M_\| = -1)} \\
\text{p}_{ss} &= \frac{N(M_\| = +1) - 2N(M_\| = 0) + N(M_\| = -1)}{N(M_\| = +1) + N(M_\| = 0) + N(M_\| = -1)}
\end{align*}
\]
TABLE III-1

<table>
<thead>
<tr>
<th>Medium Field Transition</th>
<th>Weak Field Transition</th>
<th>Vector Polarization $p_s$</th>
<th>Tensor Polarization $p_{ss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OFF</td>
<td>ON</td>
<td>$-2\eta\Delta/3$</td>
<td>0</td>
</tr>
<tr>
<td>ON</td>
<td>OFF</td>
<td>$\eta\Gamma/3$</td>
<td>$-1\eta\Gamma$</td>
</tr>
<tr>
<td>ON</td>
<td>ON</td>
<td>$\eta(2\Delta-\Gamma)/3$</td>
<td>$1\eta\Gamma(2\Delta-1)$</td>
</tr>
</tbody>
</table>

Since $\eta$ appears linearly in each value of polarization, the incomplete separation of states in the sextupole magnet serves only to reduce the ultimate value of the beam's polarization components from 100%. For these experiments the value of $p_s$ for a vector polarized only beam, (i.e. 348 MHz is off, 8 MHz is on) was inferred from measurement of $p_{ss}$ for the tensor polarized beam, (i.e. 348 MHz on, 8 MHz off; and 348 MHz on, 8 MHz on) from which the value of "$\Delta$" could be determined. The value of "$\Delta$" measured throughout this experiment was determined to be $0.998 \pm 0.005$. As mentioned before "$\Gamma$" was already determined to be very close to 1.0 ("$\Gamma$" = 0.993 ± 0.009), and so the polarization of a vector polarized only beam could be implied to be $-\frac{2}{3}$ of the measured tensor.
polarization. The uncertainties associated with the above numbers were propagated into the final results.

2. The Wein filter determines the orientation of the spin vector as the ion beam leaves the polarized ion source and ultimately determines its orientation at the target. As the deuterium beam leaves the ionizer and enters the Wien filter its spin vector is oriented in the $\hat{z}'$ direction along the beam's momentum direction, (Figure III-3). The Wien filter's fields may then precess the polarization axis an amount away from the $\hat{z}'$ axis, $\delta$, in a plane defined to be perpendicular to the planes of the Wien filter (the $\hat{y}'-\hat{z}'$ plane is defined to be the same as the $\hat{y}-\hat{z}$ plane). Then $\delta$ is the angle between the deuteron's momentum direction and its spin vector $\vec{S}'$. The angle $\chi$ is defined to be the angle between the $\hat{y}'-\hat{z}'$ plane and the $\vec{S}'-\hat{z}'$ plane. Then the cartesian components of polarization upon exiting the polarized ion source are:

$$ S_x' = S \sin \delta \sin \chi $$

$$ S_y' = S \sin \delta \cos \chi $$

$$ S_z' = S \cos \delta $$

(32)
Figure III-3  Polarized ion source and target coordinate systems. The primed coordinate system is at the exit to the polarized ion source, and the unprimed coordinate system is at the target. The $\hat{y}'-\hat{z}'$ plane is defined to be the same as the $\hat{y}-\hat{z}$ plane.
where \( S \) is the initial polarization vector magnitude. One should point out here that the magnitude of \( S \) is proportional to the electric field strength on the E-field plates, and that \( \gamma \) is the angle between the E-field plates and the \( \hat{y}'-\hat{z}' \) plane. Both of these are adjustable parameters in the polarized ion source.

In the analyzing magnet, the magnetic field couples to the magnetic moment of the particle and precesses the spin an amount, \( \mathcal{N} \), given by the ratio of the deuteron's cyclotron frequency to its Larmor precession frequency:

\[
\mathcal{N} = \Omega \frac{\mu m}{2 I m_p} \tag{33}
\]

where \( \mathcal{N} \) is the momentum's angle of rotation and is equal to \( \pi/2 \), \( \mu \) is the magnetic moment of the deuteron, and \( m \) and \( I \) are its mass and spin respectively, \( (m_p \) is the protons mass). For deuterons \( \mathcal{N} = 77.1^\circ \). At the target is the unprimed coordinate system. Here, \( \phi \) is the angle between \( \vec{S} \), the spin vector, and \( \hat{z} \), the beam's momentum direction. The angle \( \phi \) is the angle between the \( \hat{y}-\hat{z} \) plane and the \( \vec{S}-\hat{z} \) plane. Then, the components of the spin at the target can be related to those
at the polarized ion source by the rotation transformation given by:

\[ S_x = S_x' \]
\[ S_y = S_y, \sin \alpha - S_z, \cos \alpha \]
\[ S_z = S_y, \cos \alpha + S_z, \sin \alpha \quad (34) \]

These equations imply a relationship between the pair of angles \( \beta \) and \( \phi \), and the pair of angles \( \xi \) and \( \gamma \) given by:

\[ \sin \beta \sin \phi = \sin \xi \sin \gamma \]
\[ \sin \beta \cos \phi = \sin \xi \cos \gamma \sin \alpha - \cos \xi \cos \alpha \]
\[ \cos \beta = \sin \xi \cos \gamma \cos \alpha + \cos \xi \sin \alpha \quad (35) \]

Combinations of \( \beta \) and \( \phi \) which can be accurately reached limit the components of spin that one is sensitive to at the target. The combinations tabulated below are useful to isolate observables important in this experiment.
From Table III-2 it is clear that cases b), c) and d) require a rotation of the azimuthal spin angle "\( \chi \)" in the polarized ion source. Although the Wien filter may be physically rotated, there is currently no accurate remote rotation system available. Cases other than a) would each require an iterative procedure to accurately calibrate the Wien filter position. This procedure would be lengthy but possible. However, once the Wien filter position is changed away from "\( \delta = 0^\circ \)," accurately measuring the beam's polarization magnitude becomes considerably more difficult since an orientation of \( \beta = \phi = 0^\circ \) is no longer obtainable. For these reasons, only those coefficients that could be measured with case a) were attempted, (i.e. \( K_x^X(\Theta) \), \( K_y^Y(\Theta) \), and \( K_{zz}^Y(\Theta) \)).

<table>
<thead>
<tr>
<th>Case</th>
<th>( \beta )</th>
<th>( \phi )</th>
<th>( \delta )</th>
<th>( \chi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>( \ell )</td>
<td>0</td>
<td>( \pi/2 - \pi + \ell )</td>
<td>0; for all angles ( \ell )</td>
</tr>
<tr>
<td>b)</td>
<td>( \pi/2 )</td>
<td>( \pi/2 )</td>
<td>( -\pi/2 )</td>
<td>( \pi/2 )</td>
</tr>
<tr>
<td>c)</td>
<td>( \pi/4 )</td>
<td>( \pi/2 )</td>
<td>0.810 rad</td>
<td>-1.351 rad</td>
</tr>
<tr>
<td>d)</td>
<td>( \pi/2 )</td>
<td>( 3\pi/4 )</td>
<td>-1.411 rad</td>
<td>0.798 rad</td>
</tr>
</tbody>
</table>

\( K_z^X(\Theta) \)
III-C. Ion Beam Transport

Since the ion beam produced in the ionizer is physically larger than from a standard rf ion source, (and the polarized source beam intensity is much lower, $\sim 500 \text{ nA}$ at the analyzing magnet), special steps have been taken to maintain or improve the optical quality of the beam. The ion beam is transported from the accelerator tube to the target as shown in Figure III-C, which displays the relative positions of the focusing and steering magnets involved, beam defining slits, diagnostic beam scanners and experimental areas. These are discussed in more detail below.

1. A quadrupole doublet focusing magnet at the exit of the accelerator tube guides the beam into the analyzing magnet. This quadrupole is fixed in space at the base of the accelerator tube. It is useful to align the magnetic center of the quadrupole with the beam axis and eliminate any residual beam steering effects. Volkers (Vo 74f) built a system to move the magnetic center of the quadrupole away from geometric center by a current imbalance in the magnet coils. This allows the magnetic field to be adjusted concentric to the deuterium ion beam. Steering magnets at the exit of the analyzing magnet realign the beam through
Figure III-4  Diagram of the beamline components, showing magnets, slits and detector areas.
the beam line quadrupole doublet. Another set of steering magnets are conveniently positioned after the quadrupole to allow one to direct the beam through the center of the scattering chamber to the end of the beam line.

2. The polarized deuterium beam ($^2\text{H}^+$) can have a contaminant singly ionized molecular hydrogen ($^1\text{H}_2^+$) component which would not be separated out magnetically in the analyzing magnet. This contaminant beam can introduce problems in charge integration, if not constant, and in general can initiate nuclear reactions at the target, (although that is not a problem in this experiment since the very large Q values, $\sim 18$ MeV, for $^3\text{He}(d,p)^4\text{He}$ and $^3\text{H}(d,n)^4\text{He}$ produce reactant particles whose energy is well above all other reactions). Nevertheless to remove this component from the beam, a carbon stripper foil assembly is placed just prior to the analyzing magnet to break the hydrogen molecular bond. Physically, the carbon foils ($10\mu\text{g/cm}^2$ thick) are mounted on a multipositional wheel so that any one of sixteen foils can be utilized. The elimination of these protons from the deuterium beam was verified to the $\pm 0.1\%$ level by measuring Rutherford
backscattering of the beam from a thin gold foil in the scattering chamber. Such a level of contamination is an order of magnitude below uncertainties important in this experiment.

3. A system of entrance and exit slits to the analyzing magnet serve to define the energy of the deuteron beam. The entrance slits defined a 0.200" x 0.300" aperture through which the beam enters the analyzing magnet. Two exit slits, (top and bottom) then define a 0.100" gap through which the beam passes to the target area. Beam current can be monitored on any one of these slits. The energy calibration of the analyzing magnet with the slits in this configuration is discussed in section III-H.

4. In order to minimize instrumental asymmetries it is important to keep the polarized deuterium beam centered at the target. This was done by monitoring the beam on each slit of a system of 4-jaw slits at various locations along the beam path. These slits, (0.1" gaps), were located at the entrance and exit ports of the scattering chamber to define the center of the chamber independent of its rotation, and were located \( \approx 2 \) meters before
the T-Ti target in the $^3H(d,n)^4He$ experiment.

III-D. $^3H(d,n)^4He$ Experimental Apparatus

Polarization transfer coefficients for the $^3H(d,n)^4He$ reaction were measured at the end of the beam line in an experimental area suited to neutron detection. The secondary neutron beam was produced by impinging a collimated polarized deuteron beam upon a T-Ti solid target. (Figure III-5). The neutrons were then collimated through a solenoidal magnet, which was not used during this experiment, to a high-pressure $^4He$ scintillator located 32" away. The neutron polarization is analyzed by scattering from $^4He$ in the high-pressure $^4He$ scintillator into two symmetrically placed NE102 detectors at $\Theta_\alpha = 112^\circ \pm 2^\circ$ and located 18" away. This secondary scattering angle $\Theta_\alpha$ was chosen to minimize background due to forwardly scattered neutrons, and at an angle where the n-\alpha analyzing power is large, relatively flat and well known. A fast coincidence electronics circuit was operated between the $^4He$ scintillator and each plastic neutron detector to gate only those neutrons scattered at the selected angle. This method has been used successfully at this lab before by DeMartini (De 69f) and Donoghue et al. (Do 68e). These components of the experiment are discussed in more detail below.
Figure III-5  The neutron detector area where $T(\vec{d}, \vec{n})^4\text{He}$ polarization transfer measurements were performed.
Figure III-5
1. The Tritium Target

The target was fabricated by Oak Ridge and consisted of a 1.5 cm diameter Ti evaporation, (7mg/cm² thick), infused with gaseous tritium, (total activity of target is 12.4 Ci), on a 0.020" platinum backing. The target was canted at 45° to the beam's momentum for all measurements. At a machine energy of ~ 6 MeV, the energy loss through the target was ~ 500 keV similar to the energy loss in the \(^{3}\text{He}(d,p)^{4}\text{He}\) experiment. To minimize any possible tritium escape from the target, the platinum backing was freon cooled from the edges. The entire assembly was electrically isolated and electrons were prevented from escaping the assembly by a system of electrically charged collimators. The beam was then integrated with a Brookhaven model 1000 current integrator enabling charge integration during the experiment to be accurate within 0.1%, well within the limits necessary for the polarization transfer coefficient measurements. At the target, the size of the beam spot was limited to 0.100" diameter by a pair of slits located 2 and 4 meters away. The deuteron beam intensity at target was approximately 90 nA.

2. The High Pressure \(^{4}\text{He}\) Gas Scintillator

The helium gas scintillation detector shown in Figure III-6 is based on the original concept of Shamau et al.
Figure III-6  Diagram of the high pressure $^4$He gas scintillator used as a neutron polarization analyzer.
Figure III-6
(Sh 61c), and similar to that designed later at this lab by Soltez (So 66b). For this present work, a number of improvements have been made. The scintillator now consists of a cylinder of type 304 stainless steel 2" in diameter and 3" in length with 0.125" walls. To insure maximum light collection and uniform pulse height resolution, the inner walls of an aluminum oxide cup, made by the Norton Company, and which slips inside the cell, were coated with a reflective layer of MgO powder deposited by burning a Mg ribbon on the inside. Such a system reduced significantly the problem of the MgO flaking off. The cell was then baked in a high vacuum to drive off volatile contaminants and especially water which would contaminate the high purity gas. A layer of $p,p'$-diphenylstilbene was next evaporated on the MgO on the inner surface of the cup which served to shift the wavelength of the ultraviolet helium scintillations into the region of maximal sensitivity of the photomultiplier tube. A 56 DVP bi-alkali cathode photomultiplier tube was used to view the active volume of the gas through $3/4"$ thick crown tempered glass and $3/8"$ thick plexiglass (to distribute the pressure) windows. The thickness of the diphenylstilbene layer was chosen to give equal pulse heights from different parts of the cell when an internal monenergetic $^{210}$Po-alpha

2) 56 DVP photomultiplier tubes purchased from Amperex Corp.
source was moved over its length, thus insuring uniform pulse height resolution. The distribution of thickness of the diphenylstilbene is shown in Figure III-7. The glass window was also coated with a thin 20.0 \( \mu g/cm^2 \) layer of \( p,p' \) - diphenylstilbene. The cell was filled with purified helium gas (3500 psi) to which a small amount (200 psi) of purified xenon gas was added to increase the light output of the scintillator. The filling gasses were passed through liquid nitrogen, activated charcoal and Zeolite \(^4\) traps to purify them. The \(^{210}\)Po alpha source mounted in the cell as shown in Figure III-6 gave an inherent resolution of the cell as 9% full width at half maximum (FWHM). Since the \(^3\)H(d,n)\(^4\)He neutrons are well separated in energy from all competing neutron and gamma groups except at angles \( \geq 90^\circ \), this resolution was entirely satisfactory. Because of the extremely low count rates in this experiment, new plastic detectors much larger than ones used at this laboratory before were employed. These new detectors subtended considerably larger solid angles requiring averaging of the n-\(\alpha\) analyzing power over their surface, (see appendix B).

3. The NE102 Plastic Scintillator Neutron Detectors

The plastic neutron detectors consisted of 4" x 6" x 6"

\(^4\) Purchased from Linde, a division of Union Carbide.
Figure III-7 Variation of thickness of the diphenylstilbene over the inside surface of the $^3$He neutron polarization analyzer cell.
Variation of pp'-diphenyl stilbene layer

Thickness (µg/cm²)

Position (inches)

↑ Glass window

Figure III-7
NE102 blocks. Figure III-8 shows one detector in its mounting case. Recoiling protons from n-p collisions produce scintillations in the NE102 which are viewed by two photomultipliers (56-DVP).

The use of two photomultipliers provides for a more compact light guide which was designed to eliminate nearly all internal reflections. The Lucite light guides are epoxied with a special optical cement (Optical Exopy, NE581, purchased from Nuclear Enterprises, Inc.) to the NE102 detectors and both are coated with four layers of titanium dioxide paint (Titanium dioxide paint, NE560, purchased from Nuclear Enterprises, Inc.). Layers of mylar and electrical tape insure a light tight seal. The photomultiplier tubes are shielded by 1/4" soft iron tubes from stray magnet fields which could affect their gain. The detectors are shielded from low energy gamma events by a modest 0.250" shield of lead mounted only on the target side of the detectors. Shielding from up-stream gammas and breakup neutrons is accomplished by a concrete and paraffin wall before the neutron area (Figure III-5). The detectors are rigidly mounted symmetrically, either up-down or left-right depending upon the outgoing polarization component one is measuring. They are positioned at $\theta = \pm 112^\circ \pm 2^\circ$ and subtend half angles of $\Delta \theta = 6^\circ$, $\Delta \phi = 10^\circ$.

5) NE102 detectors purchased and polished at Oak Ridge.
6) Optical Exopy, NE581, purchased from Nuclear Enterprises, Inc.
7) Titanium dioxide paint, NE560, purchased from Nuclear Enterprises, Inc.
Figure III-8  Diagram of one NE102 plastic scintillator neutron detector.
Figure III-8

- ORTEC 269 PHOTOMULTIPLIER BASES
- DVP-56 PHOTOMULTIPLIER TUBES
- LUCITE LIGHT GUIDES
- 6" x 6" x 4" NE 102 PLASTIC DETECTOR
- ALUMINUM FRAME
- INCIDENT NEUTRONS
- SOFT IRON
4. Electronics

The fast anode signals from the helium cell, (0.2 volts, 8 ns rise time), and the plastic neutron detector's photomultipliers (1 volt, 4ns rise time), were routed into the control room on 50 fast signal lines where they were fed into fast Ortec constant fraction discriminators, (Figure III-9). The timing signal derived from the constant fraction discriminator for each plastic neutron photomultiplier is used as a stop pulse to a Time to Pulse Height Converter (TPHC) whose start pulse originated at the $^4$He gas scintillator, (see section III-G for sample spectra). The TPHC output for each plastic photomultiplier is then gated by pulse heights above an energy threshold from the linear helium cell signal. This eliminates many of the lower energy Compton scattered $\gamma$ events from the final timing spectra. The corresponding neutron windows in the timing spectra (4-20 ns) are then used to gate the linear energy spectra from the helium cell for each of the two plastic neutron detectors. Consequently, these spectra are those neutrons whose scattering have been recorded in the helium cell and subsequently were detected in a plastic neutron detector. The timing resolution of the system was measured from Compton scattered $\gamma$ rays to be 2.5 nanoseconds, which allowed accurate time-of-flight separation of neutron events and background $\gamma$-ray events.
Figure III-9  Block electronics diagram for $^3\text{H}(\vec{d},\vec{n})^4\text{He}$ experiment.
Figure III-9
Polarization transfer coefficients for the $^3\text{He}(d,p)^4\text{He}$ reaction were measured in the rotatable scattering chamber which was suited for charged particle detection. The secondary proton beam was produced by directing a polarized deuteron beam onto a high pressure $^3\text{He}$, $(0.950"$ diameter) gas target, (Figure III-10). The reaction protons were then collimated and allowed to enter a high pressure $^4\text{He}$ proton polarimeter, (located 1" away from the target center). The proton polarization is analyzed by scattering from $^4\text{He}$ into banks of symmetrically positioned Si surface barrier detectors at $\Theta = \pm 60^\circ \pm 0.5^\circ$ and located within the $^4\text{He}$ gas. These components of the experiment are discussed in more detail below.

1. Rotatable Scattering Chamber

The 17" diameter scattering chamber is supported at both entrance and exit ports by ball bearings which allow it to rotate with precision about the beam axis. This feature allows interchange of left and right detectors during an analyzing power measurement, an important feature in reducing instrumental errors. The target rod, mounted on one lid, (5 cm thick Al), can be raised or lowered into the path of the incident deuteron beam. This allows any of three different targets to be moved into the beam path.
Figure III-10 Diagram of rotatable scattering chamber for charged particle scattering.
Figure III-10
or allows the beam to pass unscattered through the chamber. The detector assemblies, mounted on the other chamber lid, consist of a monitor detector block and a proton polarimeter block. These are independently rotatable about the central axis of the scattering chamber to within 0.1° by a vernier scale scribed on the outside of the detector lid. The monitor detector block houses four silicon surface barrier detectors and collimating telescopes separated by 10°. The proton polarimeter will be described in more detail below. Beam defining slits are located up, down, left, and right at both the entrance and exit of the chamber, and are optically aligned to be centered about the rotation axis of the chamber to within 0.1 mm. The slits are electrically isolated from ground so that the beam current on each slit may be monitored. With that, the beam position can be maintained in the center of the chamber at all times by merely balancing the beam current on opposing slits, a procedure required for proper spin flips and associated reduction of false asymmetries. The rotation of the scattering chamber about the beam axis is monitored by an incremental optical shaft encoder that determines the angle to 0.1°.

2. $^3$He Gas Target

The $^3$He gas target mounted on the target rod in the center of the chamber is shown in Figure III-11. $^3$He gas
at 7 atmospheres is contained in a 2.5 cm diameter cell by a 2.5 μm Havar foil which is epoxied in place on a brass housing.

Although good charge integration is not essential in the $^3$He($d$,p)${}^4$He polarization transfer coefficient measurements, steps were taken to accurately collect the beam's charge. When the polarimeter was beyond $\Theta_{\text{Lab}} = 35^\circ$, the beam was allowed to exit the gas cell and the scattering chamber into an in-line polarimeter where $^3$He($d$,p)${}^4$He protons were measured at $\Theta = 0^\circ$. Charge integration was effected in the in-line polarimeter, and will be described more fully in section III-F. Angles forward of $\Theta_{\text{Lab}} = 35^\circ$ required that the beam be stopped at the target assembly before impinging on the polarimeter body. For this case, the cell was surrounded by concentric cylinders of: i) an electrically charged fine tungsten mesh to suppress electrons, and ii) a tantalum foil (125 μm thick), for charge integration of the beam. This thick tantalum foil stopped the exiting deuteron beam completely, but allowed the highly energetic $^3$He($d$,p)${}^4$He reaction protons, ($Q$ - value = 18.35 MeV), to pass through to the proton polarimeter. The charge integration reproducibility for this arrangement was measured with

8) Armstrong adhesives, epoxy A-12.
Figure III-11  Diagram of $^3$He gas target and associated faraday enclosure.
Figure III-11
varying intensity beams to be accurate to within 0.3%.

3. The Proton Polarimeter

Measuring a $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ polarization transfer coefficient requires determining the polarization of the outgoing reaction protons. To determine this polarization, a proton polarimeter utilizing $^3\text{He}(\vec{p},\vec{p})^4\text{He}$ scattering, (which is well understood in this energy range), was built. Because the count rates for this type of experiment are low, the $^4\text{He}$ gas was kept at as high a pressure as was feasible, (38 atm.). Also, a vaned collimator arrangement was used limiting the angular acceptance of the particle side detectors to

$\Delta \Theta = \pm 7^\circ$, $\Delta \phi = \pm 12^\circ$. Detection of the scattered protons at $\Theta = 60^\circ$ was chosen because $A_Y(60^\circ)$ is large and very flat as a function of energy and angle in this region.

The proton polarimeter shown in Figure III-12 is of a design similar to that reported by Clegg et al. (Cl73a). It consists of a relatively thin (25 $\mu$m) entrance foil (augmented by appropriate tantalum absorbers 25-300 $\mu$m) through which the secondary proton beam from $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ reaction may pass into a highly pressurized $^4\text{He}$ environment. The protons pass through a 500 $\mu$m partially depleted ORTEC silicon surface barrier transmission detector, (energy loss $\sim 3.0$ MeV), into the 60$^\circ$ vaned region where p-$^4\text{He}$ scattering occurs. The transmission detector was necessary to gate the
Figure III-12  Diagram of the proton polarimeter used for $^3\text{He}(d,p)^4\text{He}$ experiment.
Figure III-12
particle side detectors. This was because of the relatively large neutron background, ($\sim 10$ cnts/sec), in the particle side detectors which otherwise masked the scattered reaction protons. To help reduce this neutron background, (arising principally from deuterons reacting with the $^3$He gas cell foils), delrin plastic shielding was employed both within and around the proton polarimeter. The symmetric side detectors are 1000 $\mu$m surface barrier detectors and register the scattered proton events to be used to determine the polarization of the reaction protons. Because of the extended length and vaned nature of the polarimeter, a significant averaging of p-$\alpha$ analyzing powers was carried out. The cell has a calculated analyzing power as shown in Figure III-13. These calculations will be discussed more fully below and in appendix B. One calibration point was measured with the polarimeter, (see section III-I), and its value agreed well. For all $^3$He($^3$He,$p$)$^4$He experimental measurements, Ta absorbers at the entrance to the polarimeter were adjusted to keep the $^4$He($p$,p)$^4$He mean scattering energy nearly the same.

4. The Monitor Detector Block

The monitor detector block, shown in Figure III-14, is used in measuring reaction protons from the $^3$He($^3$He,$p$)$^4$He reaction at the center of the chamber. This allowed one to independently check the values of analyzing powers previously
Figure III-13  Graph of calibrated $p-^4\text{He}$ analyzing power $<A_y>$ of the proton polarimeter.
Figure III-13

Region of normal operation
Figure III-14  Diagram of the monitor detector block mounted in the rotatable scattering chamber.
Figure III-14
measured by Clark (Cl 80c) and used during this experiment. All values measured agreed within error bars with those already reported. The monitor detector block was also used to detect Rutherford backscattering of the beam from gold when checking for \(^{(H_2^+)}\) contamination, (see section III-C). It consists of four 500 \(\mu\)m thick silicon surface barrier detectors at \(10^\circ\) intervals collimated to a half angle \(\sim 0.1^\circ\) by 1/8" thick stainless steel collimators. In order to cause the highly energetic reaction protons from the \(^3\text{He}(d,p)^4\text{He}\) reaction to stop in these detectors, 500 \(\mu\)m to 2500 \(\mu\)m of aluminum absorbers were placed before them.

5. Electronics

The slow preamp pulses from the surface barrier detectors of both the monitor and polarimeter blocks are brought in from the target area and processed according to their origin, (Figure III-15). Signals from side detectors in the proton polarimeter are gated on the transmission detector to reduce backgrounds which arise principally from neutrons originating from the deuteron beam's interaction with the gas cell foils. Because of the very high count rate (\(\sim 10^4\) cnts/sec), of the transmission detector, pile up rejection electronics are necessary. These gated and un-gated signals are stored using an 8 stretcher Tennelec PACE System with direct memory access to an IBM 1800 computer.
Figure III-15  Block electronics diagram for $^3\text{He}(d,p)^4\text{He}$ experiment.
Figure III-15
Meanwhile, the transmission gated and ungated spectra are monitored in the ND100. Signals from the monitor detector block are simply amplified and then routed into their accorded position into the Nuclear Data ND100 multichannel analyzer. Both the PACE spectra and the ND100 spectra are then stored on magnetic disk where composite spectra are built and analyzed off-line.

III-F. \( ^3\text{He}(\vec{d},p)^4\text{He} \) Beam Polarization Monitors

The polarization of the deuterium beam was monitored using \( A_{zz}(0^\circ) \) for the \( ^3\text{He}(\vec{d},p)^4\text{He} \) reaction. This reaction observable has been previously calibrated at this lab to the isospin forbidden reaction \( ^{16}O(\vec{d},\gamma)^{14}N^* \), (Dr 79c), (Figure III-16). The \( ^{16}O(d,\gamma) \) calibration relies on the fact that the tensor analyzing power, \( A_{zz} \equiv 1 \) for all angles and energies. The initial calibration of \( ^3\text{He}(\vec{d},p)^4\text{He} \) \( A_{zz} \) at 0° at this lab was made by Dries et al. (Dr 79c), but was remeasured recently by Clark (Cl 80c) and this author previous to this experiment. Results of this remeasurement showed basic agreement with Dries et al. (Dr 79c) results and are summarized more fully by Dries et al. (Dr 80d).

Uncertainties in the absolute value of the \( ^3\text{He}(\vec{d},p)^4\text{He} \) \( A_{zz}(0^\circ) \) calibration curve are propagated into all polarization measurements (typically \( \Delta A_{zz}(0^\circ) \approx 0.02 \)).

Two physically different beam polarimeters were used during these experiments. During measurements of \( ^3\text{H}(\vec{d},\vec{n})^4\text{He} \)
Figure III-16  $^3\text{He} (\vec{d}, p)^4\text{He} A_{zz}(0^\circ)$ calibrated to $^{16}\text{O} (\vec{d}, \alpha_1)^{14}\text{N}^*$ at this laboratory.
Figure III-16
polarization transfer coefficients, a pop-in polarimeter in the scattering chamber was used to periodically check the beams' polarization using $^3\text{He}(\vec{d}, p)^4\text{He}$ $A_{zz}(0^\circ)$. During measurements of $^3\text{He}(\vec{d}, p)^4\text{He}$ polarization transfer coefficients, an in-line polarimeter immediately following the scattering chamber was used instead. Both the pop-in polarimeter and the in-line polarimeter, (Figure III-17), consist of a 1.2 cm long gas cell of $^3\text{He}$ maintained at 2 atm. by an entrance foil of 2.5 $\mu$m Havar. The reaction protons exited through a tantalum foil, (250 $\mu$m), and were collimated before entering a 1000 $\mu$m surface barrier detector. Charge integration was performed in the gas cell. The polarimeter signals require only an Ortec 109A preamplifier and 460 delay line amplifier for data collection.

III-G Data Collection Procedures

The pulse height spectra were collected and analyzed on-line with an IBM 1800 computer system. The data were then transferred to a Data General Eclipse Computer system where they were resummed off-line and analyzed in more detail. Extracting accurate yields from these raw spectra involved many considerations as to background and uncertainty. These considerations will be discussed more fully for
Figure III-17 Cut away drawings showing both the pop-in and in-line beam tensor polarimeter measuring $A_{zz}(0^\circ)$ of $^3\text{He}(d,p)^4\text{He}$. 
"POP-IN" POLARIMETER

1000-m Surface Barrier Detector

1/8" dia. Collimators (No Bevel)

3 He Gas Cell

Exit Foil & Beam Stop 0.010" Ta

Entrance Foil 0.0001" Harvar

3/16" Coll. (Biased +45Vdc)

Figure III-17
both proton and neutron spectra below.

1. Proton Polarimeter Spectra

The proton polarimeter transmission detector counted at such a rapid rate that pile-up rejection electronics were employed. The number of piled-up pulses and unpiled-up pulses were accumulated during the run allowing a correction to be applied to data. This correction was typically ~ 1% but never exceeded 1.7%. Typical transmission detector spectra are shown in Figure III-18. It is important to note that the ratio of background events to reaction protons is very small, (10^-4), which helped to keep the number of accidentals in the particle side detectors gated spectra at a minimum.

The particle side detector pair was analyzed independently. A typical pair of side detectors spectra are shown in Figure III-19. The large exponential-like background at low energies was shown to be related to breakup neutrons from the deuteron beam impinging principally on the Havar gas cell foils. This background was reduced significantly by the use of delrin and cadmium shielding around the polarimeter body. Delrin is a hydrogen rich plastic which thermalizes the neutron for capture by the cadmium. Lack of available space prevents more shielding from being utilized. One should point out that in fact this background
Figure III-18 The transmission detector spectra from the $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ experiment.
Figure III-19 Spectra from a symmetric pair of particle side detectors in the $^3\text{He}(d,p)^4\text{He}$ experiment.
Figure III-19

3He(D, p) 4He
LEFT GATED PROTONS

COUNTS (x 1)
CHANNEL NUMBER

3He(D, p) 4He
RIGHT GATED PROTONS

COUNTS (x 1)
CHANNEL NUMBER
was relatively small under experimental circumstances involving a single scattering, but very large with respect to the double scattering count rate, (5 cnts/min). Detailed analysis showed this background to be basically unpolarized, and allowed an accurate subtraction of it from the proton peak. Even so, such a background subtraction usually amounted to a correction to the measured asymmetry of the order of its statistical uncertainty. The uncertainty due to the background subtraction was propagated through to the results and will be discussed with the presentation of the results, (section III-I). Because of the vaned nature of the polarimeter and the energy loss along the reaction protons p-α scattering path, the resolution of the proton peaks was $\sim 10\%$ FWHM. Although this was entirely satisfactory in determining experimental yields from the spectra, such angular and energy averaging required a detailed analysis to arrive at an effective p-α analyzing power. This averaging procedure and its results are discussed in section III-I, and in Appendix B.

2. Neutron Spectra

The $^3\text{H}(\alpha,n)^{4}\text{He}$ experiment required a fast coincidence between the helium scintillator and the plastic neutron detectors. Typical fast coincidence timing spectra are depicted in Figure III-20. The absissa in this
Figure III-20  Fast coincidence timing spectra between the helium scintillator and a plastic neutron detector.
Figure III-20

3H(D,N)4HE
TIMING SPECTRA

3H(D,N)4HE
GATED TIMING SPECTRA
plot is labeled in time between an event in the helium cell and an event in the plastic neutron detector. By adjusting the lower level of the constant fraction discriminator, most of the $\gamma$-rays occurring at $t=0$ ns. were eliminated making the neutrons occurring above $t=3$ ns. more prominent. Beyond $t=20$ ns., much slower neutron groups from deuteron beam breakup become apparent, and so the SCA upper window level was kept below this. The discriminator gating these timing spectra were also used to gate the linear helium scintillator signals. Spectra from a typical left/right, (up/down) pair of gated helium scintillator signals are shown in Figure III-21. The energy width of these peaks is a direct result of the angular acceptance of the plastic neutron detectors, $(\Delta \Theta_\alpha = \pm 6^\circ)$. The backgrounds in these spectra are accidentals and are directly proportional to the ungated yield in the $^4\text{He}$ scintillator. Consequently, the backgrounds are nearly identical in the two spectra for any individual run. Although one might expect some background attributable to multiple scattering effects in the helium and iron walls of the scintillator, calculations have shown these contributions to be small. These effects as well as geometrical corrections due to finite size of the detectors will be discussed in section III-I.
Figure III-21 Spectra from a symmetric pair of 
left/right, (up/down), gated helium 
scintillator signals.
Figure III-21
3. A_{zz}(0^\circ) Beam Polarimeter Spectra

The polarization of the deuteron beam was monitored by measuring A_{zz}(0^\circ) for the $^3\text{He}(d,p)^4\text{He}$ reaction in the polarimeter described in section III-F. Since the cross section at $\Theta = 0^\circ$ is relatively large (15 mb/sr) and the Q value for this reaction is so large, ($Q = 18.35$ MeV), the spectra collect rapidly with very little background. A typical reaction proton spectrum is shown in Figure III-22.

III-K. Preliminary Measurements and Calibrations

The measurement of transfer coefficients relies upon a number of calibrations measured before the experiments described in the previous sections could be conducted. The measurement of spin one polarization observables requires that the orientation of the spin vector of the beam polarization ($\beta$ and $\phi$ angles as shown in Figure III-3) be accurately known. Errors in $\beta$ and $\phi$ will introduce contributions of other unwanted analyzing powers into the measurement. Calibration of the analyzing magnet for accurate determination of the incident deuteron energy is also required to determine energy averaged observables used in reducing the raw data.

1. Wien Filter $\phi$ Calibration

The spin precession unit (Wien Filter) in the polarized ion source consists of crossed E and B fields normal to the
Figure III-22  A typical reaction proton spectrum collected with a $^3$He(d,p)$^4$He beam polarization monitor.
Figure III-22

COUNTS ($\times 10^3$)

CHANNEL NUMBER

$^3\text{He}(D,p)^4\text{He}\ A22(0)$

POLARIMETER
beam momentum direction which allows the spin vector to be rotated in the plane perpendicular to the B field. In addition, the Wien filter may also be rotated as a unit about the beam axis. The combination of these two features allows the beam spin vector to be oriented in any arbitrary direction (angles $S$ and $\gamma$ Figure III-3), and transform according to equation 34 to the target coordinate system. In order to perform the $\phi$ calibration, the $p-\alpha$ elastic scattering was used. The target was 1.5 atm of $^4$He contained in a cylindrical gas cell 1.2 cm in diameter with 2.5 $\mu$m thick Havar entrance and exit window foils. The target was mounted in the rotatable scattering chamber (section III-E) with two symmetric monitor detector blocks. The $\beta$ angle was set to an arbitrary value ($\sim 90^\circ$) and the up-down ($\phi \equiv 270^\circ$, $90^\circ$) asymmetry at the target was measured as a function of the position of the rotatable scattering chamber. This position was monitored by an optical shaft encoder which was geared to the chamber and monitored its position to within 0.1$^\circ$. The yield for a spin 1/2 beam scattering is given by:

$$
\sigma(\theta) = \sigma_0(\theta) \left(1 + p_s A_y(\theta) \sin \beta \cos \phi \right)
$$

(36)

where

$$
\sigma(\theta) = \text{yield with a polarized beam}$$
\( \sigma_o(\Theta) \) = yield with an unpolarized beam

\( p_s \) = beam polarization

\( A_y(\Theta) \) = analyzing power for p-\( \alpha \) scattering at this energy

By making two runs, one with the chamber near 90° and the other with the chamber rotated exactly 180° from that position, a measurement independent of both charge integration and detector solid angle can be made. With this procedure, a proper spin flip is made as defined by (Oh 73c). Defining a geometric mean of the yields in the up and down detectors as

\[
U \equiv \sqrt{U_1 U_2} \\
D \equiv \sqrt{D_1 D_2}
\]

then the observed asymmetry will be

\[
pA \sin \beta \cos \phi = \frac{U-D}{U+D}
\]  

(38)

the Wien filter will be in the position \( \delta = \phi = 0° \) if the observed asymmetry is zero (\( \phi = 90°, 270° \)) when the scattering chamber is at 90°. This is accomplished by rotating the Wien filter about the beam axis in the polarized source. A plot of the measured asymmetry for the final position of the Wien filter as a function of chamber position is shown in Figure III-23. The solid line is a least squares linear
Figure III-23  Plot of measured asymmetry as a function of chamber position for the Wien filter calibration. The solid line is a linear least squares fit to the data.
fit to the data and shows that the asymmetry is zero for chamber position of $90.1 \pm 0.2 \degree$. Other angles of $\phi$ can be determined similarly.

2. Wien Filter $\beta$ Calibration

The $\beta$ calibration for polarized deuterons used the $A_{zz}(0^\circ)$ $^3$He$(d,p)$ reaction. At $\Theta = 0^\circ$, the yield for $^3$He$(d,p)^4$He is given by equation (11):

$$\sigma(0^\circ) = \sigma(0^\circ)[1 + 1/4 (3 \cos^2 \beta - 1) p_{ss}A_{zz}(0^\circ)]$$

Measurement of the asymmetry with a polarized/reverse-polarized method was made as a function of the Wien $E$ voltage.

$$(3 \cos^2 \beta - 1) p_{ss}A_{zz}(0^\circ) = 4 \left( \frac{Y^+}{Y^+ + Y^-} - \frac{Y^-}{Y^+ + Y^-} \right)$$

where $Y^+$, $Y^-$ are the polarized and reverse-polarized yields of the detector respectively, and

$$\beta = A_1 + A_2 E + A_3 E^2$$

$E =$ Wien $E$ voltage

The strengths of both the $E$ and $B$ fields in the Wien filter are monitored remotely by digital voltmeters, but since there is possibility of hysteresis in the $B$ field, only the $E$ field reading was used for calibration purposes. One should point out that this method is not independent of charge integration, however charge integration was measured to be accurate to within $0.3\%$. A non-linear least square fit of the asymmetry versus $E$ is shown in Figure III-24.
Figure III-24 Plot of measured asymmetry vs. Wien E voltage. The solid curve is a non-linear least square fit to the data.
Figure III-24
The result of this fit yields these parameters.

\[
\begin{align*}
A_1 &= 12.892 \pm 0.113 \\
A_2 &= 0.4216 \pm 0.0007 \\
A_3 &= 1.1 \times 10^{-4} \pm 7.1 \times 10^{-6}
\end{align*}
\]

(42)

This indicates the expected results that the rotation of the spin angle (\(\phi\)) is linear with E field strength since the asymmetry is described completely by a phase (\(A_1\)) and a frequency (\(A_2\)). The non-linear term (\(A_3\)) was zero within the precision of the least squares fit and was not required.

A calibration of \(\phi\) for the polarized proton beam was done with \(p-\alpha\) scattering thus allowing \(\phi\) for deuterons to be deduced. The two measurements yielded excellent agreement with each other well within the stated uncertainties above.

3. The Energy Calibration

The energy calibration of the Van de Graaff accelerator and analyzing magnet combination was made using two independent reactions at nearly the same energy. These reactions were the \(^{13}\text{C}(p,\gamma)^{14}\text{N}\) 1.748 MeV resonance (\(E = 77\text{eV}\)), and the \(^7\text{Li}(p,n)^7\text{Be}\) 1.881 MeV threshold, (Ma 66d).

The \(^{13}\text{C}(p,\gamma)^{14}\text{N}\) calibration was made using a\(\approx 15 \text{ keV}\) thick \(^{13}\text{C}\) target. A plot of yield versus energy is shown in Figure III-25. This energy calibration was then used in measuring the \(^7\text{Li}(p,n)^7\text{Be}\) threshold. A plot of \((\text{yield})^{2/3}\) versus the \((p,\gamma)\) calibrated energy scale is shown in
Figure III-25  Plot of yield versus beam energy for the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ resonance at 1.749 MeV used as an energy calibration.
Figure III-25

\[13C(p,\gamma)^{14}N\]
Figure III-26  Plot of \((\text{yield})^{2/3}\) versus beam energy for the \(^7\text{Li}(p,n)^7\text{Be}\) threshold reaction at 1.881 MeV used as an energy calibration.
Figure III-26
Figure III-26. The interpolated threshold energy was measured to be 1.880 MeV as compared to the actual threshold energy of 1.881 MeV. This measurement confirms the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ calibration within the uncertainty of the measurements.

III-I Data Reduction and Results

Polarization transfer coefficients for the charge symmetric $^{3}\text{He}(d,n)^{4}\text{He}$ and $^{3}\text{He}(d,p)^{4}\text{He}$ reactions which are determined from measured asymmetries, (equations 14, 18, and 25), require independent measurements of the reaction polarizations and analyzing powers. Analyzing power data for both reactions are available from work already done at this laboratory by Clark (Cl 80c), while polarization data for both reactions are available from work done elsewhere, (see Table A-1). These observables are sufficiently accurate that the uncertainty they contribute to a polarization transfer coefficient measurement is not large when compared to the statistical uncertainty in the measurement itself. Consequently, no new measurements of analyzing powers or polarizations were required.

A. Determination of $A_{2}(\Theta_{2})$

Additionally, each $^{3}\text{He}(d,p)^{4}\text{He}$ ($^{3}\text{H}(d,n)^{4}\text{He}$) measurement required knowledge of the $p-\alpha$ ($n-\alpha$) analyzing powers, $A_{2}(\Theta_{2})$, in the energy region of interest. Because of the
geometry of the experiments, this analyzing power, $A_\alpha(\theta_\alpha)$ is necessarily a geometry averaged quantity which is calculated by specially designed computer programs. These programs are discussed in detail in Appendix B, but the analyzing power calculation and results are discussed below.

1. $A_\alpha(\theta_\alpha)$ for $^4\text{He}(\vec{p},p)^4\text{He}$ Scattering in the $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ Experiment

In the $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ experiment, reaction protons with energies 20-24 MeV are incident on the proton polarimeter. Tantalum absorbers (0.2 to 0.6 mg/cm$^2$) were mounted in front of the polarimeter so that the proton's energy is attenuated to $\approx$ 16 MeV for all measurements. After passing through the polarimeter entrance foil, $^4\text{He}$ gas and the transmission detector, ($\Delta E_{\text{trans}} \approx 3$ MeV), the reaction protons enter the vaned region of the polarimeter where $^4\text{He}(\vec{p},p)^4\text{He}$ scattering takes place at $\Theta_{\text{lab}} = \pm 60^\circ$ at $\approx 10$ MeV. The proton polarimeter was designed to operate in this region since the $p-\alpha$ analyzing powers here vary slowly with energy and angle. Also, this is a region where the figure of merit, $(p^3/\sigma)$, for $p-\alpha$ scattering is large, and where energy loss by the scattered protons in the side detectors is also large.

The values of $A_\alpha(\theta_\alpha)$ for $^4\text{He}(\vec{p},p)^4\text{He}$ scattering are determined by a program, PROTEST, which was written
especially for the particular geometry of the proton polarimeter constructed for these measurements. These values of $A_2(\Theta_\alpha)$ calculated include effects due to finite geometry, energy loss, and energy spread and straggling. The program uses as input the energy of the $d$ beam, the thickness of the tantalum absorbers, and published R-matrix levels for $p-\alpha$ scattering, (St 72h). Also included in the program's input are empirical energy loss tables for havar, tantalum, $^3$He, $^4$He, and silicon from Northcliffe and Schilling (No 70b). The program then rigorously follows beam and reaction proton energy profiles through the polarimeter to their conclusion. Because the $p-\alpha$ analyzing powers in this region vary so slowly, even a 5% error in the determination of the $p-\alpha$ scattering energy would only have $\leq 0.01$ effect on the calculated value of $A_2(\Theta_\alpha)$. Therefore, the uncertainty in the calculation was assessed as being $\Delta A_2(\Theta_\alpha) \approx 0.01$.

Ideally, a check of the calculated polarimeter analyzing power with a 20-24 MeV polarized proton beam could be made. However, equipment producing such a beam is not available at this laboratory. To insure the polarimeter was in fact operating as anticipated, one value of $P_Y'$ for $^3$He($d,p)^4$He at $E_d = 6$ MeV and $\Theta_{lab} = 30^\circ$ was measured with it mounted in the scattering chamber. This measurement involved using an incident unpolarized deuterium beam from the OSU standard
rf ion source. Although a proper spin-flip for this experiment would involve rotating the proton polarimeter by 180°, interchanging left and right detectors, this option was not available in that the polarimeter was rigidly fixed to its mount. But, by rotating the entire scattering chamber, (which is believed accurate to within 0.01 cm), an effective interchange of left and right detectors was made allowing $P_y'(\Theta)$ to be determined. The measured value of $P_y'(30^\circ) = 0.469 \pm 0.009$ agrees well within the uncertainties when compared to a previous measurement, (Cl 73h) of $P_y'(30^\circ) = 0.477 \pm 0.005$.

2. $A_\alpha(\Theta_\alpha)$ for $^4$He($\vec{n}$,n)$^4$He Scattering in the $^3$H($\vec{d}$,$\vec{n}$)$^4$He Experiment

In the $^3$H($\vec{d}$,$\vec{n}$)$^4$He experiment, reaction neutrons with energies 19-24 MeV are incident on the $^4$He gas scintillator. Neutrons are then scattered from the $^4$He into symmetrically placed ($\Theta_\alpha = \pm 112^\circ$) plastic neutron detectors which subtend large solid angles. The angles of $\Theta_\alpha = \pm 112^\circ$ were chosen because the analyzing powers and figure of merit for n-α scattering at these energies is large. By having the plastic neutron detectors at back angles, multiple scattering, which is largest at forward angles, is reduced. Also, the solenoid magnet offers shielding from up-beamline events when the detectors are at back angles. Because of the large
solid angles subtended and in order to estimate the effects of multiple scattering in the measurements, a monte carlo neutron scattering program was used.

The values of $A_\alpha(\Theta_\alpha)$ for $^3\text{He}(\vec{\nu},n)^4\text{He}$ scattering are determined by an elaborate program, MOCCASINS, which is specifically suited to neutron scattering from high pressure $^4\text{He}$ analyzers. The values of $A_\alpha(\Theta_\alpha)$ calculated include effects due to finite geometry, energy spread in the target, and multiple scattering of the neutrons from the $^4\text{He}$, and from the stainless steel gas cell. The program MOCCASINS has been documented earlier, (Sa 68d) but has been somewhat modified since then. As input, MOCCASINS needs the geometry of the equipment, the incident neutron energy, and phase shifts describing n-$\alpha$ scattering. The program randomly generates 4000 neutron scattering paths and calculates an averaged analyzing power, including spin dependent effects, (see Appendix B).

Below $E_n = 21$ MeV, published phase shifts by Stammbach and Walter (St 72h) were used to calculate n-$\alpha$ observables. Therefore Stammbach and Walter (St 72h) phase shifts could only be used in calculating $A_\alpha(\Theta_\alpha)$ for $^3\text{H}(d,n)^4\text{He}$ reaction neutrons at $\Theta_{LAB} \geq 45^\circ$. Hoop and Barschall (Ho 66f) have published $^4\text{He}(n,n)^4\text{He}$ phase shifts extending from 6 MeV to 30 MeV. Below 21 MeV, the Hoop and Barschall phase shifts
differ slightly from the Stammbach and Walter phase shifts, especially at 14 MeV. Above 21 MeV, the Hoop and Barschall phase shifts are the only ones available making their use necessary. Therefore, the reliability of the present $^3H(d,n)^4He$ data where $E_n > 21$ MeV, (i.e. $\theta_{\text{LAB}} < 45^\circ$), as well as that of published values of $P^V(\Theta)$, depends on the accuracy of the Hoop and Barschall phase shifts. Unfortunately, a determination as to their accuracy can not be assessed here.

Since the $n-\alpha$ analyzing powers at $\theta_{\text{LAB}} = 112^\circ$ are slowly varying over the energy range 19-21 MeV, their sensitivity to the exact values of input phase shifts are reduced. By varying the input phase shifts slightly and monitoring the sensitivity of the calculated values of $A_3(\Theta_3)$, a calculational uncertainty of $\Delta A_3(\Theta_3) = 0.02$ was assigned.

A problem with using $^4He(n,n')^4He$ scattering as a neutron polarization analyzer in the energy region is the very narrow $^3d$ resonance which occurs at $E_n = 22.15$ MeV. Since a $^3H(d,n)^4He$ measurement at $\theta_{\text{LAB}} = 15^\circ$ would span this resonance, no data were measured at that angle. One measurement at $\theta_{\text{LAB}} = 30^\circ$ was made which overlapped into the tail region of this resonance. The value of $A_3(\Theta_3)$ here was carefully averaged to take into account the effect of the nearby resonance. Although the phases of Hoop and Barschall
(Ho 66f) over this resonance region describe the measured data well, the n-α analyzing power in this energy region depends upon their exact values. For this reason, $A_3(\Theta_3)$ for the $^3\text{H}(^3\text{He},n)^4\text{He}$ reaction at $\Theta_{LAB} = 30^\circ$ was assigned an uncertainty $\Delta A_3(\Theta_3) = 0.04$.

B. Measured Asymmetries

Table II-3 tabulates the measured experimental asymmetry and associated uncertainty. This uncertainty is predominately statistical, but includes small contributions due to background subtraction, and Wien filter calibration uncertainties, (typically $\leq 0.008$). Also included in Table III-3 are the values calculated for p-α and n-α analyzing powers, and all other observables necessary for determination of the value of the polarization transfer coefficient. The uncertainties in these values are those quoted by the authors and include most uncertainties one would associate with an analyzing power or polarization measurement. The origins of the analyzing power and polarization observables in the table are noted at the bottom.

The measurement of the polarization transfer coefficient $K_Y(\Theta)$ at $\Theta = 45^\circ$ and $60^\circ$ requires knowledge of $P_Y(\Theta)$ at those same angles. Modern measurements of $P_Y(\Theta)$ include angular distribution from $E_d = 1.0$ to $5.0$ MeV by Smith and Thornton (Sm 72b), at $E_d = 3.35$ to $5.35$ MeV by Busse et al.
TABLE III-3
Measured Asymmetries and Associated Uncertainties

<table>
<thead>
<tr>
<th>Reaction Quantity</th>
<th>Measured Asymmetry</th>
<th>$\lambda_3 (0^\circ)$</th>
<th>$\lambda_3 (0^\circ)$</th>
<th>$\lambda_{xx} (0^\circ)$</th>
<th>$\rho (0^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{(d,p)} K_x^y (0^\circ)$</td>
<td>0.004 ± 0.011</td>
<td>-0.596 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,p)} K_x^y (15^\circ)$</td>
<td>-0.011 ± 0.020</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,p)} K_x^y (30^\circ)$</td>
<td>0.137 ± 0.022</td>
<td>-0.603 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,p)} K_x^y (45^\circ)$</td>
<td>0.242 ± 0.042</td>
<td>-0.581 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,p)} K_x^y (45^\circ)$</td>
<td>0.235 ± 0.027</td>
<td>-0.581 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,p)} K_x^y (60^\circ)$</td>
<td>0.170 ± 0.030</td>
<td>-0.586 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (0^\circ)$</td>
<td>0.096 ± 0.025</td>
<td>-0.596 ± 0.010</td>
<td>0.000</td>
<td>$...$</td>
<td>$0.256 ± 0.005$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (15^\circ)$</td>
<td>0.048 ± 0.025</td>
<td>-0.605 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (30^\circ)$</td>
<td>-0.077 ± 0.017</td>
<td>-0.603 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (37.5^\circ)$</td>
<td>-0.236 ± 0.030</td>
<td>-0.602 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (45^\circ)$</td>
<td>-0.209 ± 0.031</td>
<td>-0.581 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (60^\circ)$</td>
<td>-0.093 ± 0.035</td>
<td>-0.586 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (25^\circ)$</td>
<td>0.180 ± 0.023</td>
<td>-0.593 ± 0.010</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (30^\circ)$</td>
<td>0.104 ± 0.027</td>
<td>-0.603 ± 0.040</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (45^\circ)$</td>
<td>0.180 ± 0.030</td>
<td>-0.708 ± 0.020</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (0^\circ)$</td>
<td>0.170 ± 0.030</td>
<td>0.691 ± 0.020</td>
<td>0.000</td>
<td>$...$</td>
<td>$0.000$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (45^\circ)$</td>
<td>0.235 ± 0.034</td>
<td>0.708 ± 0.020</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
<tr>
<td>$^{(d,n)} K_y^y (60^\circ)$</td>
<td>0.092 ± 0.036</td>
<td>0.742 ± 0.020</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
</tr>
</tbody>
</table>

a) $R_1$, $R_2$, or $R_3$ from equations $14, 18$, and $25$.
b) Data taken from Clark (Cl 80).
c) $(d,p)$ data taken from Clare et al. (Cl 73); $(d,n)$ data discussed in text.
d) This data point was remeasured for a better statistical uncertainty.
(Bu 67b) and at $E_d = 7$ MeV by Sunier et al. (Su 76c).

Assuming a smooth energy dependence of $P^y'(\Theta)$ in this region, an interpolation was made to the data to determine values of $P^y'(\Theta)$ at $E_d = 6$ MeV, Figure III-27. Since there are no strong resonances in this energy region one would expect the assumption of a smooth energy dependence to be fulfilled. The interpolated values of $P^y'(\Theta)$ are tabulated in Table V.

We have used these values in lieu of very old measurements by Perkins and Simmons (Pe 61a) at $E_d = 6$ MeV. Their measurements were made using $^6$LiC as a neutron analyzer, which is known to have had calibration difficulties in the past. Also, these older measurements, (Pe 61a), disagree dramatically with the more modern measurements. By interpolating values between the extremes of the uncertainties to the modern measured data, a typical uncertainty of $\Delta P^y' = 0.020$ was determined.
Figure III-27

Plot of $P^v(\Theta)$ at $E_d = 5.0$ MeV, (Sm 72b) and $E_d = 7.0$ MeV, (Su 76c). The two squares are interpolated results between the two data sets. The dashed line shows the R-matrix prediction by Dodder and Hale, (Ha 80e).
Figure III-27
IV. PRESENTATION AND DISCUSSION OF RESULTS

In this chapter the experimental results of the measurements of the vector and tensor polarization transfer coefficients \( K'_x(\Theta) \), \( K'_y(\Theta) \) and \( K'_z(\Theta) \) in the mirror reactions \(^3\text{He}(d,p)^4\text{He}\) and \(^3\text{H}(d,n)^4\text{He}\) will be presented. When possible, the data are compared to existing data. The mirror reactions are then compared to one another through the present measurements, and are compared to preliminary R-matrix predictions, (based upon previous data) undertaken by Dodder and Hale, (Do 75h). Table IV-1 tabulates the measured polarization transfer coefficients determined from the values in Table III-3 and the equations of section II-B. The uncertainties here include all uncertainties discussed up to now propagated in quadrature. It should be pointed out, however, that the dominant error in the measurements derives from the statistical uncertainty of the detector yields.

IV-A. The \(^3\text{H}(d,n)^4\text{He}\) Data

The \( K'_x(\Theta) \) data for \(^3\text{H}(d,n)^4\text{He}\) at \( E_d = 6 \text{ MeV} \) are plotted in Figure IV-1, and the \( K'_y(\Theta) \) data are plotted in Figure IV-2. The solid curves are the preliminary R-matrix calculations for \(^3\text{H}(d,n)^4\text{H}\) at \( E_d = 6 \text{ MeV} \). These calculations made by Hale (Ha 79e) are
<table>
<thead>
<tr>
<th>Lab Angle</th>
<th>C.M. Angle</th>
<th>$^3\text{H}(d,p)^4\text{He}$ Reaction</th>
<th>$^3\text{He}(d,p)^4\text{He}$ Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$K_x^x(\Theta)$</td>
<td>$K_y^y(\Theta)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_z^z(\Theta)$</td>
<td>$K_y^y(\Theta)$</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$...$</td>
<td>$0.314 \pm 0.055$</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>$17.55$</td>
<td>$...$</td>
<td>$0.298 \pm 0.036$ $-0.357 \pm 0.034$</td>
</tr>
<tr>
<td>$25^\circ$</td>
<td>$29.16$</td>
<td>$...$</td>
<td>$0.526 \pm 0.042$ $-0.772 \pm 0.074$</td>
</tr>
<tr>
<td>$37.5^\circ$</td>
<td>$43.49$</td>
<td>$...$</td>
<td>$0.374 \pm 0.048$ $-0.237 \pm 0.074$</td>
</tr>
<tr>
<td>$45^\circ$</td>
<td>$51.97$</td>
<td>$0.337 \pm 0.055$ $-0.663 \pm 0.084$</td>
<td>$...$</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>$68.54$</td>
<td>$...$</td>
<td>$-0.264 \pm 0.081$</td>
</tr>
</tbody>
</table>
Figure IV-1 Comparison of the present $k_z^x(\Theta)$ data at $E_d = 6$ MeV with that of Sunier et al. (Su 76a) at $E_d = 7$ MeV.
Figure IV-1

\[3H(d,n)\, ^4He\]

- Present Work
  6 MeV
- Sunier et al.
  7 MeV
Figure IV-2 Comparison of the present $k_y^*(\Theta)$ data at $E_d = 6$ MeV with that of Sunier et al. (Su 76c) at $E_d = 7$ MeV.
Figure IV-2

$K_y' - 0$

$\theta_{\text{LAB}}$
based principally upon cross section and analyzing power data in all channels of $^5$He, and will be discussed more fully later. In general, the measured polarization transfer coefficients reach large magnitudes, $(K^y_y = -0.663)$ and have a strong angular dependence.

Data for comparison of $^3$H(d,n)$^4$He polarization transfer coefficients are sparse in this energy region. Broste et al. (Br 70a) have measured $K^y_y(\Theta)$ at $\Theta = 0^\circ$ from 3.9 to 15 MeV, and Sunier et al. (Su 76c) have measured angular distributions of both $K^x_z(\Theta)$ and $K^y_y(\Theta)$ at $E_d = 7$ MeV. These data are shown for comparison in Figures IV-1 and IV-2. The $K^x_z(\Theta)$ data at $E_d = 6$ MeV are substantially larger in magnitude than that of Sunier et al. at $E_d = 7$ MeV suggesting that the energy dependence of the polarization transfer coefficients may be substantial. However, the R-matrix prediction at $E_d = 6$ MeV is considerably larger than either data set. The comparison of the $K^y_y(\Theta)$ data at $E_d = 6$ MeV with that of Sunier et al. at $E_d = 7$ MeV in Figure IV-2 again depicts larger magnitude in the present data especially where the data peak at around $\Theta_{LAB} = 45^\circ$. The R-matrix prediction appears to be generally similar to the data in its angular dependence, but in this case predicts a magnitude too small at $\Theta_{LAB} = 45^\circ$. An excitation curve of all existing $K^y_y(\Theta)$ at $\Theta = 0^\circ$ data from 1-10 MeV is shown in Figure IV-3. The $K^y_y(\Theta)$ at $\Theta = 0^\circ$ datum shows
Figure IV-3  
Polarization transfer coefficient $K_y^\gamma(\theta)$ at $\theta = 0^\circ$ from 1 to 10 MeV.
Figure IV-3

$^{3}\text{H}(d,n)^{4}\text{He}$

- Present Work
- Sunier et al.
- Broste et al.
excellent agreement with those of both Broste et al. and Sunier et al. The R-matrix prediction for $K_{Y}^{Y'}(\Theta)$ at $\Theta = 0^\circ$ is in excellent agreement with the data. This is the most widely measured polarization transfer coefficient, and since the previous data guided the calculation by Hale (Ha 79e), such agreement is not surprising. Also, since the equations which relate the scattering matrix elements to the observables are considerably more simple at $\Theta = 0^\circ$, (chapters I and II), a better description of these data should be expected.

In contrast to the $K_{Y}^{Y'}$ data at $\Theta = 0^\circ$, the preliminary R-matrix predictions by Hale (Ha 79e) show only qualitative similarities to the measured data. The lack of detailed agreement is not surprising since there have been little previous data to guide the calculations. Inclusion of the present data into the R-matrix calculations for $^5$He should therefore improve the fits and help in determining the level structure for this few nucleon system.

IV-B. The $^3$He($\vec{d}$,$\vec{p}$)$^4$He Data

The $K_{Z}^{X'}(\Theta)$ data for $^3$He($\vec{d}$,$\vec{p}$)$^4$He at $E_d = 6$ MeV are plotted in Figure IV-4; the $K_{Y}^{Y'}(\Theta)$ data are plotted in Figure IV-5; and the $K_{zz}^{Y'}(\Theta)$ datum is plotted in Figure IV-6. The solid curves are the preliminary R-matrix calculations for $^3$He($\vec{d}$,$\vec{p}$)$^4$He by Dodder (Do 75h) at $E_d = 6$ MeV. These calculations are based only upon data in the
\(^{3}\text{Li}\) channels and include principally cross section and analyzing power data.

Data for comparison of \(^{3}\text{He}(d,p)^{4}\text{He}\) polarization transfer coefficients are again sparse in this energy region. Hardekopf et al. (Ha 73n) has measured \(K_y^Y(\Theta)\) at \(\Theta = 0^\circ\) from 4 to 14 MeV, and also has measured angular distributions of \(K_y^Y(\Theta)\), \(K_z^Z(\Theta)\) and \(K_{zz}^Y(\Theta)\) at \(E_d = 8\) MeV. These data are also shown in Figures IV-4 to IV-6. The \(K_z^Z(\Theta)\) data in Figure IV-4 agree surprisingly well with the preliminary R-matrix prediction of Dodder (Do 80g). This may be somewhat fortuitous since the only \(K_z^Z\) polarization transfer data included in the calculation were those of Hardekopf at \(E_d = 8\) MeV. The data point at \(\Theta = 0^\circ\) was measured with our experimental set-up to insure that there were no instrumental asymmetries. The measured value of \(K_z^Z(\Theta) = 0.008 \pm 0.019\) is consistant with the expected 0.0 value at \(\Theta = 0^\circ\). The data of Hardekopf et al. at \(E_d = 8\) MeV are similar in angular dependence at angles forward of \(\Theta_{lab} = 45^\circ\), but are considerably different at \(\Theta_{lab} = 60^\circ\). Unfortunately, because of the large difference in energy between that measurement and the present data, it is difficult to draw any conclusions from the differences. The comparison of the \(K_y^Y(\Theta)\) data at \(E_d = 6\) MeV with that of Hardekopf et al. at \(E_d = 8\) MeV in Figure IV-5 again depicts similar angular dependence, but considerable magnitude differences.
Figure IV-4: Comparison of the present $K^*(\Theta)$ data at $E_d = 6 \text{ MeV}$ with that of Hardekopf et al. (Ha 73n) at $E_d = 8 \text{ MeV}$. 
Figure IV-4

\[ \frac{^3\text{He}(d,p)^4\text{He}}{K_z} \]

- Present Work 6 MeV
- Hardekopf et al. 8 MeV
Figure IV-5  Comparison of the present $k'_y(\Theta)$ data at $E_d = 6$ MeV with that of Hardekopf et al. (Ha 73n) at $E_d = 8$ MeV.
Figure IV-5

$^3$He(d, p)$^4$He

- Present Work
  6 MeV
- Hardekopf et al.
  8 MeV

$K_y'$ vs. $\theta_{LAB}$
Figure IV-6  Comparison of the present $k^\nu_{zz}(\Theta)$ data at $E_d = 6$ MeV with that of Hardekopf et al. (Ha 73n) at $E_d = 8$ MeV.
\[ \frac{3}{4} \text{He}(d,p) \frac{4}{4} \text{He} \]

- Present Work 6 MeV
- Hardekopf et al. 8 MeV

Figure IV-6

\[ K_{zz}^{y'} \]

\[ \theta_{\text{LAB}} \]

1.0
0.5
0.0
-0.5
-1.0

0 90 180
The large magnitude of $K_y^y(\Theta)$ at $\Theta_{LAB} = 45^\circ$ prompted an additional measurement at $\Theta_{LAB} = 37.5^\circ$. As is seen from the figure, the measurement substantiated the large magnitude of this polarization transfer coefficient in the angular region $\Theta_{LAB} = 35^\circ$ to $50^\circ$. The R-matrix prediction for $K_y^y(\Theta)$ at $E_d = 6$ MeV is in good agreement with the data except in this region of large magnitude between $\Theta_{LAB} = 35^\circ$ to $50^\circ$ where the R-matrix is considerably smaller in magnitude.

Although measurement of a complete angular distribution of the polarization transfer coefficient $K_{zz}^y(\Theta)$ would have been desirable, this could not be done because of time restrictions. A tensor polarization transfer coefficient takes 50\% longer to measure than either of the vector polarization transfer coefficients therefore one measurement at $\Theta_{LAB} = 25^\circ$ was selected. This particular angle was chosen where $K_{zz}^y(\Theta)$ was expected to be large in magnitude as predicted by the R-matrix calculations. The magnitude of the measured $K_{zz}^y(\Theta)$ datum at $E_d = 6$ MeV is larger than any reported by Hardekopf et al. at $E_d = 8$ MeV, but is in reasonable agreement with the R-matrix prediction there.

An excitation curve of all existing $K_y^y(\Theta)$ at $\Theta = 0^\circ$ data from 1 to 10 MeV is shown in Figure IV-7. The measured $K_y^y(\Theta)$ at $\Theta = 0^\circ$ datum is in excellent agreement with that of Hardekopf at $E_d = 6$ MeV. Again, the R-matrix predictions for $\Theta = 0^\circ$ are in good agreement with all existing data.
Figure IV-7  Polarization transfer coefficient $k_y'(\Theta)$ at $\Theta = 0^\circ$ from 1 to 10 MeV.
Figure IV-7

$^3\text{He}(d,p)^4\text{He}$

- Present Work
- Hardekopf et al.
IV-C. Comparison of Polarization Transfer Coefficients in the Charge Symmetric Reactions: $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ and $^3\text{H}(\vec{d},\vec{n})^4\text{He}$

It is interesting to compare directly the measured polarization transfer coefficients for the two mirror reactions. Figures IV-8 and IV-9 compare the measured $K_x'(\Theta)$ and $K_y'(\Theta)$ data respectively for the $^3\text{H}(\vec{d},\vec{n})^4\text{He}$ and $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ reactions. The appropriate R-matrix fits from $^3\text{He}$ and $^3\text{Li}$ are also plotted. Strong differences of the R-matrix predictions, especially at back angles, are not surprising since these fits were done independently on two different bodies of data and may well involve different level structures. Figure IV-10 compares the measured $K_y'(\Theta)$ at $\Theta = 0^\circ$ datum for each reaction along with their respective R-matrix predictions. These comparisons will be discussed below.

Comparison of the polarization transfer coefficient $K_z'(\Theta)$ between the two mirror reactions, (Figure IV-8), shows what appears to be a significant magnitude difference at $45^\circ$. Unfortunately, the lack of a $^3\text{H}(\vec{d},\vec{n})^4\text{He}$ datum at $\Theta_{\text{LAB}} = 60^\circ$ hampers the comparison. Certainly more data over this angular region would aid in determining whether such differences persist. Comparison of the polarization transfer coefficient $K_y'(\Theta)$ between the two mirror reactions, shows good agreement at all angles measured,
Comparison of the measured data for the polarization transfer coefficient $K_{Z}(\Theta)$ for $^3\text{H}(\vec{d},\vec{p})^4\text{He}$ and $^4\text{He}(\vec{d},\vec{p})^4\text{He}$. The curves are the respective R-matrix predictions, (see text).
Figure IV-9  Comparison of the measured data for the polarization transfer coefficient $k^y_y(\Theta)$ for $^3\text{H}(\vec{d},\vec{n})^4\text{He}$ and $^3\text{He}(\vec{d},\vec{p})^4\text{He}$. The curves are the respective R-matrix predictions, (see text).
Figure IV-9

\[ K'_y \]

\[ \theta_{LAB} \]

\[ ^3\text{He}(d,p)^4\text{He} \]

\[ ^3\text{H}(d,n)^4\text{He} \]
Comparison of the measured data for the polarization transfer coefficient $K_{Y}^{y'}(\Theta)$ at $\Theta = 0^\circ$ for $^3\text{He}(^{3}\text{He},^{3}\text{He})^{3}\text{He}$ and $^3\text{He}(^{3}\text{He},^{3}\text{He})^{3}\text{He}$. The curves are the respective R-matrix predictions, (see text).
Figure IV-10

$E_d$ (MeV)

$K_y(0^\circ)$

$^3\text{He}(d,p)^4\text{He}$

$^3\text{H}(d,n)^4\text{He}$
including $\Theta_{\text{LAB}} = 45^\circ$, although neither R-matrix prediction approaches the measured magnitude there. The small difference at $\Theta = 0^\circ$ has been noted between these two reactions and is discussed below.

Figure IV-10 depicts the two measured $K^y_y(\Theta)$ at $\Theta = 0^\circ$ data points plotted on the respective R-matrix excitation curves. All current experimental evidence confirms that these two observables have a smooth energy dependence, and a rather constant magnitude difference between them at $\Theta = 0^\circ$, (see Figures IV-3 and IV-7 also).
V. SUMMARY

Measurement of polarization transfer coefficients for the $^3\text{H}(\vec{d},\vec{n})^4\text{He}$ and $^3\text{He}(\vec{d},\vec{p})^4\text{He}$ reaction were performed for a multiplicity of reasons. First these measurements provide new information which is sensitive to matrix elements previously untested in an energy region where questions on the structure of mass-5 exist. Secondly, comparison of polarization transfer observables of charge symmetric reactions offers an unusual and sensitive tool through which one may investigate charge symmetry of the nuclear force. In particular, although large differences were seen at $E_d = 6$ MeV in $A_{zz}(0)$ for these reactions, whether these differences would manifest themselves in polarization transfer coefficients was of interest. Lastly, this study extends the body of independent observables measured at $E_d = 6$ MeV for the mass 5 system in the pursuit of eventually accomplishing a "complete experiment," allowing one to calculate the scattering matrix elements. Certainly, the present data alone are not enough to base an analysis upon in a system as complex as mass 5. However, analysis of the more complete cross section and analyzing power measurements may find the current data important in their
conclusion. For instance, Jenny et al. (Je 80f) in a phase shift analysis of $^7$Li found more than one solution between which he could not distinguish. Polarization transfer coefficients may allow an analysis to distinguish between solutions otherwise equivalent. Although there are differences between the observables in the two charge symmetric reactions, most notably $K_{y'}(0^o)$, understanding the mechanisms which cause the observed differences is very complex and beyond the scope of this work. Perhaps the best method for understanding the present data and the mass 5 system is by a charge independent R-matrix analysis on all reaction channels, such as that underway at L.A.S.L. Data from both $^3$He(d,p)$^4$He and $^3$H(d,n)$^4$He will be added to the data base for the L.A.S.L. R-matrix search.

The R-matrix search as yet has not been carried out in a charge independent manner. Limitations due to the physical memory size of the L.A.S.L. CDC 7600 computer forced previous searches to focus either on $^3$He or $^7$Li independently. Recent installation of a Cray array processing computer promises to remedy this problem in the near future. The R-matrix parametrization will be compared with all data on any open channel in the mass 5 isobar. The scope of the problem may be realized if one considers that well over 10,000 data points will figure into the search.
Clearly, a detailed discussion of the R-matrix calculation will not be presented here, although Dodder and Hale (Do75^) have reported some details of their work before. Since this work is continuing at L.A.S.L., level parameters are as yet not available.

Preliminary analysis of $^3$He$(\vec{d},\vec{p})^4$He and $^3$H$(\vec{d},\vec{n})^4$He analyzing powers, (Cl 80c), by the R-matrix analysis suggested that the observed differences may arise from the Coulomb effects, (Ha 79e). Whether or not the observed differences in $^3$He$(\vec{d},\vec{p})^4$He and $^3$H$(\vec{d},\vec{n})^4$He polarization transfer coefficients can also be explained as arising entirely from coulomb effects remains to be established. It is premature to speculate at this time whether such differences may indicate a violation of charge symmetry in the mass 5 system.

In conclusion, this measurement of polarization transfer coefficients in the mass 5 system has made a number of significant contributions to the knowledge of light mass systems. The measurements have provided new and difficult to measure data which may prove valuable in studying the level structure in $^5$He and $^5$Li. In addition, comparison of the vector polarization transfer coefficients between the two reactions has shown some large differences, particularly at $\Theta = 0^\circ$ and $\Theta_{\text{lab}} = 45^\circ$ which are as yet unexplained.
Whether these differences may be a manifestation of the proposed more complex level structures discussed earlier is not clear. Also, the L.A.S.L. R-matrix analysis on the mass five system underway by Dodder and Hale (Ha 80e) will benefit from these new and unique charge symmetric data. Certainly they will offer the R-matrix an opportunity to explain observed differences within the context of charge symmetry.
APPENDIX A

Determination of a set of independent observables from the 20 different ones included in equation (1) requires tedious algebraic manipulation. One should be aware that the relations in equation (3) are the only linear dependent equations that one can write between observables. These effectively reduce the 20 observables to 18, of which only 10 are independent. Which set of 10 one chooses is dependent upon the reader's perseverance in its determination. The set that this author is interested in has not been shown before to be independent and so is shown here.

The remaining 18 observables are related not linearly, but quadratically. Figure A-1 depicts 12 quadratic relations which may be derived from manipulation of the definitions in Figure I-3. A more formal outline of this procedure is in Keaton et al (Ke 74e) and will not be reproduced here. Given these 12 quadratic relations, I intend to show that the observables measured during this experiment are in fact independent, and identify those measurements necessary to completely determine the $1/2(1,1/2)0$ system.
Figure A-1  The 12 quadratic relations for $\frac{1}{2}(\tilde{1}, \frac{1}{2})_0$, from (Ke 74e) and (Oh 72e).
<table>
<thead>
<tr>
<th>Step</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = (1-A_{yy})(1-A_{zz}) - (p_{yy} - K_{yy}^e)(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>2</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = (1-A_{yy})(1-A_{xx}) - (p_{yy} - K_{yy}^e)(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>3</td>
<td>((\frac{3}{2}A_{yz})^2 + (A_{xx})^2 + (\frac{3}{2}K_{yz})^2 + (K_{xx})^2 = (1-A_{zz})(1-A_{zz}) + (p_{yy} - K_{yy}^e)(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>4</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{zz})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>5</td>
<td>((\frac{3}{2}A_{yz})^2 + (A_{xx})^2 + (\frac{3}{2}K_{yz})^2 = \frac{1}{2}(1-A_{zz})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>6</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>7</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>8</td>
<td>((\frac{3}{2}A_{yz})^2 + (A_{xx})^2 + (\frac{3}{2}K_{yz})^2 = \frac{1}{2}(1-A_{zz})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>9</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>10</td>
<td>((\frac{3}{2}A_{yz})^2 + (A_{xx})^2 + (\frac{3}{2}K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
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<tr>
<td>11</td>
<td>((\frac{3}{2}x^2t^2 + (K_{yz})^2 + 2x^2t^2 + (K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
<tr>
<td>12</td>
<td>((\frac{3}{2}A_{yz})^2 + (A_{xx})^2 + (\frac{3}{2}K_{yz})^2 = \frac{1}{2}(1-A_{yy})(p_{yy} - K_{yy}^e) + \frac{1}{2}(1-A_{xx})(p_{yy} - K_{yy}^e))</td>
</tr>
</tbody>
</table>

**Figure A-1**
First, let us divide all observables into two sets:

**Set I**

$I_0(\Theta), P^{y'}(\Theta)

$(A_{xx}(\Theta)-A_{yy}(\Theta)), A_{zz}(\Theta)

$(K_{xx}'(\Theta)-K_{yy}'(\Theta)), K_{zz}'(\Theta)$

**Set II**

$K_x'(\Theta), K_y'(\Theta), K_z'(\Theta), K_z'(\Theta), K_x'(\Theta), K_y'(\Theta)$

The observables in Set I can be shown to be independent of one another (see Ke 74e) and appear only on the right-hand side of quadratic relations 1-6. The observables of Set II appear only on the left-hand side of quadratic relations 1-6. Therefore, if the observables of Set I are considered to have already been measured, then the right-hand side of relations 1-6 are determined, and of the four observables in each line of Set II, one may be eliminated as redundant. I choose to eliminate $K_{yz}'(\Theta), K_{xy}'(\Theta)$, and $K_{xz}'(\Theta)$. One needs now to determine only four independent observables from the remaining nine in Set II. My choices here will be guided by experimental limitations and experience concerning ease of measurement.

Following arguments similar to those presented by Keaton et al. (Ke 74e), the procedure now is to eliminate redundant coefficients by use of the quadratic relations 7 through 12, (Figure A-1). For example, quadratic relation 7 relates all the coefficients in the first and third lines
of Set II to the coefficients $K^x_z(\Theta)$ and $K^y_{xy}(\Theta)$. Therefore, any one of those eight coefficients can be written as a function of the other seven and may be eliminated from the independent set, and from equations 8-12, (Figure A-1). I choose to remove the coefficient $K^z_x(\Theta)$ from the set. Similarly, one may use quadratic relation 8 to eliminate $K^z_x(\Theta)$, relation 9 to eliminate $K^x_{xy}(\Theta)$, relation 10 to eliminate $K^x_{yz}(\Theta)$, and relation 11 to eliminate $K^y_x(\Theta)$. With elimination of those eight coefficients, all the coefficients in the first line of Set II have been eliminated. Quadratic relation 12 offers no new information between coefficients and is itself redundant. Therefore, the independent observables left in Set II are $K^x_z(\Theta)$, $A_{xz}(\Theta)$, $K^y_y(\Theta)$ and $A_y(\Theta)$. Therefore, one set of ten independent observables for the $1/2 + 1/2 \rightarrow 1/2 + 0$ reaction are:

\[
\begin{align*}
I_o(\Theta), \enspace P^y(\Theta), & \quad K^x_z(\Theta), \ K^y_y(\Theta), \\
A_y(\Theta), \ A_{xz}(\Theta), \ (A_{xx}(\Theta) - A_{yy}(\Theta))/2, & \quad (K^y_{yy}(\Theta) - K^y_{yy}(\Theta))/2, \\
A_{zz}(\Theta) & \quad K^y_{zz}(\Theta)
\end{align*}
\]

Measurements in this experiment were limited to measuring the independent coefficients $K^x_z(\Theta)$, $K^y_y(\Theta)$ and $K^y_{zz}(\Theta)$.
In the analysis of data for this experiment, a number of computer programs were written and adapted for an IBM 1800 and Data General Eclipse computers. These programs can be divided into four general categories: 1) proton polarimeter analyzing power calculations, 2) monte carlo neutron analyzing power calculations, 3) on-line/off-line peak summing calculations, and 4) off-line asymmetry reanalysis calculations. Each of these categories and their results will be discussed below.


In order to calculate polarization transfer coefficients for the $^3\text{He}(^7\text{Be},p)^4\text{He}$ reaction, the proton polarimeter's analyzing power was calculated as a function of laboratory angle, and verified experimentally. The program PROTEST calls a number of subroutines and directs the calculation. A brief description of the subroutines that are called follows:
INCID initializes the program with a gaussian energy profile of the polarized deuteron beam. The beams initial energy width was set to be 20 keV.

TRANS does energy loss and straggling of an energy profile of a beam of charged particles through matter.

SCAMX traces the energy profile of the incident deuteron beam through the high pressure $^3$He cell and calculates the energy profile of the resultant proton beam taking into account energy loss, kinematics and the $^3$He(d,p)$^4$He differential reaction cross sections.

RMATX calculates coulomb wave functions and phase shifts as a function of energy from input R-matrix parameters. The input R-matrix parameters for p-α scattering were taken from Stammbach and Walter (St 72h).

SCRAM calculates center-of-mass polarizations and cross sections as a function of center-of-mass angle from input phase shifts for p-α scattering.
PHICOR integrates $A_y \cos \phi$ over the azimuthal angle $\phi$ subtended by each detector element through each vane of the vaned polarimeter.

KINMA calculates outgoing laboratory angles and energies for nuclear scattering and reaction products. It also converts center-of-mass cross sections into relative laboratory cross sections.

RDSCAT traces the energy profile and relative yields of the scattered reaction protons through the proton polarimeter and into the symmetric surface barrier detectors. It transmits the secondary proton beam through the polarimeter absorbers, polarimeter entrance foil, $^4$He gas, transmission Si surface barrier detector and to the vaned region of the polarimeter where $p-\alpha$ scattering at $\sim 10$ MeV takes place. The asymmetric yields are then used to calculate a typical beam energy, profile and analyzing power for this reaction. Since $p-\alpha$ analyzing powers are rather large and extremely flat at $\Theta_{ab} = 60^\circ$ around $E_{p-\alpha} = 10$ MeV, the entrance absorbers were adjusted at each reaction laboratory angle to keep the energy of the $p-\alpha$ scattering
in the vaned region of the polarimeter approximately the same throughout the experiment. A separate calculation was made however for every angle and the $p-\alpha$ analyzing power calculated is believed to be accurate within $\Delta \Lambda^2(\theta_\alpha) = \pm 0.01$.


The program MOCCASINS (Sa 68d) was written to determine the average analyzing power for a neutron polarimeter which consists of a central detector of analyzer substance, and two symmetric detectors at angle $\theta_\alpha$ from the neutron beam. It calculates a geometry correction to the analyzing power arising from the non-point geometry of the detector arrangement and a double scattering correction due to scattering twice from the analyzer substance. Since the analyzer substance can include up to three components (He, Xe, and Fe), wall scattering of neutrons from the central detector container can also be calculated. The calculation of cross sections, polarizations and total cross sections is made using a set of real phase shifts and inelastic parameters which are input from a disk file at a series of energies. More detailed information concerning input to MOCCASINS may be
obtained from Rhea (Rh 73m) and Lisowski (Li 73j). The principle components of the program are described below.

The program is written in Fortran V and modified to run on the Data General Eclipse Computer. Included in it are the following subroutines:

POLPAC reads in the phase shifts necessary for the calculation of observables from disk and builds a table for cross sections, polarizations, and Wolfenstein's R-parameters. Then, the mean free path of neutrons in the $^4$He cell, $\text{n} + ^4\text{He}$ total cross section and the neutron detector mean free path as a function of incident neutron energy are calculated. Phase shifts are taken from Stammbach and Walter (St 72h) and Hoop and Barschall (Ho 66f).

RNDM then selects random points (RANDU) in the detectors to designate neutron paths. For this the shape of the $^4$He cell was specified to be the intersection of two cylinders at right angles. To save computation time and to ensure a relatively even distribution of neutron paths, the second path uses the same
point in the side detector and a point in the $^4$He cell which is the initial point reflected across the line connecting the detector centers. The side detector is then reflected about the line of centers to give a third path, and then the $^4$He cell point is reflected again to give a fourth. Two new random points are selected and the process continues until the total number of paths reaches the specified limit set near to be 4000. For each of these paths the values of the analyzing power and relative probability are calculated from values linearly interpolated from the POLPAC table. The interpolation is done by the subroutines INTPE and INTPTE. After a complete single scattering calculation is done, two points are selected in the $^4$He cell for each path for a double scattering calculation.

For estimating wall scattering the following approximations were used:

a) The $\text{Fe}(n,n)\text{Fe}$ cross section was appreciable only at forward angles and therefore back scattered events could be ignored.
b) The randomly selected points are projected onto the surface of the cell, and then the back half of the surface is projected onto the "front" where the "front" is the side closest to the target. One must then estimate the amount of wall material which effectively enters into a scattering, i.e. the program must be told the ratio of effective number of wall material atoms to the number of atoms in the gas.

c) The effect of D, R, and A, (Wo 56a) for scattering from iron assured to be unimportant and was therefore ignored.

PDET calculates the detection probability for each neutron when a pulse height window in the recoil-spectrums is used. Then the calculated recoil energy spectra in the $^4$He cell is calculated and smeared by the gaussian resolution of the system. The left and right spectra along with the asymmetry are then tabulated and plotted as a function of energy.
In this calculation, then, the following effects are included explicitly:

a) Neutron attenuation in all three detectors.

b) Energy dependence of the efficiency in the side detectors for a given bias energy.

c) Wolfenstein's R-parameter for spin rotation in the first scattering if a double scattering calculation from $^4$He is made.

d) Effect of the central detector resolution upon the pulse height window for the analysis.

e) Scattering points in the central detector and detection points in the side detector are chosen randomly for every neutron and its scattering angle is calculated.


All of the data collected in these experiments were acquired as histogram spectra. These spectra were acquired and analyzed on-line by the IBM 1800 computer where each run was stored on magnetic disk. The on-line analysis consisted of reducing
the spectra to detector yields by summing the number of counts in the peak and correcting for detector dead time. Since each polarization transfer coefficient data run had statistically poor information, a resummed total of the individual runs according to spin type was constructed and analyzed separately. After a set of detector yields had been accumulated, the asymmetries were then computed according to the measurement. This real-time interactive program package is described more fully by Clark (Cl 80c).

Since each data point measurement involved typically between 20 and 50 independent but statistically poor measurements of the same asymmetry, the results of these calculations, and the result of the calculation on the resummed spectra were transferred to the Data General Eclipse Computer where they were statistically averaged and compared. This process was employed to help identify inconsistencies in the data and analysis procedures. Programs named for the data they analyzed (i.e. KZ.X, KY.Y, and KZZ.Y) handled this entire process and included subroutines.
PAVG statistically averaged the results of all polarization runs over the length of a data point measurement and determined its total uncertainty.

TAVG statistically averaged the resultant asymmetries of all polarization transfer coefficient runs over the length of a data point measurement and determined its statistical uncertainty.

VALUE gathered from tables accumulated on magnetic disk the appropriate values of $A_\alpha(\Theta_\alpha)$, $P^Y(\Theta)$, $A_y(\Theta)$, and $A_{zz}(\Theta)$ and their uncertainties when necessary to a particular calculation.

The program would then calculate the appropriate polarization transfer coefficient and its overall uncertainty from the above inputs. There were versions of these programs and value tables tailored to both the neutron and proton part of the experiment.

Values of observables $P^Y(\Theta)$, $A_y(\Theta)$, and $A_{zz}(\Theta)$ for $^3\text{He}(^3\text{He},p)^4\text{He}$ and $^3\text{H}(^3\text{He},n)^4\text{He}$ were calculated from Legendre polynomial fits to existing data provided by sources listed in Table A-1. Values of
\( A_a(\Theta_a) \) for the \(^3\text{He}(\vec{d},\vec{p})^4\text{He}\) experiment were calculated from PROTEST, and values of \( A_a(\Theta_a) \) for the \(^3\text{H}(\vec{d},\vec{n})^4\text{He}\) experiment were calculated from MOCCASINS, both described earlier.

### TABLE A-1

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experiment</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P^V'(\Theta) )</td>
<td>(^3\text{He}(\vec{d},\vec{p})^4\text{He})</td>
<td>(Cl 73h)</td>
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<tr>
<td>( P^V'(\Theta) )</td>
<td>(^3\text{H}(\vec{d},\vec{n})^4\text{He})</td>
<td>(Sm 72b, Bu 67b)</td>
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<tr>
<td>( A_y(\Theta), A_{zz}(\Theta) )</td>
<td>(^3\text{He}(\vec{d},\vec{p})^4\text{He}, \ ^5\text{H}(\vec{d},\vec{n})^4\text{He})</td>
<td>(Cl 80c)</td>
</tr>
</tbody>
</table>

4. Off-Line Asymmetry Reanalysis Calculations

Off-line, the entire experiment's data was transferred to the Data General Eclipse Computer and stored on magnetic tape. Program TOUTH would then resum desired runs of corresponding spin type for a particular measurement, and derive asymmetries as calculated according to one of three possible modes of operation. Mode = 1 allows one to sum a fixed number of channels to form a window, and then calculates and plots adjacent window asymmetries as a function of the pulse height. Mode = 2 is similar, but plots accumulative window asymmetries as a function of pulse height. Mode
= 3 again sums a fixed number of channels to form a window, but then calculates and plots windows shifted by a single channel number as a function of the pulse height. This analysis was done to investigate the significance and effect of any possible background on the calculated asymmetries, and to look for inconsistencies in the data collection. This analysis typically showed a flat asymmetry across the peaks of interest lending confidence to the data and method, and helping guide channel selection for the subsequent peak summation. The program TOUTH makes use of the following subroutines:

STARTAPE which initializes an index on disk to all the data runs stored on magnetic tape.

TAPEPLOT which gets a run numbered spectra and plots it for viewing on a 4050 Tektronix Terminal.

RESUM which searched the tape index to determine which runs are to be resummed together, gets them, corrects them for deadtime, and accumulates both the data run and the scalers for that measurement.
BRING gets a run from magnetic tape of a specified run number.

BSCAL retrieves the scalers from magnetic tape of a specified run number.

GAREA calculates the numerical area between two channels.

BKRNK calculates the numerical background between two channels from four other channels selected to determine the type and extent of the background subtraction.

PLOT plots the resultant resummed spectra on either the 4050 Tektronix Terminal, or on a Printronix Printer/Plotter.
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<thead>
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<th>Reference</th>
<th>Title</th>
<th>Authors</th>
<th>Journal/Report</th>
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<tr>
<td>Ch 65a</td>
<td>&quot;Neutron Polarization in the T(d,n)$^4$He Reaction at $E_\gamma$ = 2.1 and 2.9 MeV,&quot; J. Christiansen, W. Busser, F. Niebergall and G. Söhngen</td>
<td>Nucl. Phys. 62 (1965) 133.</td>
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<tr>
<td>Cl 73h</td>
<td>&quot;Measurement of the Proton Polarization in the $^3$He(d,p)$^4$He Reaction Between 2.0 and 6.0 MeV,&quot; J.F. Clare</td>
<td>Nucl. Phys. A217 (1973) 342.</td>
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</tbody>
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