LA-5393-T

THESIS

Analyzing Power, Polarization, and
Polarization Transfer Measurements in the
Reaction $T(p,n)^3\text{He}$

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UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$5.45; Microfiche \$1.45

LA-5393-T

Thesis

UC-34c

ISSUED: November 1973

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Analyzing Power, Polarization, and Polarization Transfer Measurements in the Reaction $T(p,n)^3\text{He}$

by

John J. Jarmer

Financial assistance provided by an Associated Western Universities Fellowship

This report is derived from a dissertation submitted to the Department of Physics and Astronomy of the Graduate School of the University of Wyoming in partial fulfillment of requirements for the Degree of Doctor of Philosophy.

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ABSTRACT

Experimental studies of polarization effects in the reaction $T(p,n)^3\text{He}$ were undertaken for the following basic purposes:

- (1) To provide experimental data which will help in the understanding of spin dependent effects in the $T(p,n)^3\text{He}$ reaction and which will give information about the nucleus ^4He .
- (2) To confront the existing theory of ^4He with new data.
- (3) To provide data which will be useful in any reanalysis of the 4-body system.

The experimental work fell into three catagories as follows:

- (1) Analyzing power measurements with the incident proton beam polarized. Angular distributions were measured for proton energies of 6.00, 9.96, and 13.55 MeV. The analyzing power was also measured at 45° for a proton energy range from 1.51 to 11.95 MeV.
- (2) Neutron polarization measurements with incident proton beam unpolarized. Angular distributions were measured for proton energies of 5.97 and 9.87 MeV.
- (3) Polarization transfer measurements which consisted of measuring the neutron polarization

with the incident proton beam polarized. Angular distributions of the transfer observables $K_x^{x'}$, $K_z^{x'}$, and $K_y^{y'}$ were measured for proton energies of 5.97 and 9.94 MeV. The transfer observable $K_z^{z'}$ was measured at 0° for proton energies from 4.0 to 15.0 MeV and an angular distribution was measured at 10.0 MeV. The $K_z^{z'}$ measurements were made possible by the use of a dipole spin precession magnet and represent the first measurements of this observable at Van de Graaff energies and the first measurement of $K_z^{z'}$ in a nuclear reaction at any energy.

A comparison of the experimental values of the analyzing power and polarization indicates that at the energies of 6.00, 9.96, and 13.55 MeV the data are consistent with equality of these observables.

The polarization transfer observables $K_y^{y'}$ and $K_z^{z'}$ are measured to be about 80% of their maximum value. This indicates a large transfer of polarization from the incident proton to the outgoing neutron.

All of the data are compared to R-matrix calculations based on the current level structure of ^4He . The calculations reproduce qualitative aspects of the data but quantitative agreement is lacking. In some cases the calculations deviate considerably from the experimental data. The comparison indicates that changes in the current level structure of ^4He will be necessary to accommodate the data.

CHAPTER I

INTRODUCTION

1.1 Motivation for the Experiments

The basic purpose of the $T(p,n)^3\text{He}$ polarization measurements to be reported in this thesis is to provide experimental data which will be of use in the understanding of the nucleus ^4He . Of the few-nucleon systems, ^4He , which consists of two protons and two neutrons, is one of the lightest systems for which excited nuclear states are known to exist.¹ All of the excited states are unstable to particle decay since they lie above an excitation energy of 19.8 MeV which is the energy needed to dissociate ^4He into a proton and triton.

An R-matrix² analysis of differential cross section and polarization data from the $T(p,n)^3\text{He}$ reaction was done in 1968 by Werntz and Meyerhof³ (henceforth referred to as WM). This analysis resulted in two level schemes of ^4He which will be referred to as WMI and WMII. Even though it was not possible for WM to distinguish between the two solutions with the data available at that time their results were significant in that both WMI and WMII indicated a number of states in ^4He above 20.2 MeV excitation energy.

The advent of polarized ion sources has made practical experiments to measure observables which before were impractical or at best extremely difficult. The comparison of recent measurements⁴ in the

$T(p,n)^3\text{He}$ reaction, initiated with a polarized proton beam, with R-matrix calculations based on the WM level scheme of ^4He has indicated that neither of their solutions account for the data. The suggestion has been made⁴ that a comprehensive multichannel analysis of data on the four-body system should be made in order to obtain a reliable level structure. The success of any analysis depends directly on the type and quality of the experimental data used. Thus an additional impetus for the measurements was to provide experimental data for a number of observables which will be helpful in any reanalysis of the four-body system.

1.2 Type of Measurements Performed

One can obtain information about ^4He by studying a number of scatterings and reactions. Study of the $T(p,n)^3\text{He}$ reaction is an important process. Differential cross sections have already been measured, a study of polarization phenomena in the $T(p,n)^3\text{He}$ reaction brings in new information by providing measurements of different observables. Initiating the reaction $T(p,n)^3\text{He}$ with a polarized proton beam and then measuring the neutron polarization allows one to determine a number of different observables. The type of measurements that were performed are indicated schematically in Fig. 1. In this figure the polarization of the incident particle is referred to the laboratory initial coordinate system and the polarization of final particle to the laboratory final coordinate system. These two coordinate systems have a common y axis parallel to the initial momentum crossed into the final momentum $\vec{k} \times \vec{k}'$. The z axis of the

initial laboratory system is parallel to the incident momentum $\vec{k}$ and the z' axis of the final laboratory system is parallel to the final momentum $\vec{k}'$. The x axis of both coordinate systems is chosen to form a right-handed coordinate system. In Fig. 1 an arrow above the particle indicates that its polarization is either measured or known. The absence of an arrow above a detected particle indicates that only intensities are measured. Starting in the upper left-hand corner of Fig. 1 is shown the neutron polarization P_y' . To measure P_y' the reaction is initiated with an unpolarized proton beam and the polarization of the neutrons normal to the reaction plane is measured. The observable in the upper right-hand corner is the analyzing power A_y . To measure A_y a proton beam polarized in the y direction is used to initiate the reaction and the left-right scattering intensity of the neutrons is measured. The rest of the observables shown are polarization transfer coefficients and are designated as $K_i^{j'}$. In this notation the subscript on the K refers to the polarization of the incident particle, and the superscript refers to the polarization of the detected particle. Thus $K_x^{x'}$ indicates that the incident proton beam is polarized in the x direction and the x' component of neutron polarization is measured. Similarly for the rest of the transfer coefficients shown. These observables are equivalent to the well known Wolfenstein⁵ parameters for nucleon-nucleon scattering, the relation to them being⁶

Fig. 1. Schematic of the Measurements.

$$\begin{aligned}
K_X^{Z'} &= R', & K_Z^{X'} &= A \\
K_X^{X'} &= R, & K_Z^{Z'} &= A' \quad . & (1-1) \\
K_Y^Y &= D
\end{aligned}$$

1.3 Summary of Data to be Presented

A summary tabulation of the observables measured and the energies at which they were measured is presented below. In the reaction notation an arrow above the particle indicates that its polarization is either measured or known. The absence of an arrow above a detected particle means that only intensities are measured.

TABLE I

Type of Measurements Performed

<u>Reaction</u>	<u>Proton Energy</u>	<u>Observable Measured</u>
$T(\vec{p}, n)^3\text{He}$	1.5 + 12 MeV	$A_y(45^\circ)$
$T(\vec{p}, n)^3\text{He}$	6.00, 9.96, 13.55 MeV	$A_y(\theta)$
$T(p, \vec{n})^3\text{He}$	5.97, 9.87 MeV	$P_{y'}(\theta)$
$T(\vec{p}, \vec{n})^3\text{He}$	5.97, 9.94 MeV	$K_X^{X'}(\theta), K_Z^{X'}(\theta), K_Y^{Y'}(\theta)$
$T(\vec{p}, \vec{n})^3\text{He}$	4 + 15 MeV	$K_Z^{Z'}(0^\circ)$
$T(\vec{p}, \vec{n})^3\text{He}$	10 MeV	$K_Z^{Z'}(\theta)$

CHAPTER II
SPIN STRUCTURE AND SCATTERING AMPLITUDES
OF THE REACTION $T(p,n)^3\text{He}$

2.1 Spin Structure of $T(p,n)^3\text{He}$

The intrinsic spin angular momentum of each of the four particles involved in the reaction $T(p,n)^3\text{He}$ is $S = 1/2$, and the intrinsic parity of each of the four is positive. The description of a nuclear scattering or reaction where both particles involved in the initial and final channel possess intrinsic spin $1/2$ is accomplished by specifying the amplitude of any outgoing spin and momentum state as a function of the incident spin and momentum.⁷ The scattering amplitude $f(\theta)$ is replaced by a scattering matrix $M(\theta, \phi)$. The M matrix transforms the initial spin and momentum state into the final spin and momentum state.

A nuclear scattering conserves energy, momentum, angular momentum, and parity. The M matrix must also conserve these quantities. Conservation of angular momentum requires the M matrix to be rotationally invariant. This, in turn, restricts the M matrix to a scalar or pseudoscalar operator. The conservation of parity requires the operator to be a pseudoscalar operator.

The description of a nuclear scattering requires the use of a coordinate system. In the discussion that follows and unless otherwise stated, the coordinate systems shown in Fig. 2 will be used.

Fig. 2. Laboratory Initial and Final Coordinate Systems.

Figure 2 shows two frames of reference; the incident laboratory frame defined by the orthonormal basis $\hat{x}, \hat{y}, \hat{z}$ and the final or scattered laboratory frame described by the orthonormal basis $\hat{x}', \hat{y}', \hat{z}'$. The two frames have a common y axis $\hat{y} = \hat{y}' = \hat{n}$, defined by the normal to the scattering plane $\hat{n} = (\vec{k} \times \vec{k}') / |\vec{k} \times \vec{k}'|$, where $\vec{k}$ and $\vec{k}'$ are the incident and scattered direction of motion in the laboratory system. The axes $\hat{z}$ and $\hat{z}'$ are taken along $\vec{k}$ and $\vec{k}'$.

Measurable observations are related to the M matrix by the density matrix formalism.⁶ The initial density matrix for a polarized proton beam expressed in the incident laboratory frame may be written as⁸

$$\rho_i = \frac{1}{4} (1 + \sum_{j=1}^3 p_j \sigma_j) , \quad (2-1)$$

where $j = 1, 2, 3$ corresponds to x, y, z , p_j is the magnitude of the j^{th} component of proton polarization, and σ_j is the Pauli spin matrix. The final normalized density matrix is

$$\rho_f = \frac{M \rho_i M^\dagger}{\text{Tr}[M \rho_i M^\dagger]} \quad (2-2)$$

The polarization of the outgoing neutron referred to the scattered laboratory frame is given by

$$p_{k'} \equiv \langle \sigma_{k'} \rangle = \frac{\text{Tr} \rho_f \sigma_{k'}}{\text{Tr} \rho_f} . \quad (2-3)$$

In this equation and equations that follow the prime indicates that p_k , refers to the outgoing neutron polarization described in the laboratory final coordinate system. The absence of a prime on the incident proton polarization p_j indicates that this quantity is described in the laboratory initial coordinate system. The cross section for a polarized incident beam is given by

$$I(\theta, \phi) = \frac{\text{Tr} M \rho_i M^\dagger}{k^2} = \frac{\text{Tr} \rho_f}{k^2} , \quad (2-4)$$

and the cross section for an unpolarized incident beam is

$$I_o(\theta) = \frac{\text{Tr} M M^\dagger}{4k^2} \quad (2-5)$$

where k is the magnitude of the center-of-mass wave vector of the incident proton. If one substitutes the expression for ρ_i in the expression for the differential cross section $I(\theta, \phi)$ one obtains

$$\begin{aligned} I(\theta, \phi) &= \frac{1}{k^2} \text{Tr} M \frac{1}{4} \left(1 + \sum_{j=1}^3 p_j \sigma_j \right) M^\dagger \\ &= \frac{1}{4k^2} \text{Tr} M M^\dagger + \frac{1}{4k^2} \sum_{j=1}^3 p_j \text{Tr} M \sigma_j M^\dagger \\ &= I_o \left(1 + \sum_{j=1}^3 p_j \frac{\text{Tr} M \sigma_j M^\dagger}{\text{Tr} M M^\dagger} \right) \end{aligned} \quad (2-6)$$

By defining

$$A_j(\theta) = \frac{\text{Tr} M \sigma_j M^\dagger}{\text{Tr} M M^\dagger} \quad , \quad (2-7)$$

one may write for the differential cross section

$$I(\theta, \phi) = I_o(\theta) \left[1 + \sum_{j=1}^3 p_j A_j(\theta) \right] \quad . \quad (2-8)$$

$A_j(\theta)$ is the analyzing power of the reaction for the j th initial polarization component. This notation for the analyzing power is consistent with the Madison Convention.⁹ In a similar manner substituting for ρ_i in the expression for the scattered neutron polarization one obtains

$$I(\theta, \phi) p_{k'} = I_o(\theta) \left[P_{k'}(\theta) + \sum_{j=1}^3 p_j K_j^{k'}(\theta) \right] \quad , \quad (2-9)$$

where

$$P_{k'}(\theta) = \frac{\text{Tr} M M^\dagger \sigma_{k'}}{\text{Tr} M M^\dagger} \quad (2-10)$$

and

$$K_j^{k'}(\theta) = \frac{\text{Tr} M \sigma_j M^\dagger \sigma_{k'}}{\text{Tr} M M^\dagger} \quad . \quad (2-11)$$

$P_k(\theta)$ is the k 'th component of polarization produced by an unpolarized beam. $K_j^{k'}(\theta)$ is the polarization transfer coefficient and it relates the j th initial polarization component to the k 'th final polarization component.

Writing the expanded form for the cross section and polarizations one obtains

$$\begin{aligned}
 I(\theta, \phi) &= I_0(\theta) [1 + p_x A_x(\theta) + p_y A_y(\theta) + p_z A_z(\theta)] \\
 p_x, I(\theta, \phi) &= I_0(\theta) [P_x(\theta) + p_x K_x^{x'}(\theta) + p_y K_y^{x'}(\theta) + p_z K_z^{x'}(\theta)] \\
 p_y, I(\theta, \phi) &= I_0(\theta) [P_y(\theta) + p_x K_x^{y'}(\theta) + p_y K_y^{y'}(\theta) + p_z K_z^{y'}(\theta)] \quad (2-12) \\
 p_z, I(\theta, \phi) &= I_0(\theta) [P_z(\theta) + p_x K_x^{z'}(\theta) + p_y K_y^{z'}(\theta) + p_z K_z^{z'}(\theta)] .
 \end{aligned}$$

These forms of the observables are the most general allowed by rotational invariance; by requiring the observables to conserve parity these expressions reduce to⁶

$$\begin{aligned}
 I &= I_0 (1 + p_y A_y) \\
 p_x, I &= I_0 (p_x K_x^{x'} + p_z K_z^{x'}) \\
 p_y, I &= I_0 (P_y + p_y K_y^{y'}) \\
 p_z, I &= I_0 (p_x K_x^{z'} + p_z K_z^{z'}) .
 \end{aligned} \quad (2-13)$$

These forms apply for any choice of x, z and x', z' axes, but y and y' must lie along $\vec{k} \times \vec{k}'$.⁶

Consider how one would measure the observables. The differential cross section for an unpolarized incident beam I_0 is measured by detecting the number of neutrons produced, for a given number of incident protons, into a given element of solid angle $\Delta\Omega$ as a function of proton energy and scattering angle. Next consider how one would measure the analyzing power A_y . Let N_+ be the number of neutrons detected in $\Delta\Omega$ at the angle θ when the reaction is initiated with the incident proton beam polarized in the $+\hat{y}$ direction; then

$$N_+ = CI_0(\theta)[1+p_y A_y(\theta)] \quad . \quad (2-14)$$

The constant C involves the detection efficiency, target thickness, number of incident protons, etc., and p_y is the magnitude of the beam polarization. Similarly let N_- be the number of neutrons detected at the angle θ (for the same number of incident protons as N_+) when the reaction is initiated with the incident proton beam polarized in the $-\hat{y}$ direction; then

$$N_- = CI_0(\theta)[1-p_y A_y(\theta)] \quad . \quad (2-15)$$

With these measured numbers the analyzing power is given by

$$A_y = \frac{N_+ - N_-}{p_y (N_+ + N_-)} = \frac{e}{p_y} \quad , \quad (2-16)$$

where

$$e = \frac{N_+ - N_-}{N_+ + N_-} \quad (2-17)$$

Next consider how one would measure the polarization transfer coefficient $K_x^{x'}$. To measure $K_x^{x'}$ one would initiate the reaction with the incident proton beam polarized in the $+\hat{x}$ direction, i.e., $p_y = p_z = 0$, and then measure the $\hat{x}'$ component of polarization of the emitted neutron. For this case $I(\theta) = I_0(\theta)$ (since $p_y = p_z = 0$) and $p_{x'} = p_x K_x^{x'}$, or

$$K_x^{x'} = \frac{p_{x'}}{p_x} \quad (2-18)$$

In a similar fashion one could measure $K_x^{z'}$, $K_z^{x'}$, and $K_z^{z'}$. Finally consider how one would determine $K_y^{y'}$. From Eq. 2-13 $K_y^{y'}$ is given by

$$K_y^{y'} = \frac{p_{y'}(1 + p_{yy} A_y) - P_{y'}}{p_y} \quad (2-19)$$

To obtain p_y , one would polarize the beam in the $\hat{y}$ direction and measure the outgoing neutron polarization $p_{y'}$. Using an unpolarized incident beam one would measure $P_{y'}$. Assuming that A_y had been measured in a previous experiment one could then extract $K_y^{y'}$.

2.2 The Scattering Amplitudes of the $T(p,n)^3\text{He}$ Reaction

The elements of the M matrix relate initial spin and momentum states to final spin and momentum states. The nuclear physics concerning the interaction is contained in the elements of the M matrix.

The utility of measuring the various observables lies in that they involve different combinations of the M-matrix elements and as such they are sensitive to different aspects of the interaction.

The reaction $T(p,n)^3\text{He}$ involves four particles of spin 1/2. The incident channel consisting of the proton and triton can interact in the spin singlet state or the spin triplet state. The final channel consisting of the neutron and ^3He can also interact in the spin singlet or triplet state. In the spin singlet state $s = 0$ and $m_s = 0$; in the spin triplet state $s = 1$ and $m_s = 1, 0, -1$. From this point of view there are sixteen spin transitions possible. For example, consider the incident proton and triton interacting in the spin singlet state; from this initial spin configuration four possible final channel spin states are available to the scattered neutron and ^3He , the spin singlet and the three spin triplet states ($m_s = 1, 0, -1$). Thus in the singlet-triplet representation the M matrix may be written as

$$M = \begin{pmatrix} M_{SS} & M_{S1} & M_{S0} & M_{S-1} \\ M_{1S} & M_{11} & M_{10} & M_{1-1} \\ M_{0S} & M_{01} & M_{00} & M_{0-1} \\ M_{-1S} & M_{-11} & M_{-10} & M_{-1-1} \end{pmatrix} \quad (2-20)$$

The notation of the M-matrix elements is as follows:

$$M_{m_s, m_s'}$$

m_s = magnetic substate of the incident proton and triton

m_s' = magnetic substate of the scattered neutron and ^3He

m_s or $m_{s'}$, is replaced by an S if the particles interact in the spin singlet state. Thus, for example, M_{SS} corresponds to the proton and triton interacting in the spin singlet state and the scattered neutron and ^3He interaction in the spin singlet state. M_{01} corresponds to the incident particles in the spin triplet state with $m_s = 1$ and the scattered particles in the spin triplet state with $m_{s'} = 0$.

The general form of the M matrix does not conserve parity. A parity conserving M matrix is obtained by requiring

$$PMP^\dagger = M \quad (2-21)$$

where P is the parity operator. The parity operator is given by

$$P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \quad (2-22)$$

The justification for this form of the parity operator is given in Appendix A. Performing the indicated matrix multiplication one obtains the following relations among the matrix elements

$$\begin{aligned} M_{11} &= M_{-1,-1} & M_{10} &= -M_{-10} \\ M_{01} &= -M_{0,-1} & M_{S1} &= M_{S-1} \\ M_{1-1} &= M_{-11} & M_{-1S} &= M_{1S} \\ M_{S0} &= 0 & M_{0S} &= 0 \end{aligned} \quad (2-23)$$

Thus the most general parity conserving M matrix in the singlet triplet representation is given by

$$M = \begin{pmatrix} M_{SS} & M_{S1} & 0 & M_{S1} \\ M_{1S} & M_{11} & M_{10} & M_{1-1} \\ 0 & M_{01} & M_{00} & -M_{01} \\ M_{1S} & M_{1-1} & -M_{10} & M_{11} \end{pmatrix} .$$

The basis spinors in the singlet-triplet representation are given by

$$\begin{aligned} \chi_{S,S} &= \begin{vmatrix} 1 \\ 0 \\ 0 \\ 0 \end{vmatrix} & \chi_{1,1} &= \begin{vmatrix} 0 \\ 1 \\ 0 \\ 0 \end{vmatrix} \\ \chi_{1,0} &= \begin{vmatrix} 0 \\ 0 \\ 1 \\ 0 \end{vmatrix} & \chi_{1,-1} &= \begin{vmatrix} 0 \\ 0 \\ 0 \\ 1 \end{vmatrix} . \end{aligned} \quad (2-25)$$

In order to calculate expressions for the observables one needs the spin operators in the singlet-triplet representation. The appropriate operators are given by

$$\begin{aligned} \sigma_x \otimes I &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -1 & 0 & 1 \\ -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{pmatrix} & I \otimes \sigma_x &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -1 & 0 & 1 & 0 \end{pmatrix} \\ \sigma_y \otimes I &= \frac{i}{\sqrt{2}} \begin{pmatrix} 0 & -1 & 0 & -1 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \end{pmatrix} & I \otimes \sigma_y &= \frac{i}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 & 1 \\ -1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \end{pmatrix} \end{aligned}$$

$$\sigma_z \otimes I = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad I \otimes \sigma_z = \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \quad (2-26)$$

The symbol $\otimes$ indicates direct product. For example, to calculate the observable $K_y^{y'}(\theta)$ one would use the equation

$$K_y^{y'}(\theta) = \frac{\text{Tr}[M\sigma_y \otimes IM^\dagger\sigma_y \otimes I]}{\text{Tr}[MM^\dagger]}, \quad (2-27)$$

and substituting the expressions for the M matrix and the operators one obtains

$$K_y^{y'}(\theta) = \frac{\text{Re}[2M_{SS}^*(M_{11}^* + M_{1-1}^*) - 4M_{S1}M_{1S}^* - 4M_{1S}M_{01}^* + 2M_{00}(M_{11}^* - M_{1-1}^*)]}{|M_{SS}|^2 + |M_{00}|^2 + 2|M_{S1}|^2 + 2|M_{10}|^2 + 2|M_{01}|^2 + 2|M_{1-1}|^2 + 2|M_{11}|^2 + 2|M_{1S}|^2}. \quad (2-28)$$

Each of the M-matrix elements can be written as a sum of collision amplitudes.¹¹ Expressed in this manner the various possible relative orbital angular momentum states in the incident and final channel, consistent with conservation of total angular momentum and parity, are explicitly demonstrated. Blatt and Biedenharn¹¹ have derived a general expression (Eq. 3.14 of Ref.11) from which each of the M-matrix elements can be expressed as a sum of the collision amplitudes. It has been pointed out¹² that the general expression of Blatt and Biedenharn does not lead to the proper time reversal invariance of the scattering matrix, and the signs of the collision amplitudes that change angular momentum should be changed. Using the Blatt and Biedenharn general expression and changing the sign of those amplitudes that change ℓ the following is obtained for the M-matrix elements.¹³

$$M_{SS} = \sum_{\ell=0}^{\infty} \frac{(2\ell+1)}{2} P_{\ell}(\cos\theta) U_{\ell 0, \ell 0}^{\ell}$$

$$M_{S1} = - \frac{e^{i\phi}}{2\sqrt{2}} \sum_{\ell=1}^{\infty} \frac{2\ell+1}{\sqrt{\ell(\ell+1)}} P_{\ell}^1(\cos\theta) U_{\ell 0, \ell 1}^{\ell}$$

$$M_{1S} = \frac{e^{-i\phi}}{2\sqrt{2}} \sum_{\ell=1}^{\infty} \frac{2\ell+1}{\sqrt{\ell(\ell+1)}} P_{\ell}^1(\cos\theta) U_{\ell 1, \ell 0}^{\ell}$$

$$M_{01} = \frac{e^{i\phi}}{2\sqrt{2}} \sum_{\ell=1}^{\infty} \frac{1}{\sqrt{\ell(\ell+1)}} P_{\ell}^1(\cos\theta) \left[-\sqrt{(\ell-1)(\ell+1)} U_{\ell 1, \ell-21}^{\ell-1} \right.$$

$$\left. - (\ell-1) \sqrt{\frac{\ell+1}{\ell}} U_{\ell 1, \ell 1}^{\ell-1} - \frac{(2\ell+1)}{\sqrt{\ell(\ell+1)}} U_{\ell 1, \ell 1}^{\ell} \right.$$

$$\left. + (\ell+2) \sqrt{\frac{\ell}{\ell+1}} U_{\ell 1, \ell 1}^{\ell+1} + \sqrt{\ell(\ell+2)} U_{\ell 1, \ell+21}^{\ell+1} \right]$$

$$M_{10} = - \frac{e^{-i\phi}}{2\sqrt{2}} \sum_{\ell=1}^{\infty} P_{\ell}^1(\cos\theta) \left[\sqrt{\frac{\ell-1}{\ell}} U_{\ell 1, \ell-21}^{\ell-1} - U_{\ell 1, \ell 1}^{\ell-1} \right.$$

$$\left. + U_{\ell 1, \ell 1}^{\ell+1} - \sqrt{\frac{\ell+2}{\ell+1}} U_{\ell 1, \ell+21}^{\ell+1} \right]$$

$$\begin{aligned}
M_{00} &= \frac{1}{2} \sum_{\ell=0}^{\infty} P_{\ell}(\cos\theta) \left[-\sqrt{\ell(\ell-1)} U_{\ell 1, \ell-21}^{\ell-1} + \ell U_{\ell 1, \ell 1}^{\ell-1} \right. \\
&\quad \left. + (\ell+1) U_{\ell 1, \ell 1}^{\ell+1} - \sqrt{(\ell+2)(\ell+1)} U_{\ell 1, \ell+21}^{\ell+1} \right] \\
M_{11} &= \frac{1}{4} \sum_{\ell=0}^{\infty} P_{\ell}(\cos\theta) \left[\sqrt{\ell(\ell-1)} U_{\ell 1, \ell-21}^{\ell-1} + (\ell-1) U_{\ell 1, \ell 1}^{\ell-1} \right. \\
&\quad \left. + (2\ell+1) U_{\ell 1, \ell 1}^{\ell} + (\ell+2) U_{\ell 1, \ell 1}^{\ell+1} + \sqrt{(\ell+1)(\ell+2)} U_{\ell 1, \ell+21}^{\ell+1} \right] \\
M_{1-1} &= \frac{e^{-2i\phi}}{4} \sum_{\ell=2}^{\infty} \frac{1}{\sqrt{(\ell-1)(\ell+1)(\ell+2)}} P_{\ell}^2(\cos\theta) \left[-(2\ell+1) \sqrt{\frac{(\ell-1)(\ell+2)}{\ell(\ell+1)}} U_{\ell 1, \ell 1}^{\ell} \right. \\
&\quad \left. + \sqrt{\frac{\ell(\ell-1)(\ell+2)}{\ell+1}} U_{\ell 1, \ell 1}^{\ell+1} + \sqrt{\frac{(\ell-1)(\ell+1)(\ell+2)}{\ell}} U_{\ell 1, \ell 1}^{\ell-1} \right. \\
&\quad \left. + \sqrt{\ell(\ell-1)} U_{\ell 1, \ell+21}^{\ell+1} + \sqrt{(\ell+1)(\ell+2)} U_{\ell 1, \ell-21}^{\ell-1} \right]
\end{aligned}$$

In these expressions the following notation holds for the collision amplitudes.

$$U_{\ell'S', \ell S}^J$$

ℓ = relative orbital angular momentum of the two incident particles in the center-of-mass system.

S = incident channel spin formed from the vector addition of the intrinsic spins of the two particles in the incident channel.

ℓ' = relative orbital angular momentum of two scattered particles in the center-of-mass system.

S' = final channel spin formed from the vector addition of the intrinsic spins of the two particles in the final channel.

J = total angular momentum formed by the vector addition of ℓ and S or ℓ' and S' .

The $P_\ell(\cos\theta)$ and $P_\ell^1(\cos\theta)$, $P_\ell^2(\cos\theta)$ are the Legendre and associated Legendre functions defined by Jackson.¹⁴ The expressions for the M-matrix elements contain two angles θ and ϕ . These angles specify the direction of the scattered particles momentum in the center-of-mass system. If one is to apply the relations among the M-matrix elements obtained from conservation of parity to the expressions given above, one must set $\phi = 0$.

CHAPTER III

EXPERIMENTAL APPARATUS

3.1 Experimental Layout

The general experimental layout used for all the measurements is shown diagrammatically in Fig. 3. A beam of polarized H^- ions produced by the polarized ion source passed through a spin precessor and was then injected into the tandem accelerator. After acceleration the beam was energy analyzed by the 90° energy analyzing magnet. The beam was then sent through a switching magnet and focussed onto the target with the aid of two focussing lenses. The beam polarization was measured at the analyzing cup by a quench ratio method. More will be mentioned about the quench ratio method in the next section. Neutrons produced from the reaction were detected by the appropriate neutron detector. The electronic signals from the detector were processed by an electronic system which then presented the desired signals to the computer. In addition to storing the experimental data the computer performed certain on-line analysis, and after a run was complete wrote the data on magnetic tape.

3.2 Polarized Ion Source

The Los Alamos Lamb-shift polarized ion source provided the beam for all the measurements discussed in this work. The name Lamb-shift source arises because the source utilized the metastable

Fig. 3. Schematic of Experimental Facilities.

character of the 2s electronic state of hydrogen^{*} in producing the polarized beam. The source was designed and developed at Los Alamos and a complete description of it may be found in a series of papers and reports.^{15,16,17} Figure 4 is a functional flow diagram which illustrates the essential elements of the source. A beam of protons is produced in the positive ion source. The proton beam is accelerated and passes into the cesium cell where a charge exchange reaction occurs which selectively transfers an electron to the 2s metastable state. Other charge transfer reactions may occur such as transfer of an electron to the 2p state or the 1s ground state; however, the probability for transfer to the 1s state is smaller and the 2p state has a very short lifetime compared to the 2s metastable state and thus quickly decays to the ground state. The beam that emerges from the cesium cell consists of hydrogen atoms in the 2s and 1s state, and H^+ and H^- ions. An ion deflection field removes the H^+ and H^- ions. The beam then passes through the spin filter which consists of crossed, static, electric, and magnetic fields and an rf electric field. The spin filter quenches to the 1s ground state those hydrogen atoms whose nuclear spin is not in the $m_I = +1/2$ state. The beam that emerges from the spin filter is neutral and consists of hydrogen atoms in the 2s state whose nuclear spin is in the $m_I = +1/2$

* The metastable character of the 2s state is related to the energy difference of the 2s and 2p states. This energy difference was discovered by Willis E. Lamb, Jr., and is called the Lamb-shift.

LAMB-SHIFT POLARIZED ION SOURCE SCHEME

Fig. 4. Schematic of Polarized Ion Source.

state and hydrogen atoms in the 1s ground state. The beam then enters the argon gas cell. Argon gas has a large cross section for transferring an electron to a hydrogen atom in the 2s metastable state and a much smaller cross section for transferring an electron to an atom in the 1s state. As a result, the beam that emerges from the argon cell has three components: a neutral component of H atoms, a H^- component with the desired nuclear polarization, and an unpolarized H^- component. The H^- components are then accelerated to the proper energy for injection into the accelerator. Immediately before injection the beam passes through a spin precessor. The spin precessor allows one to select any desired spatial orientation for the direction of the beam polarization on target. The precessor accomplishes this by precessing the spin to the appropriate direction so that after acceleration, switching, and focusing the beam arrives on target with the desired polarization direction. The capability of being able to select the polarization direction is a tremendous advantage since it allows one to use various simplifications that result when one judiciously chooses the appropriate polarization direction.

The Los Alamos Lamb-shift source is routinely capable of producing a 90% polarized proton beam with beam currents in excess of 300 na. It was this large beam current (for polarized beams) coupled with a highly efficient liquid helium polarimeter that made possible the measurements reported in this thesis.

As was mentioned in the previous section, the beam polarization was measured at the analyzing cup by a quench ratio method. This

method consists simply of measuring the normal output current, i , and the background current, i_B , which remains when the $H(2s)$ atoms are quenched to the ground state. The beam polarization is then given by $p = (i - i_B)/i$ since the component, $i - i_B$, is (nominally) 100% polarized. The beam is quenched by greatly increasing the transverse dc electric field in the spin filter. Using this method the beam polarization could routinely be measured to a precision of ± 0.015 ; however, greater precision is attainable if several small effects are considered. The quench ratio method is thoroughly discussed in Ref. 18, and a complete description of the source which discusses topics of interest to experimenters has been prepared.¹⁹

3.3 Accelerator Facility

The Van de Graaff accelerator facility at Los Alamos consists of two Van de Graaff accelerators. The smaller accelerator is a single stage, vertical machine capable of accelerating singly charged ions to 7 MeV. The beam from this machine can be sent directly to an experimental area or injected into the tandem for further acceleration. The second accelerator is an FN tandem Van de Graaff built by High Voltage Engineering Corporation and is capable of terminal voltages up to 8.5 MeV. All of the data reported in this thesis was obtained by using the tandem accelerator only.

3.4 Target and Target Gas

If one is to study the reaction $T(p,n)^3\text{He}$ one must have available a suitable tritium target. The LASL Van de Graaff accelerator facility is set up so that tritium can be used in gaseous form as a target.

Since tritium is radioactive the problems inherent with handling it require special consideration. The tritium was stored in a cylindrical stainless steel furnace filled with uranium chips. Uranium, upon contact with the hydrogen isotopes at room temperature, forms a compound uranium-hydride. At elevated temperatures the hydrogen isotopes dissociate from the uranium and are then available in the gaseous state. Upon cooling the uranium will recombine with the hydrogenic gases to form uranium-hydride. Since this procedure is repeatable, it is a particularly convenient way to store and handle small quantities of tritium gas. An assay of the gas was not made; however, another group²⁰ at the laboratory has done assays of similar furnaces and from discussions with them one can estimate the purity to be better than 95%.

The gas target was a cylinder of 0.51-mm-thick stainless steel, 3 cm long, with an i.d. of 0.9 cm. The end wall of the target, which also served as the beam stop, was 0.44-mm-thick gold, hard-soldered into place. Three different entrance foils were used. The first foil was a 9.8-mg/cm² molybdenum foil plated with 2.4-mg/cm² nickel so it could be soft soldered to the target barrel. The other two foils were 2.1-mg/cm² or 5.27-mg/cm² Havar. Havar²¹ is a high tensile strength nickel-cobalt alloy manufactured by the Hamilton Watch Company.

The 5.27-mg/cm² Havar foil was sealed to the target barrel by compressing two indium gaskets.²² Each indium gasket was a ring gasket with an inner hole of sufficient diameter so that no indium

would be in the way of the impinging beam. A gasket was placed on each side of the Havar foil and the target barrel was drawn down to a mating flange on the end of the beam tube. As the target was tightened, the indium gaskets were crushed forming a very tight compression seal.

3.5 Neutron Polarimeter

3.5a General Considerations

To determine the polarization of neutrons one must have available a suitable neutron polarization analyzer. The most common method of measuring the polarization of lower energy (< 30 MeV) neutrons⁶ is to scatter them from helium and measure the resulting left-right scattering asymmetry. The relationship between the scattering asymmetry and the neutron polarization is

$$e = PA(\theta) = \frac{L-R}{L+R} \quad , \quad (3-1)$$

where e is the scattering asymmetry, P is the neutron polarization, A is the analyzing power of the scatterer, and L and R are the number of neutrons scattered left and right at the angle θ for a given number of incident neutrons. A number of different methods could be used to determine the scattering asymmetry e ; among these one could place matched detectors left and right, or a single counter alternately left and right, or a combination of these two. These methods have the disadvantage that false asymmetries can be introduced from the mechanical positioning of the detectors or the matching of their efficiencies.

Hillman et al.²³ have described a method which eliminates most of the problems just described. This method consists of using a magnetic field to precess the neutron spin 0° or 180° about its direction of motion before it reaches the analyzing scatterer. The spin precession has the same effect as mechanically interchanging the two detectors but false asymmetries are not introduced because the detectors are left in a fixed position. For the neutron polarization measurements reported in this thesis, neutrons produced in the horizontal plane from the reaction passed through an air core magnet where their spins were precessed plus or minus 90° . The neutrons were then scattered in a vertical plane from a volume of liquid helium into one of two fast plastic proton recoil scintillators positioned 115° on each side of the liquid helium cell. The entire assembly of spin precession magnet, liquid helium cell, and side plastic scintillators was mounted on a rigid frame and was called the neutron polarimeter. The polarimeter in turn was mounted on a gun mount which allowed it to be rotated in a horizontal plane about the target center. The polarimeter is shown schematically in Fig. 5. The liquid helium cell was cylindrical in shape with a diameter of 5.9 cm and a length of 6.1 cm. The cell was positioned with its axis in the horizontal plane and perpendicular to the flight path of the incident neutrons. For all of the polarization measurements except $K_Z^{Z'}$, the distance from the target center to the helium cell center (S1) was 99 cm. The helium scintillator subtended an angle of $\Delta\theta = 3.56^\circ$ and $\Delta\phi = 3.41^\circ$ which was the full angular spread over which the measurements were averaged.

Elevation View

Fig. 5. Neutron Polarimeter Schematic.

For the measurement of $K_z^{Z'}$ this distance was increased to 132 cm to provide adequate clearance for the larger dipole magnet. For a distance of 132 cm the helium scintillator subtended an angle of $\Delta\theta = 2.67^\circ$ and $\Delta\phi = 2.57^\circ$ which was the full angular spread over which the $K_z^{Z'}$ measurements were averaged. The distance from the helium cell center to the center of the side scintillators (S2 and S3) was 34.3 cm for all measurements. The various components of the polarimeter will be discussed in the sections that follow.

3.5b Spin Precession Magnets

Two different spin precession magnets were used during the course of the experiments. To measure the component of the neutron's spin perpendicular to the reaction plane a solenoid precession magnet was employed. The solenoid provided an axial field (parallel to the neutrons velocity) which would precess the component of the spin perpendicular to its direction of motion. The solenoid was manufactured by Pacific Electric Motor Company of Oakland, California. It consisted of a number of adjacent spirally wound, double layer pancakes connected in series, with a hole through their centers sufficiently large to allow a brass collimator to be placed in the bore. The windings were enclosed in a box of soft iron, 2.5 cm thick on the sides and 5.1 cm thick on the ends. The extra thickness on the ends was to help prevent stray fields from affecting the accelerator beam or photomultipliers of the polarimeter.

For measuring the longitudinal component of polarization, an H-frame dipole magnet was used. The dipole magnet was also

manufactured by Pacific Electric Motor Company of Oakland, California. The dipole magnet provided a magnetic field perpendicular to the neutrons velocity and as such would precess the longitudinal component of the neutron spin. The dipole magnet consisted of two rectangularly wound coils positioned to provide a pole gap width of three inches. A brass collimator was machined and positioned in the pole gap. The coils were enclosed in a soft iron H frame, 12.7 cm thick on the top, bottom, and sides. Specific details about the magnets such as field strength vs current, integrated field length, etc., are discussed in Ref. 24 and Appendix B.

One problem that arises with the use of magnets for spin precession purposes is that unwanted spin precession can be induced by fringe fields. The net effect of the unwanted fringe field precession is a depolarization of the neutron. A calculation was made using techniques developed by Stevens et al.²⁵ to determine fringe field depolarization. The calculation showed that depolarization from fringe fields was less than 0.002 even for extreme cases, and no corrections were made. The fields of the magnets were sufficiently homogeneous so that no corrections were made for the depolarization that can arise from small integrated field differences for the various trajectories.

3.5c The Liquid Helium Cryostat and Scintillation Detector

As mentioned in a previous section, the most common method of measuring neutron polarization is to scatter the neutrons from helium and measure the resulting left-right scattering asymmetry. The reason that helium is such a popular neutron polarization analyzer is that it

possesses a number of the desirable properties an analyzer should have. A good analyzer should have a smoothly varying analyzing power that is known with some degree of confidence over a reasonable energy range and the analyzing power should be large. Since the elastic scattering of an uncharged spin-1/2 particle from a spin-0 particle is one of the simplest cases to treat mathematically, n- α scattering has been the source of an extended theoretical and experimental effort. This has resulted in a number of sets of phase shifts from which the n- α analyzing power can be calculated. For a laboratory scattering angle of 115° , the n- α analyzing power is greater than 0.95 and almost constant for neutron energies from about 3 to > 20 MeV. In addition to these properties helium has another property which proves to be of immense experimental value. It is known that helium scintillates^{26,27} when an alpha particle recoils from its encounter with an incident neutron. This scintillation can be detected by a photomultiplier tube and if this signal is used in coincidence with the signal from the scattered neutron detector, background events can be significantly reduced.

One of the problems in neutron polarization measurements is achieving sufficiently high counting rates in order to reduce the statistical error in the measurements. Higher counting rates can be obtained by increasing the size of the scatterer and the scattered particle detectors; however, these methods can be carried only so far before they seriously degrade energy and angular resolution. To increase the scattering efficiency further one can increase the density

of helium nuclei in the scatterer. A number of groups ^{28,29,30} have reported using helium under high pressure (≈ 150 atmospheres). The high pressure helium gas polarimeters provide workable counting rates for neutron polarization measurements when the reaction is initiated with an unpolarized beam (with an unpolarized beam an on-target current of several microamps is typically obtainable). However, for neutron polarization transfer measurements where the reaction is initiated with a polarized incident beam and typical on-target currents are less than 100 nanoamps, an even higher scattering efficiency is highly desirable from a count rate viewpoint. For the neutron polarization measurements reported in this thesis a liquid helium polarimeter was used. The larger count rate obtainable by using helium in the liquid state is obvious when one considers that liquid helium has a density of 0.125 gm/cc which is roughly 5 times larger than gas at 150 atmospheres.

Helium liquifies at about 4.2° Kelvin, and in order to maintain a volume of it at this temperature a special low heat load cryostat is required. The cryostat that was used was designed by J. E. Simmons, G. S. Mutchler, and J. C. Martin, and is discussed in Ref. 24. One of the most important features of the design is the capability of viewing the helium scintillations, the importance of which was mentioned previously.

A cross-section drawing showing the essential features of the cryostat is shown in Fig. 6. The purpose of the heat shield was to reduce the radiant heat input to the helium region. The photomultiplier for detecting the helium scintillations was also connected to

Fig. 6. Cross Section of Liquid Helium Cryostat.

the heat shield and it operated at a temperature of about 120°K. The extensive shielding around the photomultiplier was used to shield it from any stray fields from the spin precession magnet. The liquid helium reservoir had a capacity of about 5 liters and would keep the helium cell full for about 16 hours. The helium cell contained 4.8 moles of liquid helium which is about 0.15 liters.

3.5d Scattered-Neutron Detectors

The neutrons scattered from the liquid helium were detected by either one of two detector assemblies. Each detector assembly consisted of a 5.1 cm x 7.6 cm x 19.1 cm rectangular block of NE102 plastic scintillator coupled to an RCA 8575 photomultiplier tube through a 25.4-cm long lucite light pipe. The 5.1-cm dimension was perpendicular to the neutrons flight path, the 7.6-cm dimension was along the flight path, and the 19.1-cm dimension was perpendicular to the n- α scattering plane. Both photomultipliers were shielded with several layers of mu-metal and soft iron.

Each side counter assembly was mounted on an arm which pivoted about an axis on which the liquid helium cell was centered. Relative angular position of the arms could be read to $\pm 0.1^\circ$ on a circular angular scale.

3.6 Analyzing Power Detector

To measure the $T(p,n)^3\text{He}$ analyzing power, one must measure the neutron asymmetry that results when the reaction is initiated with a polarized proton beam. The detector that was chosen to measure the neutron flux consisted of a cylindrical (4.44 cm diameter by 4.44 cm

length) NE213 scintillator optically coupled to an RCA 8575 photomultiplier tube. The detector was positioned directly behind and on the centerline of the bore of the spin precession solenoid whose collimator then served as a collimator for this detector. The axis of the scintillator was in the horizontal plane and perpendicular to the flight path of the incident neutron. The distance from the tritium target cell center to the center of the scintillator was 85 cm. At this distance the scintillator subtended an angle of $\Delta\theta = 3^\circ$ and $\Delta\phi = 3^\circ$. In addition to the neutrons that are produced from the reaction, background gamma rays are also present. Both the neutrons and gamma rays can interact within the scintillator and give rise to signals. Neutrons interact primarily by elastically scattering from protons in the scintillator. Gamma rays interact primarily by Compton scattering from electrons. A recoiling proton or electron dissipates its energy by exciting atoms of the scintillator. The atoms decay by emitting photons which are in turn detected by the photomultiplier tube. The net effect of the gamma ray signal is to reduce the magnitude of the measured asymmetry unless appropriate steps are taken to remove them. It is well known that NE213 gives rise to a different pulse shape for interactions resulting from neutrons and gamma rays.³¹ The pulse shape difference is related to the difference in the energy loss per unit path length for recoil protons and electrons. One can take advantage of this pulse shape difference and electronically separate the neutron signal from the gamma ray signal.

3.7 Electronics and On-Line Analysis

3.7a Neutron Polarimeter Electronics

The polarimeter's electronic system consisted of two parts, a fast and a slow system. The fast system was capable of handling high count rates such as those that would be encountered in a neutron polarization measurement when the reaction is initiated with an unpolarized incident beam. The fast coincidence requirements would prevent high counting rates from entering the slow system. Figure 7 is a functional schematic of the electronics. Various details such as delays, pulse shapers, etc., are not shown. In the figure S1 is the photomultiplier which detected the scintillations from the liquid helium while S2 and S3 are the side counters. The anode signals from the photomultipliers were fed to fast discriminators which were used to set a lower discrimination level on these signals. The discriminator outputs were fed to AND circuits which signaled a 1-2 or 1-3 coincidence. The output of the AND's were used to gate the fast linear signals from dynode 10 of S2 or S3. The AND's also gated the time-to-amplitude converters (TAC). The start and stop signals to the TAC's were obtained from the fast discriminators. After fast amplification and fast gating the linear signals from S1, S2, and S3 were fed to slow amplifiers. The TAC outputs were also sent to slow amplifiers. The horizontal row of five amplifiers in Fig. 7 marks the beginning of the slow system. The bipolar outputs of the slow amplifiers were sent to slow discriminators and the unipolar outputs were sent to slow linear gates. The gate signal to the slow linear gates was obtained from the coincidence circuits labeled 1-2T, 1-2A, 1-3T, and 1-3A. While in a data-taking

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mode the coincidence circuits required a 3-fold coincidence with the additional provision that no signal appear at the anti-coincidence input. An anti-coincidence input appeared if S1-S2 and S1-S3 coincidences occurred within 1 microsecond in the fast system. The requirements needed for a valid event were S1 and S2 or S3 pulse height greater than some lower level and the TAC output between a lower and upper level.

The output time spectra of the TAC's contained a well-defined peak. This peak was caused by full energy neutrons scattering from the helium into one of the side counters. A discriminator was used to set a window on this peak and the signals from it were used as the time requirement for the 1-2T and 1-3T coincidence units. The time requirement for the 1-2A and 1-3A coincidence units were obtained from discriminator windows set on a region in the accidental part of the TAC spectra.

In order to keep track of target integrity and to normalize each run, an external neutron monitor was used. The monitor detector consisted of a plastic scintillator coupled directly to a photomultiplier tube. The output of the monitor detector was preamplified and sent to a slow amplifier. Discriminators were set on the amplifier output and these in turn drove a set of scalers. A second monitor was the singles output of the helium scintillator. The S1 anode signal was split and sent to two fast amplifiers. The handling of one of the signals has been discussed previously. The second signal was amplified, shaped, and sent to a discriminator which in turn drove a scaler.

The scaler outputs were compared with current integrator readings and thus served as a check on the tritium target and as a monitor for false asymmetries.

3.7b On-Line Computer Analysis

In a normal data taking operation the gated alpha recoil spectra were stored as the raw data since these spectra gave the best separation of good events from background. The signals from the main electronic system were sent to an ADC and then fed to an SDS-930 computer for storage. Events were stored in one of four 256 channel spectra in computer memory with routing signals provided by the coincidence units. The four spectra corresponded to the four possible coincidences 1-2T, 1-2A, 1-3T, or 1-3A. The computer could be placed in a semi-automatic mode which expected data in a +--+ or -+- spin sequence. When the reaction was initiated with a polarized incident beam + and - referred to the incident beam polarization. For the case where the incident beam was unpolarized + and - referred to the neutron spin rotation sequence. At the conclusion of a run the beam polarization was automatically measured by direct computer control. The accumulated data could then be plotted, printed, or written on magnetic tape. With the last two options a run identification number, title, beam polarization magnitude, display scale, lost counts, and accumulated counts in up to six scalers were also recorded. Data were normally taken in a +--+ sequence to reduce the effect of electronic drifts. On-line asymmetries were obtained by displaying the S1 recoil spectra and visually setting a light pen bite on the peak in the

spectrum. After each +- run the computer would calculate the asymmetry from the formula $e = (N_+ - N_-) / (N_+ + N_-)$ where N_+ and N_- were the counts in the light pen bites. In the same manner asymmetries were calculated for the scalars that recorded counting time, integrated beam current, and the S1 singles rate. These asymmetries were used to indicate possible false asymmetries and were in general zero within the statistical accuracy.

3.7c Analyzing Power Electronics

In order to utilize pulse shape difference to separate neutron signals from gamma ray signals the appropriate electronic system must be employed. Figure 8 is a functional schematic of the electronic system that was used. Two signals were obtained from the photomultiplier tube, a timing signal and a linear signal. The rise time of the linear neutron signal was different from that of the linear gamma ray signal; as a result, when the linear signals were amplified and shaped into bipolar pulses the time at zero crossing was different for the two different types. The bipolar signals were sent to a timing single channel analyzer which produced a timing pulse depending on zero crossing. This timing pulse was used as the start signal for a time-to-amplitude converter. The stop signal was obtained from the timing signal from the photomultiplier tube. The timing signal was sent through a time pickoff unit which also provided lower level discrimination and then through a delay before arriving at the stop input. The output time spectra of the time-to-amplitude converter consisted of two peaks, one peak containing signals from neutrons and the other signals from

Fig. 8. Block Diagram of Analyzing Power Electronics.

gamma rays. A typical time spectra is shown in Fig. 9. The output of the time-to-amplitude converter was amplified and sent to another single channel analyzer which was used to set a window on the neutron peak. The output of this single channel analyzer was used as a gate signal to the linear gate. The gated output of the linear gate consisted of the desired neutron signals and was sent to the SDS computer for processing and storage. The linear signal was also sent to two single channel analyzers. These were used to set two windows on the recoil proton distribution. The signals from these windows were counted by scalers and on-line asymmetries were obtained from the scaler numbers. The start and stop count rates to the time-to-amplitude converter were also monitored by scalers. It was necessary to monitor the TAC start signal rate to ensure that counts were not being lost during the conversion cycle of the TAC. The TAC was capable of handling a start signal rate of 245,098 counts per second, the start signal rate was typically 1000 counts per second and in no case did it exceed 2000 counts per second.

Fig. 9. Time Spectrum from Time to Amplitude Converter.

CHAPTER IV

POLARIZATION DATA REDUCTION AND RESULTS

4.1 Reduction of Neutron Polarization Data

After a run was complete it was necessary to further analyze the data and apply various correction factors before final results were obtained.

As was mentioned previously, the data were taken in a $+-+$ spin sequence and in general two sequences were taken for each asymmetry measurement. A computer program was used to sum the spectra for a particular neutron energy and spin direction. The difference of the summed true and accidental spectra were plotted for visual inspection. From the plots channels corresponding to the peaks full width at half maximum and 20% of full height were chosen. Two asymmetries were then computed for both portions of the peak, one for the S1-S2 system and one for the S1-S3 system. The asymmetries for the S1-S2 and S1-S3 systems were then averaged to further reduce spurious asymmetries. Asymmetries were also calculated for the tail region of the distribution. The tail region was taken as the region extending from the lowest cut-off channel up to the low channel of the 20% of full height portion of the peak. The tail region was divided into three approximately equal segments and an asymmetry was calculated for each. Another asymmetry was calculated for the entire tail region. These asymmetries were in

general zero within the statistical accuracy. Typical spectra are shown in Fig. 10. The solid curve is a Monte Carlo simulation of the data, while the dashed line is an estimate of the background. The arrowed brackets indicate the portions of the peak corresponding to full width at half maximum and 20% of maximum. Note that for a given proton energy the background contribution increases as the neutron energy decreases. Also note that the background is larger in the distribution at 9.94 MeV and 100° than in the distribution at 5.97 MeV and 15° while the neutron energies are roughly the same (1.2 MeV difference).

4.2 Corrections to Measured Asymmetries

The measured asymmetries were corrected for background, multiple scattering, and finite geometry. The latter two corrections were chiefly functions of the neutron's energy whereas the background correction varied with the incident beam energy and neutron production angle.

4.2a Background Correction

As the spectra in Fig. 10 indicated, there was a contribution from background neutrons whose tail extended under the main alpha recoil peak. Target empty spectra indicated the majority of the background neutrons were produced in the metal of the target, collimating slits, etc., and that this background was unpolarized. Target full runs taken with sufficient brass positioned between the tritium target and helium cell to absorb the direct neutrons from the reaction indicated that background from room scattered neutrons was negligible. In order to estimate if any additional background was present, the target empty

Fig. 10. Alpha Recoil Spectra.

spectra were normalized to the corresponding target full spectra and then the target empty were subtracted from the target full. The resulting distribution was then compared with the Monte Carlo simulation. Since the Monte Carlo simulation was free of background this comparison would indicate if other background was present. The comparison showed that there was a small contribution of background in addition to the background mentioned. This background was of unknown origin and was assumed to be unpolarized.

Because it was not practical to take a target empty spectrum for each target full, an estimate of the background tail was drawn on the plots of the recoil alpha distributions. The estimate of the background was drawn relative to the Monte Carlo simulation such that when they were added together the resulting distribution provided a reasonable fit to the actual alpha distribution. This procedure of estimating the background was compared with those cases where target empty spectra were taken and this indicated that the method provided a reasonable estimate of background.

Once the estimate of the background had been drawn the number of background counts under the peak could be determined. If B is the number of background counts in the + and - peaks together and S is the number of counts in the + and - peaks combined, then the background correction factor f is $f = 1 + [B/S - B]$.

4.2b Multiple Scattering and Finite Geometry Corrections

The asymmetry of neutrons which multiply scatter is different than for neutrons which scatter only once. Because of the higher density

of liquid helium the probability that a neutron will multiply scatter is not negligible and the measured asymmetry must be corrected for this effect. Also because of the rather large size of the side counters and liquid helium cell, the measured asymmetries were actually averages over the finite geometry of the helium scatterer and side detectors. As a result a correction factor had to be applied which took into account this averaging effect. Both the multiple scattering and finite geometry corrections were obtained from a modified LASL code⁸ which also provided the simulation of the alpha recoil spectra.

Figure 11 is a plot of the correction factors as a function of neutron energy. The multiple scattering correction increased with decreasing neutron energy while the finite geometry correction remained almost constant. In the figure the background correction is labeled f and the multiple scattering and finite geometry corrections are labeled g and h, respectively. The squares are the zero degree background corrections. The line through these corrections was drawn simply to guide the eye.

4.3 Errors in the Measured Polarizations

After the corrections were applied to the measured asymmetry, the final corrected asymmetry represented the asymmetry which would have been measured had it been possible to do a background free, point geometry experiment, and it is designated as e. It is given by

$$e = fghe_M, \quad (4-1)$$

where e_M is the measured asymmetry, f the background correction, g and

Fig. 11. Smoothed Representations of Correction Factors.
The Squares Represent 0° Background.

h the multiple scattering and finite geometry corrections, respectively. The uncertainty in e_M was just the statistical uncertainty Δe_M . The uncertainty Δe in e was taken to be the quadratic combination of the uncertainties in e_M , f , g , and h . Because of the manner in which the background was estimated an uncertainty of $\Delta f = \pm 2/3(1-f)$ was ascribed to the background correction factor. Due to the uncertainty in some aspects of the Monte Carlo calculation⁸ the uncertainty in the multiple scattering and finite geometry corrections was estimated to be one third of the correction or $\Delta g = \pm 1/3(g-1)$ and $\Delta h = \pm 1/3(h-1)$. In almost all cases these uncertainties in g and h were larger than the statistical uncertainty that resulted from the Monte Carlo calculation.

The final corrected asymmetries calculated from the peaks full width half maximum and the 20% of maximum were then compared. These asymmetries agreed within the errors. Because of the better statistical precision the asymmetry calculated from the 20% of maximum was used in calculating the neutron polarization. The neutron polarization was obtained by dividing the asymmetry by the n - α analyzing power at 115° . The n - α analyzing power was calculated from the phase shifts of Satchler and Owen³² and no uncertainty was given to these calculated numbers.

In order to extract the polarization transfer coefficients it was necessary to divide the neutron polarization by the beam polarization. The beam polarization was measured by an atomic beam technique to ± 0.015 and was discussed in Chapter III. The errors in the transfer coefficients do not contain a contribution from an uncertainty in the

beam polarization. It is felt that an uncertainty of this type is better represented as a systematic error. To obtain an estimate of the systematic error the following was taken into consideration. A polarization measurement consisted of at least one and typically two cycles of $+-$ spin precession or beam polarization, depending on the measurement. Each $+$ and $-$ run within a cycle was normalized to the same number of counts from an external neutron monitor detector. As a check on the monitor detector scalers recorded the integrated beam current and S1 singles count, and asymmetries were calculated for each. These asymmetries averaged typically 0.002 and 0.003, respectively, and were in general zero within the statistical accuracy. Repeat measurements were performed on different days and in most cases the measurements repeated within the errors. The repeat measurements are tabulated in Table II. At 9.87 MeV a measurement of P_y was performed at zero degrees where this observable is theoretically zero. The result was 0.008 ± 0.014 . From these considerations the systematic error in the polarization measurements is believed to be less than 0.010.

A beam profile measurement was performed with the A_y detector to determine the true zero of angle. The measurement indicated that a correction of $0.26 \pm 0.06^\circ$ should be applied to the angles. The laboratory angle presented in the data tables corresponds to a point geometry angle which is the angle between the incident beam direction and the line extending from the tritium target cell center to the helium cell center. The center-of-mass angle in the data tables was obtained by converting the lab angle to the center of mass. For all of the measurements except $K_z^{Z^+}$ the helium cell subtended a lab angle of $\Delta\theta = 3.56^\circ$

TABLE II
Repeat Measurements

<u>Proton Energy</u>	<u>Lab Angle</u>	<u>Observable[*]</u>
10.0 MeV	0°	$K_z^{x'} = 0.839 \pm 0.044$
10.0 MeV	0°	$K_z^{z'} = 0.834 \pm 0.033$
9.94 MeV	0°	$K_x^{x'} = 0.737 \pm 0.025$
[†] 9.95 MeV	0°	$K_y^{y'} = 0.670 \pm 0.050$
5.97 MeV	0°	$K_x^{x'} = 0.639 \pm 0.030$
[†] 5.93 MeV	0°	$K_y^{y'} = 0.724 \pm 0.036$

$$*K_x^{x'}(0^\circ) = K_y^{y'}(0^\circ)$$

[†]Measurements of Donoghue et al. (Ref. 4).

which was the full angular spread over which the measurements were averaged. For the $K_z^{z'}$ measurements the helium cell subtended a lab angle of $\Delta\theta = 2.67^\circ$ which was the full angular spread over which the $K_z^{z'}$ measurements were averaged.

4.4 Polarization Data $P_{y'}$

The neutron polarization $P_{y'}$ was measured by initiating the reaction with an unpolarized proton beam and then measuring the neutron polarization in the y' direction. This was accomplished by precessing the neutron spin $\pm 90^\circ$ about the z' direction so that its spin would be normal to the neutron polarimeter scattering plane which was the vertical plane. In terms of the final laboratory coordinate system the x' direction is normal to the polarimeter scattering plane. With the solenoid energized to precess the neutron spin $+90^\circ$ (from y' to x') two numbers were extracted, $S12 (+90^\circ)$ and $S13 (+90^\circ)$. $S12 (+90^\circ)$ corresponded to the number of neutrons which after $+90^\circ$ precession scattered from the liquid helium cell S1 into the side counter S2. Similarly, for -90° precession one obtained $S12 (-90^\circ)$ and $S13 (-90^\circ)$. $S12 (\pm 90^\circ)$ and $S13 (\pm 90^\circ)$ were the number of counts under the 20% of maximum portion of the recoil alpha peak. With these numbers two asymmetries were calculated

$$e(12) = \frac{S12(+90^\circ) - S12(-90^\circ)}{S12(+90^\circ) + S12(-90^\circ)} \quad (4-2)$$

$$e(13) = \frac{S13(+90^\circ) - S13(-90^\circ)}{S13(+90^\circ) + S13(-90^\circ)} .$$

The measured asymmetry was then obtained by averaging

$$e_M = \frac{e(12)+e(13)}{2} . \quad (4-3)$$

The corrected asymmetry e was obtained by multiplying the measured asymmetry by the three correction factors f , g , and h corresponding to background, multiple scattering, and finite geometry

$$e = fghe_M . \quad (4-4)$$

The neutron polarization $P_{y'}$ was then obtained by dividing the corrected asymmetry by the n - α analyzing power at 115° lab $P(n-\alpha, 115^\circ)$

$$P_{y'} = \frac{e}{P(n-\alpha, 115^\circ)} = \frac{fghe_M}{P(n-\alpha, 115^\circ)} . \quad (4-5)$$

The uncertainty in $P_{y'}$ was obtained by combining the errors in quadrature

$$P_{y'} = \sqrt{\left(\frac{\partial P_{y'}}{\partial e_M}\right)^2 \Delta e_M^2 + \left(\frac{\partial P_{y'}}{\partial f}\right)^2 \Delta f^2 + \left(\frac{\partial P_{y'}}{\partial g}\right)^2 \Delta g^2 + \left(\frac{\partial P_{y'}}{\partial h}\right)^2 \Delta h^2} . \quad (4-6)$$

The polarization data $P_{y'}$ is presented in Table III. The table includes the correction factors f , g , and h , the measured asymmetry e_M , the corrected asymmetry e , and the n - α analyzing power at 115° lab $P(n-\alpha, 115^\circ)$.

4.5 Least Squares Analysis of Polarization Data $P_{y'}$

A least squares analysis was made of the angular distribution data at 5.97, 9.87, and 13.55 MeV. The polarization data at 13.55 MeV was measured by Haight et al.⁸ with the same experimental apparatus as was used for the measurements at 5.97 and 9.87 MeV. The least squares analysis was made by fitting³³ the data to the expression³

TABLE III

 P_y , Polarization Data.

$E_p^a) \pm \frac{1}{2}\Delta E_p^b)$	$\theta_L^c)$	$\theta_{cm}^c)$	$E_n^d)$	$e_M \pm \Delta e_M^e)$	f	g	h	$P(n-\alpha)^f)$	$e \pm \Delta e^g)$	$P_y \pm \Delta P_y^g)$
5.97 $\pm$ 0.09	15.3	20.8	5.07	-0.062 $\pm$ 0.013	1.027	1.083	1.044	0.972	-0.072 $\pm$ 0.016	-0.074 $\pm$ 0.016
5.97 $\pm$ 0.09	30.3	41.0	4.70	-0.146 $\pm$ 0.015	1.036	1.101	1.051	0.970	-0.176 $\pm$ 0.018	-0.181 $\pm$ 0.019
5.97 $\pm$ 0.09	45.3	60.4	4.16	-0.159 $\pm$ 0.018	1.041	0.109	1.038	0.965	-0.191 $\pm$ 0.022	-0.198 $\pm$ 0.023
5.97 $\pm$ 0.09	60.3	78.7	3.55	-0.050 $\pm$ 0.016	1.062	1.166	1.045	0.957	-0.064 $\pm$ 0.022	-0.067 $\pm$ 0.023
5.97 $\pm$ 0.09	80.3	101.5	2.74	0.126 $\pm$ 0.019	1.093	1.218	1.045	0.916	0.175 $\pm$ 0.029	0.191 $\pm$ 0.032
9.87 $\pm$ 0.06	0.3	0.3	9.10	0.008 $\pm$ 0.013	1.026	1.044	1.036	0.988	0.008 $\pm$ 0.014	0.008 $\pm$ 0.014
9.87 $\pm$ 0.06	15.3	20.6	8.87	-0.136 $\pm$ 0.015	1.029	1.041	1.033	0.988	-0.150 $\pm$ 0.017	-0.152 $\pm$ 0.017
9.87 $\pm$ 0.06	30.3	40.6	8.25	-0.209 $\pm$ 0.017	1.042	1.049	1.034	0.987	-0.236 $\pm$ 0.020	-0.239 $\pm$ 0.020
9.87 $\pm$ 0.06	33.9	45.3	8.05	-0.226 $\pm$ 0.013	1.054	1.052	1.041	0.986	-0.261 $\pm$ 0.017	-0.264 $\pm$ 0.017
9.87 $\pm$ 0.06	45.3	59.8	7.35	-0.216 $\pm$ 0.017	1.055	1.046	1.041	0.985	-0.248 $\pm$ 0.020	-0.252 $\pm$ 0.021
9.87 $\pm$ 0.06	60.3	78.2	6.30	-0.111 $\pm$ 0.017	1.048	1.071	1.041	0.980	-0.130 $\pm$ 0.021	-0.133 $\pm$ 0.021
9.94 $\pm$ 0.06	80.3	100.7	4.97	0.001 $\pm$ 0.014	1.071	1.083	1.044	0.971	0.001 $\pm$ 0.017	0.001 $\pm$ 0.018
9.94 $\pm$ 0.06	100.3	120.6	3.82	0.151 $\pm$ 0.019	1.101	1.116	1.041	0.962	0.193 $\pm$ 0.026	0.201 $\pm$ 0.027

a) Proton Laboratory energy (MeV) at the tritium gas cell center.

b) $\frac{1}{2}\Delta E_p$ is the half energy loss (MeV) in the tritium gas cell.

c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Neutron lab energy (MeV).

e) Δe_M is statistical only expressed as standard deviation.

f) $P(n-\alpha)$ is the n- α analyzing power at 115° lab.

g) Δe and ΔP_y contain a contribution from the uncertainty in f, g, and h.

$$k^2 \frac{d\sigma}{d\Omega} P_{y'} = \sum_{\ell=1}^{\ell_{\max}} A_{\ell} P_{\ell}^1(\cos\theta) . \quad (4-7)$$

In the expression $d\sigma/d\Omega$ is the unpolarized center-of-mass differential cross section, k is the magnitude of the center-of-mass wave vector of the initial channel, and $P_{\ell}^1(\cos\theta)$ are the associated Legendre polynomials. The constants A_{ℓ} were those that minimized χ^2 .

$$\chi^2 = \sum_{i=1}^N \left[\frac{Y(\theta_i) - Y_{\text{cal}}(\theta_i)}{\Delta Y(\theta_i)} \right]^2 , \quad (4-8)$$

where

N = number of data points

$$Y(\theta_i) = k^2 \frac{d\sigma(\theta_i)}{d\Omega} P_{y'}(\theta_i)$$

$$\Delta Y(\theta_i) = \text{error in } k^2 \frac{d\sigma(\theta_i)}{d\Omega} P_{y'}(\theta_i)$$

$$Y_{\text{cal}}(\theta_i) = \sum_{\ell} A_{\ell} P_{\ell}^1(\cos\theta_i) .$$

The values for $k^2(d\sigma/d\Omega)$ were obtained from the Legendre coefficients of McDaniels et al.³⁴ A linear interpolation was made between the coefficients at 13 and 14 MeV to obtain the coefficients at 13.55 MeV. The coefficients at 6 and 10 MeV were used for the 5.97 and 9.87 MeV polarization data. The error in $k^2(d\sigma/d\Omega)$ was calculated from the expression

$$\left(\Delta k^2 \frac{d\sigma}{d\Omega}\right)^2 = \sum_i \left(\frac{\partial k^2 \frac{d\sigma}{d\Omega}}{\partial B_i} \Delta B_i \right)^2, \quad (4-9)$$

where ΔB_i are the errors in the Legendre coefficients. The error in $k^2(d\sigma/d\Omega)$ was then combined in quadrature with the error in $P_{y'}$ to obtain ΔY .

The criterion for a best fit to the data was obtained by observing the weighted variance WV , ($\chi^2/\text{degree of freedom}$). The number of coefficients, $\ell_{\max}$, was varied from one to five and a fit to the data was generated for each value of $\ell_{\max}$. The weighted variance was calculated for each fit. The weighted variance decreased when $\ell_{\max}$ was increased from one to three but for larger values no significant decrease was observed. The results of the least squares analysis is presented in Table IV.

4.6 Polarization Transfer Data $K_y^{y'}$

The polarization transfer coefficient $K_y^{y'}$ was measured by initiating the reaction with the incident proton beam polarized in the y direction and then measuring the neutron polarization in the y' direction. The neutron polarization, $p_{y'}$, was measured in the same manner as was $P_{y'}$. To extract $K_y^{y'}$ the neutron polarization, $p_{y'}$, was combined with $P_{y'}$ and the analyzing power A_y to yield $K_y^{y'}$. The expression relating the quantities is

$$\frac{p_{y'}(1+p_y A_y) - P_{y'}}{p_y} = K_y^{y'} \quad (4-11)$$

The error in $K_y^{y'}$ was taken as the quadratic combination of the

Table IV

Associated Legendre Coefficients Obtained
From Least Squares Fit to P_y' Data

$E_p^a)$ (MeV)	WV ^{b)}	$l_{\max} = 2$		WV	$l_{\max} = 3$		
		$A_1(P)$	$A_2(P)$		$A_1(P)$	$A_2(P)$	$A_3(P)$
5.97	1.4	0.0101 ± 0.0045	-0.0446 ± 0.0040	2.1	0.0120 ± 0.0085	-0.0466 ± 0.0083	0.0015 ± 0.0052
9.87 ^{c)}	1.2	-0.0203 ± 0.0037	-0.0479 ± 0.0025	0.7	-0.0192 ± 0.0029	-0.0528 ± 0.0028	0.0053 ± 0.0022
13.55	1.3	-0.0352 ± 0.0040	-0.0456 ± 0.0034	1.6	-0.0355 ± 0.0045	-0.0450 ± 0.0042	-0.0011 ± 0.0036

a) Proton lab energy at tritium cell center.

b) WV = weighted variance (χ^2 per degree of freedom).

c) $E_p = 9.94$ MeV for the 80° and 100° points.

errors as in Eq. 4-6. The errors in the neutron polarizations p_y , and P_y , have been discussed previously; the error in the analyzing power A_y was statistical only and is discussed in Chapter V, Section 2. The contribution from an uncertainty in the beam polarization was not included. The $K_y^{y'}$ data is presented in Table V.

4.7 Polarization Transfer Data $K_x^{x'}$ and $K_z^{x'}$

The polarization transfer coefficients $K_x^{x'}$ and $K_z^{x'}$ are related to the final neutron polarization p_x , by the following expressions:

$$K_x^{x'} = \frac{P_{x'}}{p_x} \quad \text{proton beam polarized in the x direction } p_y = p_z = 0$$

$$K_z^{x'} = \frac{P_{x'}}{p_z} \quad \text{proton beam polarized in the z direction } p_x = p_y = 0. \quad (4-12)$$

To measure the neutron polarization in the x' direction, spin precession was not necessary because the neutron spin component in the x' direction is already normal to the polarimeter scattering plane.

In the measurement of $K_x^{x'}$ the proton beam was polarized in the x direction, and with the solenoid turned off two numbers were obtained, $S12 (+x)$ and $S13 (+x)$. $S12 (+x)$ corresponded to those neutrons which were produced with the beam polarized in the $+x$ direction and which in turn scattered from the liquid helium cell $S1$ into the side detector $S2$, similarly for $S13 (+x)$. With the incident proton beam polarized in the $-x$ direction the neutron polarization, p_x , is reversed as can be seen from the equation above. With the beam in the $-x$ direction $S12 (-x)$ and $S13 (-x)$ were obtained. From these numbers two asymmetries were calculated:

TABLE V
Polarization Transfer Data $K_y^{y'}$

E_p a) $\pm \frac{1}{2} \Delta E_p$ b)	θ_L c)	θ_{cm} c)	P_y d)	E_n e)	$e_M \pm \Delta e_M$ f)	f	g	h	$P(n-\alpha)$ g)	$e \pm \Delta e$ h)	$P_y \pm \Delta P_y$ h)	$K_y^{y'} \pm \Delta K_y^{y',h}$
5.97±0.09	15.3	20.8	0.881	5.07	0.447±0.018	1.030	1.083	1.044	0.972	0.520±0.024	0.535±0.025	0.652±0.032
5.97±0.09	30.3	41.0	0.882	4.70	0.317±0.021	1.040	1.101	1.051	0.970	0.382±0.028	0.393±0.029	0.598±0.036
5.97±0.09	45.3	60.4	0.881	4.16	0.119±0.027	1.046	1.109	1.038	0.965	0.144±0.033	0.149±0.034	0.372±0.042
5.97±0.09	60.3	78.7	0.877	3.55	-0.155±0.020	1.068	1.166	1.045	0.957	-0.202±0.028	-0.211±0.029	-0.148±0.040
5.97±0.09	80.3	101.5	0.876	2.74	0.039±0.028	1.093	1.217	1.045	0.916	0.054±0.039	0.058±0.042	-0.141±0.066
9.87±0.06	0.3	0.3	0.866	9.10	0.487±0.026	1.043	1.044	1.036	0.988	0.549±0.032	0.556±0.032	0.642±0.037
9.87±0.06	15.3	20.6	-0.875	8.87	-0.630±0.026	1.030	1.041	1.033	0.988	-0.698±0.032	-0.706±0.032	0.734±0.046
9.87±0.06	30.3	40.6	-0.878	8.25	-0.544±0.031	1.054	1.049	1.034	0.987	-0.622±0.039	-0.630±0.040	0.608±0.060
9.87±0.06	45.3	59.8	-0.876	7.35	-0.374±0.029	1.044	1.046	1.041	0.985	-0.425±0.034	-0.432±0.035	0.310±0.051
9.87±0.06	60.3	78.2	-0.882	6.30	-0.114±0.032	1.050	1.071	1.041	0.980	-0.134±0.038	-0.136±0.039	0.025±0.056
9.94±0.06	80.3	100.7	0.893	4.97	-0.055±0.028	1.092	1.083	1.044	0.971	-0.068±0.035	-0.070±0.036	-0.078±0.044
9.94±0.06	100.3	120.6	0.893	3.82	0.179±0.049	1.101	1.116	1.041	0.962	0.229±0.064	0.238±0.067	0.078±0.090

a) Proton lab energy (MeV) at the tritium gas cell center.

b) $\frac{1}{2} \Delta E_p$ is the half energy loss (MeV) in the tritium gas cell.

c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Average beam polarization.

e) Neutron lab energy (MeV).

f) Δe_M is statistical only expressed as standard deviation.

g) $P(n-\alpha)$ is the $n-\alpha$ analyzing power at 115° lab.

h) Δe and ΔP_y contain a contribution from the uncertainty in f, g, and h. $\Delta K_y^{y'}$ is the quadratic combination of ΔP_y , $\Delta P_{y'}$, and ΔA_y .

$$e(12) = \frac{S12(+x) - S12(-x)}{S12(+x) + S12(-x)} \quad (4-13)$$

$$e(13) = \frac{S13(+x) - S13(-x)}{S13(+x) + S13(-x)} .$$

The measured asymmetry was obtained by averaging

$$e_M = \frac{e(12) + e(13)}{2} .$$

In general, two cycles of +x -x -x +x beam polarization were taken.

The correction factors were applied to obtain the corrected asymmetry from which the neutron polarization, $p_{x'}$, was calculated

$$p_{x'} = \frac{f g h e_M}{P(n-\alpha, 115^\circ)} . \quad (4-14)$$

The polarization transfer coefficient $K_x^{x'}$ was then calculated by dividing $p_{x'}$ by the beam polarization p_x . The error in the transfer coefficient $K_x^{x'}$ was taken as the quadratic combination of the errors as in Eq. 4-6. A contribution from an uncertainty in the beam polarization was not included.

$K_z^{x'}$ was determined in a strictly analogous fashion. The proton beam was polarized in the +z direction and S12 (+z) and S13 (+z) determined. By reversing the beam polarization to the -z direction S12 (-z) and S13 (-z) were obtained. With these numbers the two asymmetries $e(12)$ and $e(13)$ were calculated and then averaged to obtain e_M . The procedure of obtaining $K_z^{x'}$ was then the same as that used to obtain $K_x^{x'}$. The $K_x^{x'}$ data is presented in Table VI and $K_z^{x'}$ in Table VII.

TABLE VI

Polarization Transfer Data $K_x^{x'}$

E_p a) $\pm \frac{1}{2} \Delta E_p$ b)	θ_L c)	θ_{cm} c)	p_x d)	E_n e)	$e_M \pm \Delta e_M$ f)	f	g	h	$P(n-\alpha)$ g)	$e \pm \Delta e$ h)	$p_{x'} \pm \Delta p_{x'}$ h)	$K_x^{x'} \pm \Delta K_x^{x'}$ h)
5.97 $\pm$ 0.09	15.3	20.8	0.882	5.07	0.470 $\pm$ 0.019	1.030	1.083	1.044	0.972	0.548 $\pm$ 0.026	0.564 $\pm$ 0.026	0.639 $\pm$ 0.030
5.97 $\pm$ 0.09	30.3	41.0	0.881	4.70	0.372 $\pm$ 0.019	1.045	1.101	1.051	0.970	0.449 $\pm$ 0.027	0.463 $\pm$ 0.027	0.526 $\pm$ 0.031
5.97 $\pm$ 0.09	41.0	55.0	0.876	4.33	0.198 $\pm$ 0.019	1.048	1.096	1.043	0.967	0.237 $\pm$ 0.024	0.245 $\pm$ 0.025	0.280 $\pm$ 0.028
5.97 $\pm$ 0.09	60.3	78.7	0.870	3.55	0.100 $\pm$ 0.031	1.066	1.166	1.045	0.957	0.129 $\pm$ 0.041	0.135 $\pm$ 0.043	0.155 $\pm$ 0.050
5.97 $\pm$ 0.09	80.3	101.5	0.870	2.74	0.334 $\pm$ 0.031	1.105	1.217	1.045	0.916	0.469 $\pm$ 0.053	0.512 $\pm$ 0.058	0.589 $\pm$ 0.067
9.94 $\pm$ 0.06	0.3	0.4	0.890	9.17	0.579 $\pm$ 0.022	1.037	1.041	1.038	0.989	0.649 $\pm$ 0.022	0.656 $\pm$ 0.022	0.737 $\pm$ 0.025
9.94 $\pm$ 0.06	15.3	20.6	0.892	8.94	0.566 $\pm$ 0.023	1.032	1.041	1.033	0.988	0.627 $\pm$ 0.030	0.635 $\pm$ 0.031	0.712 $\pm$ 0.034
9.94 $\pm$ 0.06	30.3	40.6	0.894	8.32	0.434 $\pm$ 0.026	1.040	1.049	1.034	0.987	0.490 $\pm$ 0.031	0.497 $\pm$ 0.031	0.555 $\pm$ 0.035
9.94 $\pm$ 0.06	45.3	59.8	0.887	7.40	0.189 $\pm$ 0.022	1.051	1.046	1.041	0.985	0.216 $\pm$ 0.026	0.219 $\pm$ 0.026	0.247 $\pm$ 0.029
9.94 $\pm$ 0.06	60.3	78.2	0.887	6.37	0.061 $\pm$ 0.020	1.056	1.071	1.041	0.981	0.072 $\pm$ 0.023	0.073 $\pm$ 0.024	0.082 $\pm$ 0.027
9.94 $\pm$ 0.06	80.3	100.7	0.889	4.97	0.103 $\pm$ 0.021	1.093	1.083	1.044	0.971	0.127 $\pm$ 0.027	0.131 $\pm$ 0.028	0.147 $\pm$ 0.031
9.94 $\pm$ 0.06	100.3	120.6	0.887	3.82	0.206 $\pm$ 0.034	1.103	1.083	1.044	0.962	0.257 $\pm$ 0.044	0.267 $\pm$ 0.046	0.301 $\pm$ 0.052

a) Proton lab energy (MeV) at the tritium gas cell center.

b) $\frac{1}{2} \Delta E_p$ is the half energy loss (MeV) in the tritium gas cell.c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Average beam polarization.

e) Neutron lab energy (MeV).

f) Δe_M is statistical only expressed as standard deviation.g) $P(n-\alpha)$ is the n- α analyzing power at 115° lab.h) Δe , $\Delta p_{x'}$, and $\Delta K_x^{x'}$ contain a contribution from the uncertainty in f, g, and h.

TABLE VII

Polarization Transfer Data $K_z^{x'}$

E_p a) $\frac{1}{2}\Delta E_p$ b)	θ_L c)	θ_{cm} c)	p_z d)	E_n e)	$e_{M \pm \Delta e_M}$ f)	f	g	h	$P(n-\alpha)$ g)	$e \pm \Delta e$ h)	$p_{x'} \pm \Delta p_{x'} h)$	$K_z^{x'} \pm \Delta K_z^{x'} h)$
5.97 $\pm$ 0.09	15.3	20.8	0.881	5.07	-0.173 $\pm$ 0.019	1.034	1.083	1.044	0.972	-0.203 $\pm$ 0.023	-0.208 $\pm$ 0.024	-0.237 $\pm$ 0.027
5.97 $\pm$ 0.09	30.3	41.0	0.885	4.70	-0.319 $\pm$ 0.019	1.047	1.101	1.051	0.970	-0.387 $\pm$ 0.027	-0.399 $\pm$ 0.028	-0.451 $\pm$ 0.031
5.97 $\pm$ 0.09	41.0	54.9	0.884	4.33	-0.355 $\pm$ 0.016	1.042	1.096	1.043	0.967	-0.422 $\pm$ 0.023	-0.437 $\pm$ 0.024	-0.494 $\pm$ 0.027
5.97 $\pm$ 0.09	80.3	101.5	0.870	2.74	-0.159 $\pm$ 0.033	1.106	1.217	1.045	0.916	-0.223 $\pm$ 0.049	-0.244 $\pm$ 0.053	-0.281 $\pm$ 0.062
9.94 $\pm$ 0.06	0.3	0.4	0.895	9.17	-0.013 $\pm$ 0.026	1.040	1.041	1.038	0.987	-0.015 $\pm$ 0.029	-0.015 $\pm$ 0.030	-0.017 $\pm$ 0.033
9.94 $\pm$ 0.06	15.3	20.6	0.891	8.94	-0.199 $\pm$ 0.027	1.037	1.041	1.033	0.988	-0.222 $\pm$ 0.031	-0.225 $\pm$ 0.031	-0.252 $\pm$ 0.035
9.94 $\pm$ 0.06	30.3	40.6	0.890	8.32	-0.319 $\pm$ 0.027	1.044	1.049	1.034	0.987	-0.361 $\pm$ 0.032	-0.366 $\pm$ 0.033	-0.411 $\pm$ 0.037
9.94 $\pm$ 0.06	45.3	59.8	0.887	7.40	-0.307 $\pm$ 0.020	1.062	1.046	1.041	0.985	-0.355 $\pm$ 0.026	-0.360 $\pm$ 0.026	-0.406 $\pm$ 0.029
9.94 $\pm$ 0.06	60.3	78.2	0.887	6.37	-0.201 $\pm$ 0.019	1.167	1.071	1.041	0.981	-0.234 $\pm$ 0.023	-0.234 $\pm$ 0.023	-0.269 $\pm$ 0.026
9.94 $\pm$ 0.06	80.3	100.7	0.888	4.97	-0.098 $\pm$ 0.021	1.114	1.083	1.044	0.971	-0.123 $\pm$ 0.027	-0.127 $\pm$ 0.028	-0.143 $\pm$ 0.032
9.94 $\pm$ 0.06	100.3	120.6	0.889	3.82	-0.335 $\pm$ 0.032	1.099	1.116	1.041	0.962	-0.428 $\pm$ 0.046	-0.445 $\pm$ 0.048	-0.500 $\pm$ 0.054

a) Proton lab energy (MeV) at the tritium gas cell center.

b) $\frac{1}{2}\Delta E_p$ is the half energy loss (MeV) in the tritium gas cell.c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Average beam polarization.

e) Neutron lab energy (MeV).

f) Δe_M is statistical only expressed as standard deviation.g) $P(n-\alpha)$ is the $n-\alpha$ analyzing power at 115° lab.h) Δe , $\Delta p_{x'}$, and $\Delta K_z^{x'}$ contain a contribution from the uncertainty in f, g, and h.

4.8 Polarization Transfer Data $K_z^{z'}$

The polarization transfer coefficient $K_z^{z'}$ is related to the final neutron polarization p_z , by

$$K_z^{z'} = \frac{p_{z'}}{p_z} . \quad (4-15)$$

To measure the neutron polarization in the z' direction a dipole spin precession magnet was used. The dipole magnet provided a transverse magnetic field which precessed the z' component of neutron polarization $\pm 90^\circ$ about the y' direction so the z' component of neutron spin would be normal to the polarimeter scattering plane. With the incident proton beam polarized in the z direction and the dipole magnet energized for $+90^\circ$ precession (z' to x') the two quantities $S12 (+z)$ and $S13 (+z)$ were obtained. By reversing the direction of proton polarization to $-z$ the neutron polarization p_z , is also reversed. This configuration then yields $S12 (-z)$ and $S13(-z)$. With these numbers the transfer coefficient $K_z^{z'}$ was calculated in exactly the same way as $K_x^{x'}$. The $K_z^{z'}$ data is presented in Table VIII.

TABLE VIII

Polarization Transfer Data $K_z^{z'}$

E_p a) $\pm \frac{1}{2} \Delta E_p$ b)	θ_L c)	θ_{cm} c)	p_z d)	E_n e)	$e_M \pm \Delta e_M$ f)	d_g g)	f	g	h	$P(n-\alpha)$ h)	$e \pm \Delta e$ i)	$p_z \pm \Delta p_z$ i)	$K_z^{z'} \pm \Delta K_z^{z'} i)$
4.00±0.12	0.3	0.4	0.893	3.22	0.214±0.015		1.040	1.150	1.046	0.948	0.268±0.022	0.282±0.023	0.316±0.026
5.00±0.10	0.3	0.4	0.890	4.22	0.298±0.014		1.042	1.096	1.043	0.966	0.355±0.020	0.368±0.020	0.413±0.024
6.00±0.09	0.3	0.4	0.890	5.23	0.361±0.014		1.045	1.080	1.039	0.974	0.423±0.020	0.434±0.021	0.488±0.023
7.00±0.08	0.3	0.4	0.880	6.23	0.458±0.023	1.002	1.067	1.071	1.041	0.980	0.546±0.033	0.557±0.034	0.632±0.039
8.00±0.07	0.3	0.4	0.880	7.23	0.590±0.023	1.001	1.049	1.046	1.041	0.984	0.676±0.032	0.687±0.032	0.781±0.037
9.00±0.06	0.3	0.4	0.877	8.23	0.681±0.026	1.001	1.045	1.049	1.034	0.988	0.773±0.035	0.783±0.035	0.892±0.040
10.00±0.06	0.3	0.4	0.858	9.23	0.632±0.028		1.042	1.041	1.038	0.989	0.712±0.037	0.720±0.038	0.839±0.044
10.00±0.06	0.3	0.4	0.884	9.23	0.644±0.020		1.048	1.041	1.038	0.989	0.729±0.029	0.737±0.030	0.834±0.033
11.00±0.05	0.3	0.4	0.878	10.23	0.689±0.017	1.001	1.045	1.035	1.044	0.990	0.689±0.025	0.660±0.025	0.793±0.029
12.00±0.05	0.3	0.4	0.877	11.23	0.520±0.028	1.009	1.052	1.028	1.043	0.990	0.592±0.035	0.598±0.036	0.682±0.041
13.00±0.05	0.3	0.4	0.884	12.23	0.519±0.028	1.002	1.049	1.020	1.034	0.989	0.575±0.034	0.581±0.034	0.658±0.039
14.00±0.04	0.3	0.4	0.863	13.23	0.480±0.023		1.045	1.028	1.033	0.988	0.533±0.029	0.539±0.029	0.625±0.034
15.00±0.04	0.3	0.4	0.875	14.23	0.386±0.026	1.002	1.067	1.034	1.034	0.986	0.442±0.033	0.448±0.034	0.512±0.038
10.00±0.06	15.3	20.6	0.859	9.00	0.651±0.029		1.054	1.044	1.036	0.988	0.743±0.039	0.752±0.039	0.875±0.046
10.00±0.06	30.3	40.6	0.861	8.37	0.554±0.030		1.034	1.049	1.034	0.987	0.622±0.036	0.630±0.036	0.732±0.042
10.00±0.06	45.3	59.8	0.861	7.46	0.161±0.027		1.076	1.046	1.041	0.985	0.188±0.032	0.191±0.033	0.222±0.038
10.00±0.06	60.3	78.2	0.862	6.40	-0.090±0.023		1.056	1.071	1.041	0.981	-0.106±0.028	-0.108±0.028	-0.126±0.033
10.00±0.06	70.3	89.7	0.866	5.68	-0.248±0.043		1.152	1.056	1.035	0.977	-0.312±0.058	-0.320±0.059	-0.369±0.068
10.00±0.06	80.3	100.7	0.865	5.00	-0.242±0.028		1.119	1.083	1.044	0.971	-0.306±0.039	-0.316±0.040	-0.365±0.047
10.00±0.06	100.3	120.6	0.862	3.85	-0.256±0.030		1.123	1.116	1.041	0.962	-0.334±0.044	-0.347±0.045	-0.403±0.052

a) Proton lab energy (MeV) at the tritium gas cell center.

b) $\frac{1}{2} \Delta E_p$ is the half energy loss (MeV) in the tritium gas cell.c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Average beam polarization.

e) Neutron lab energy (MeV).

f) Δe_M is statistical only expressed as standard deviation.g) d_g = correction factor for incorrect spin precession. $e = df g e_M$.h) $P(n-\alpha)$ is the $n-\alpha$ analyzing power at 115° lab.i) Δe , Δp_z , and $\Delta K_z^{z'}$ contain a contribution from the uncertainty in f, g, and h.

CHAPTER V

ANALYZING POWER DATA REDUCTION AND RESULTS

5.1 Reduction of Analyzing Power Data

The analyzing power was calculated from the expression

$$A_y = \frac{N_+ - N_-}{(p_-)(N_+) - (p_+)(N_-)} \quad (5-1)$$

where $N_{\pm}$ is the number of neutrons detected with the incident proton beam polarization parallel (+) or antiparallel (-) to the normal to the reaction plane; $p_{\pm}$ is the average of the beam polarization. Gamma rays were electronically separated from neutrons by pulse shape discrimination. To estimate how well the gamma rays were rejected several n- γ rejection ratios were calculated. The rejection ratio was obtained by extrapolating the gamma ray peak under the neutron peak in the time distribution (see Chapter III, Fig. 9) and taking the ratio of their areas. The rejection ratios and the energies and angles for which the rejection ratios were calculated are presented in Table IX.

In order to reduce the effect of electronic drifts the data were taken in two cycles of +--+ beam polarization. Each + and - run within a cycle was short; a run time of two minutes was typical. The beam polarization was measured after each + and - run in a cycle.

The shape of the recoil proton distribution exhibited the well-

TABLE IX
Rejection Ratios

<u>Proton Energy</u>	<u>Lab Angle</u>	<u>n-γ Rejection Ratio</u>
13.55 MeV	15°	0.0006
13.55 MeV	110°	0.0046
10.00 MeV	120°	0.0035
6.00 MeV	110°	0.0023

known shape^{35,36} for elastic low energy (< 10 MeV) n-p scattering. The distribution is flat from the low energy cutoff up to the high energy edge which is rounded because of the finite energy resolution of the detector. The shape of the recoil proton distribution served as a diagnostic check since a deviation from the expected shape would indicate possible experimental difficulties or significant background. In cases where the shape of the recoil distribution indicated that background neutrons were not negligible target empty runs were taken. The target empty runs indicated that the majority of the background neutrons were produced in the metal of the target, collimating slits, etc. The target empty runs were taken in the same +--+ sequence as target full runs and for the same integrated beam current. It was observed that for a given proton energy the background was isotropic and exhibited no asymmetry when the beam polarization was reversed from + to -. The background was most serious for the back angles ($> 90^\circ$ lab) where the neutron energy is lower. It was also observed that the background decreased with decreasing proton energy.

On-line asymmetries were obtained by setting two windows on the

recoil proton distribution. These windows were designated the lower window (LW) and upper window (UW), respectively. The channel number of the lower cutoff of the lower and upper window was typically 50% and 75%, respectively, of the channel number of the recoil one-half point of the distribution. The recoil one-half point was the channel number at the high energy end of the distribution where the number of counts per channel decreased to one-half the counts per channel in the flat part of the distribution. The upper cutoff was the same for both windows and was set high enough to include the entire rounded edge at the high energy end of the distribution, typically 10 to 20 channels above the recoil one-half point. After each $\pm$ sequence in a cycle an asymmetry was calculated for each window. These asymmetries were compared and served as a running check on possible electronic drifts, background, etc.

To indicate the quality of the experimental data, Fig. 12 shows four typical recoil proton distributions. In all the distributions the lower cutoff is due to electronics and the low energy tail is due to target empty neutrons. The arrows labeled L and U indicate the lower level of the lower and upper windows chosen to calculate the analyzing power. In Fig. 12 the upper left figure shows the recoil proton distribution measured at 45.3° lab for a proton energy of 13.55 MeV. At this angle the energy of the neutrons from the reaction is well above the energy of the target empty neutrons; consequently they are not a problem at this angle. The upper right figure shows the distribution at 110.3° lab for a proton energy of 13.55 MeV. Also plotted in this

Fig. 12. Recoil Proton Distributions. Dots Correspond to Target Full Runs, x to Target Empty Runs, - to Target Full Minus Target Empty Runs.

figure is a target empty distribution and the distribution that results when target empty is subtracted from target full. At this angle the energy of the neutrons from the reaction is lower and as a result the contribution of the target empty neutrons to the total spectrum is significant. One notes, however, that by subtracting the target empty distribution from the target full the resulting distribution yields the expected shape. This subtraction does not remove background neutrons caused by proton breakup of the tritium gas or room scattered neutrons, but since the shape of the target full minus target empty distribution has the expected shape this indicates that background from these sources is small. The lower left and right figures show the distributions measured at 45.3° and 110.3° , respectively, for a proton energy of 6 MeV. Also plotted in the lower right figure is a target empty distribution. The contribution of the target empty neutrons to the total spectrum at 110.3° and 6 MeV is quite small, especially for the upper window. For example, the asymmetry calculated for the upper window before background was subtracted was 0.1216 ± 0.0024 ; after background was subtracted the asymmetry was 0.1244 ± 0.0025 .

It was necessary to monitor the start signal rate to the time to amplitude converter of the n- γ discrimination system (see Fig. 9 of Chapter III) because the TAC start input had the lowest signal rate capability of any module in the system. The TAC was capable of handling a start signal rate of 245,096 counts per second. The start signal rate was typically 1000 counts per second and in no case did it exceed 2000 counts per second.

After a run was completed, the data were further processed with the aid of a computer program. The program summed the four + and - recoil distributions and corrected them for dead time. A dead time correction was possible because a scaler counted all signals that were not accepted by the ADC while it was processing a signal. The dead time correction was made by increasing the number of counts in the entire distribution by a multiplicative factor of one plus the ratio of lost counts to total counts in the distribution. These ratios were small, typically less than 0.02. The dead time correction to the two scalers that counted the signals from the lower and upper windows was negligible because of their extremely high count rate capability (100,000,000 counts per second). The program also summed the scaler numbers from the lower and upper windows for the four + and - runs. The four + and - beam polarizations were summed and their average computed. For cases where target empty runs were taken, the program would sum the four + and - target empty runs and subtract them from the summed target full runs. The distributions were plotted for visual inspection. From the plots the distributions were divided into three or four approximately equal segments. For each segment an asymmetry was calculated. The asymmetries calculated from the segments were then compared with each other and with those calculated from the lower and upper window to see the effect of background. For example, for a proton energy of 13.55 MeV and a lab angle of 110.3° the asymmetry calculated from the lower and upper windows was 0.0969 ± 0.0022 and 0.1055 ± 0.0034 . These numbers disagree as can be expected from observing the shape of the spectrum

in Fig. 12. If background corrections are made as described in Sec. 5.2, then asymmetries calculated using data from the upper and lower window are brought into agreement. The asymmetries calculated from segments where background was negligible or where background had been subtracted agreed within the statistical uncertainty. For example, for a proton energy of 13.55 MeV at a lab angle of 45.3° the asymmetry calculated from the lower and upper window was -0.2209 ± 0.0020 and -0.2245 ± 0.0025 . These values agree within the errors indicating that background is negligible here. The analyzing powers calculated from the segments were also compared with those calculated from the lower and upper window chosen during the run. This comparison showed that the values agreed within statistical error. In order to reduce the effect of background neutrons, the analyzing power calculated from the upper window has been put in the data tables.

Repeat measurements of five different data points were taken. Each measurement repeated within the statistical error which was typically ± 0.003 . The stability of the current integrator was checked and it proved to be stable to better than 0.3% over a period of 1-1/2 hrs. As was discussed in Chapter III, the beam polarization was measured to an accuracy of ± 0.015 . The errors in the analyzing power were taken as the statistical error expressed as standard deviation and do not contain a contribution from an uncertainty in the beam polarization which is regarded as being better represented as a systematic error.

To obtain an estimate of systematic error measurements were performed at 0.3° lab, for proton energies of 13.55 and 6.00 MeV. The

results were extrapolated to 0° where the analyzing power is theoretically zero, the extrapolated results were 0.0023 ± 0.0026 and -0.0048 ± 0.0023 . The weighted average of the absolute value of the extrapolated results was 0.0037 and from this the systematic error in A_y is estimated to be less than 0.005.

A beam profile measurement was taken at 13.55 MeV to establish the true zero of angle. The measurement indicated that a correction of $0.26 \pm 0.06^\circ$ should be applied to the angles; all of the angles have been corrected by this amount. The laboratory angle presented in the data tables corresponds to a point geometry angle which is the angle between the incident beam direction and the line extending from the tritium target cell center to the NE-213 scintillator center. The center of mass angle in the data tables was obtained by converting the lab angle to the center of mass. For all the measurements the scintillator subtended a lab angle of $\Delta\theta = 3^\circ$ which was the full angular spread over which the measurements were averaged.

5.2 Analyzing Power Data

The results of the analyzing power measurements are tabulated in Tables X through XIII. For cases where background neutrons were negligible the analyzing power was calculated from Eq. 5-1. The error in the analyzing power ΔA_y was taken as the quadratic combination of the errors

$$\Delta A_y = \sqrt{\left(\frac{\partial A_y}{\partial N_+}\right)^2 \Delta N_+^2 + \left(\frac{\partial A_y}{\partial N_-}\right)^2 \Delta N_-^2}$$

$$\Delta N_+ = \sqrt{N_+} \quad \Delta N_- = \sqrt{N_-} \quad (5-2)$$

TABLE X

 $T(p,n)^3\text{He}$ Analyzing Power for $E_p = 6.00^{a)} \pm 0.05^{b)}$ MeV.

$\theta_L^{c)}$	$\theta_{cm}^{c)}$	$E_n^{d)}$	Average Beam Polarization		Measured Asymmetry	Background Asymmetry	Background Fraction	Corrected Asymmetry	Analyzing Power
			P_+	P_-	$e_M \pm \Delta e_M$	$e_B \pm \Delta e_B$	f	$e/\Delta e$	$A_y \pm \Delta A_y^{e)}$
0.3	0.4	5.23	0.899	0.896				-0.0056 $\pm$ 0.0021	-0.0062 $\pm$ 0.0023
7.8	10.6	5.20	0.900	0.897				-0.0375 $\pm$ 0.0021	-0.0418 $\pm$ 0.0024
15.3	20.8	5.10	0.901	0.899				-0.0654 $\pm$ 0.0022	-0.0726 $\pm$ 0.0025
22.8	30.9	4.94	0.899	0.898				-0.0947 $\pm$ 0.0018	-0.1054 $\pm$ 0.0020
33.5	45.2	4.62	0.905	0.904				-0.1290 $\pm$ 0.0021	-0.1426 $\pm$ 0.0023
37.8	50.8	4.47	0.907	0.906				-0.1371 $\pm$ 0.0022	-0.1513 $\pm$ 0.0025
45.3	60.4	4.19	0.900	0.897				-0.1345 $\pm$ 0.0023	-0.1496 $\pm$ 0.0026
52.8	69.8	3.88	0.896	0.893				-0.1146 $\pm$ 0.0029	-0.1281 $\pm$ 0.0032
60.3	78.9	3.57	0.901	0.900				-0.0697 $\pm$ 0.0029	-0.0774 $\pm$ 0.0032
70.3	90.5	3.16	0.900	0.901				0.0479 $\pm$ 0.0031	0.0532 $\pm$ 0.0035
80.3	101.5	2.76	0.901	0.899				0.1612 $\pm$ 0.0030	0.1791 $\pm$ 0.0033
90.3	111.8	2.41	0.903	0.895	0.1882 $\pm$ 0.0025	-0.0089 $\pm$ 0.0175	0.021	0.1923 $\pm$ 0.0025	0.2140 $\pm$ 0.0028
100.3	121.5	2.10	0.901	0.896	0.1623 $\pm$ 0.0025	-0.0048 $\pm$ 0.0173	0.022	0.1661 $\pm$ 0.0026	0.1849 $\pm$ 0.0029
110.3	130.4	1.84	0.902	0.907	0.1216 $\pm$ 0.0024	-0.0062 $\pm$ 0.0164	0.022	0.1244 $\pm$ 0.0025	0.1375 $\pm$ 0.0027
120.3	138.8	1.63	0.906	0.906				0.0891 $\pm$ 0.0024	0.0983 $\pm$ 0.0026
130.3	146.6	1.50	0.905	0.911				0.0670 $\pm$ 0.0022	0.0738 $\pm$ 0.0025

a) Proton lab energy at the tritium gas cell center.

b) Half the energy loss in the tritium gas cell.

c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Neutron lab energy in MeV.

e) Errors are statistical only expressed as standard deviations. Estimated systematic error of 0.005 for all measurements.

TABLE XI

 $T(\vec{p}, n)^3\text{He}$ Analyzing Power for $E_p = 9.96^{a)} \pm 0.06^{b)}$ MeV.

$\theta_L^{c)}$	$\theta_{cm}^{c)}$	$E_n^{d)}$	Average Beam Polarization		Measured Asymmetry	Background Asymmetry	Background Fraction	Corrected Asymmetry	Analyzing Power
			P_+	P_-	$e_M \pm \Delta e_M$	$e_B \pm \Delta e_B$	f	$e \pm \Delta e$	$A_y \pm \Delta A_y^{e)}$
7.8	10.5	9.11	0.900	0.894				-0.0604 ± 0.0023	-0.0673 ± 0.0026
15.3	20.6	8.96	0.906	0.899				-0.1291 ± 0.0025	-0.1430 ± 0.0027
22.8	30.6	8.69	0.904	0.895				-0.1900 ± 0.0023	-0.2110 ± 0.0025
30.3	40.6	8.33	0.908	0.900				-0.2335 ± 0.0024	-0.2580 ± 0.0027
37.8	50.3	7.90	0.899	0.891				-0.2425 ± 0.0028	-0.2706 ± 0.0030
45.3	59.8	7.42	0.903	0.896				-0.2174 ± 0.0025	-0.2415 ± 0.0026
52.8	69.2	6.90	0.899	0.893				-0.1817 ± 0.0027	-0.2026 ± 0.0030
60.3	78.2	6.36	0.907	0.904				-0.1418 ± 0.0027	-0.1566 ± 0.0030
70.3	89.7	5.65	0.908	0.905				-0.0914 ± 0.0030	-0.1008 ± 0.0033
80.3	100.7	4.98	0.907	0.906				-0.0164 ± 0.0036	-0.0181 ± 0.0040
90.3	111.0	4.37	0.906	0.904	0.0764 ± 0.0034	0.0014 ± 0.0169	0.043	0.0797 ± 0.0037	0.0880 ± 0.0040
100.3 ^{f)}	121.0	3.83	0.901	0.891	0.1244 ± 0.0030	-0.0116 ± 0.0102	0.095	0.1374 ± 0.0034	0.1534 ± 0.0038
110.3	130.0	3.38	0.905	0.903	0.1290 ± 0.0036	-0.0050 ± 0.0102	0.101	0.1426 ± 0.0041	0.1577 ± 0.0046
120.3	138.1	3.00	0.906	0.904	0.0894 ± 0.0028	0.0061 ± 0.0093	0.103	0.0980 ± 0.0033	0.1083 ± 0.0036
130.3	146.0	2.70	0.902	0.903	0.0627 ± 0.0024	0.0002 ± 0.0075	0.111	0.0697 ± 0.0028	0.0772 ± 0.0031
80.3 ^{f)}	100.7	5.01	0.904	0.904	-0.0146 ± 0.0033	-0.0325 ± 0.0217	0.023	-0.0142 ± 0.0034	-0.0157 ± 0.0037
90.3 ^{f)}	111.0	4.39	0.899	0.895	0.0726 ± 0.0017	-0.0038 ± 0.0065	0.078	0.0785 ± 0.0020	0.0875 ± 0.0022

a) Proton lab energy at the tritium gas cell center.

b) Half the energy loss in the tritium gas cell.

c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Neutron lab energy in MeV.

e) Errors are statistical only expressed as standard deviations. Estimated systematic error of 0.005 for all measurements.

f) Repeat measurements. For these measurements $E_p = 10.00 \pm 0.03$ MeV.

TABLE XII

 $T(p,n)^3\text{He}$ Analyzing Power for $E_p = 13.55^{a)} \pm 0.05^{b)}$ MeV.

$\theta_L^{c)}$	$\theta_{cm}^{c)}$	$E_n^{d)}$	Average Beam Polarization		Measured Asymmetry	Background Asymmetry	Background Fraction	Corrected Asymmetry	Analyzing Power
			P_+	P_-	$a_M \pm \Delta a_M$	$a_B \pm \Delta a_B$	f	$a \pm \Delta a$	$A_Y \pm \Delta A_Y^{e)}$
0.4	0.5	12.79	0.918	0.915				0.0043 $\pm$ 0.0024	0.0047 $\pm$ 0.0026
7.8	10.5	12.71	0.907	0.903				-0.0422 $\pm$ 0.0018	-0.0467 $\pm$ 0.0020
15.3	20.6	12.48	0.906	0.900				-0.0893 $\pm$ 0.0020	-0.0988 $\pm$ 0.0022
22.8	30.5	12.11	0.907	0.901				-0.1500 $\pm$ 0.0019	-0.1658 $\pm$ 0.0021
30.3	40.4	11.62	0.899	0.897				-0.2126 $\pm$ 0.0023	-0.2366 $\pm$ 0.0025
37.8	50.1	11.02	0.898	0.897				-0.2533 $\pm$ 0.0026	-0.2821 $\pm$ 0.0030
45.3	59.6	10.36	0.905	0.903				-0.2245 $\pm$ 0.0025	-0.2484 $\pm$ 0.0028
52.8	68.9	9.64	0.905	0.901				-0.1918 $\pm$ 0.0028	-0.2122 $\pm$ 0.0032
60.3	77.9	8.91	0.905	0.905				-0.1357 $\pm$ 0.0032	-0.1500 $\pm$ 0.0035
70.3	89.5	7.93	0.903	0.901	-0.0579 $\pm$ 0.0027	-0.0316 $\pm$ 0.0172	0.026	-0.0996 $\pm$ 0.0028	-0.1105 $\pm$ 0.0031
80.3	100.4	7.00	0.907	0.906	-0.0473 $\pm$ 0.0030	-0.0559 $\pm$ 0.0136	0.050	-0.0469 $\pm$ 0.0032	-0.0517 $\pm$ 0.0035
90.3	110.7	6.15	0.907	0.905	0.0158 $\pm$ 0.0034	-0.0071 $\pm$ 0.0120	0.084	0.0178 $\pm$ 0.0038	0.0196 $\pm$ 0.0042
100.3	120.4	5.40	0.907	0.902	0.0858 $\pm$ 0.0036	-0.0116 $\pm$ 0.0088	0.194	0.1047 $\pm$ 0.0045	0.1158 $\pm$ 0.0050
110.3	129.4	4.77	0.906	0.905	0.1055 $\pm$ 0.0034	-0.0089 $\pm$ 0.0068	0.320	0.1420 $\pm$ 0.0050	0.1568 $\pm$ 0.0055
120.3	137.8	4.25	0.906	0.902	0.0805 $\pm$ 0.0032	-0.0010 $\pm$ 0.0060	0.421	0.1149 $\pm$ 0.0053	0.1270 $\pm$ 0.0058

a) Proton lab energy at the tritium gas cell center.

b) Half the energy loss in the tritium gas cell.

c) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

d) Neutron lab energy in MeV.

e) Errors are statistical only expressed as standard deviations. Estimated systematic error of 0.005 for all measurements.

TABLE XIII
T($\bar{p}, n$) ^3He Analyzing Power near 45° c.m. from 1.51-11.95 MeV.

$\Delta E^a)$	$E_p^b) \pm \frac{1}{2} \Delta E_p^c)$	$\theta_L^d)$	$\theta_{cm}^d)$	$E_n^e)$	Average Beam Polarization		Measured Asymmetry	Analyzing Power
					p_+	p_-	$e \pm \Delta e$	$A_y \pm \Delta A_y^f)$
0.19	1.51 $\pm$ 0.05	29.8	46.7	0.59	0.906	0.911	0.1644 $\pm$ 0.0050	0.1810 $\pm$ 0.0055
0.18	1.67 $\pm$ 0.04	30.3	45.9	0.75	0.898	0.904	0.2690 $\pm$ 0.0048	0.2983 $\pm$ 0.0053
0.17	1.76 $\pm$ 0.14	30.5	45.6	0.83	0.907	0.911	0.3198 $\pm$ 0.0040	0.3515 $\pm$ 0.0052
0.17	1.85 $\pm$ 0.04	30.5	45.1	0.92	0.911	0.914	0.3636 $\pm$ 0.0037	0.3983 $\pm$ 0.0040
0.17	1.92 $\pm$ 0.04	30.9	45.4	0.98	0.906	0.909	0.3943 $\pm$ 0.0037	0.4340 $\pm$ 0.0041
0.16	2.01 $\pm$ 0.04	30.9	45.1	1.06	0.904	0.909	0.4191 $\pm$ 0.0036	0.4616 $\pm$ 0.0040
0.16	2.13 $\pm$ 0.04	31.4	45.3	1.17	0.905	0.908	0.4357 $\pm$ 0.0041	0.4804 $\pm$ 0.0045
0.15	2.26 $\pm$ 0.04	31.6	45.2	1.28	0.902	0.908	0.4262 $\pm$ 0.0035	0.4701 $\pm$ 0.0039
0.14	2.51 $\pm$ 0.10	32.0	45.3	1.50	0.902	0.905	0.3757 $\pm$ 0.0028	0.4156 $\pm$ 0.0031
0.13	2.76 $\pm$ 0.10	32.2	45.2	1.73	0.905	0.907	0.3131 $\pm$ 0.0023	0.3454 $\pm$ 0.0025
0.13	3.00 $\pm$ 0.09	32.6	45.4	1.95	0.903	0.909	0.2545 $\pm$ 0.0024	0.2807 $\pm$ 0.0026
0.12	3.50 $\pm$ 0.08	32.8	45.3	2.40	0.903	0.906	0.1673 $\pm$ 0.0032	0.1848 $\pm$ 0.0035
0.11	4.00 $\pm$ 0.07	33.1	45.3	2.84	0.900	0.905	0.0932 $\pm$ 0.0023	0.1032 $\pm$ 0.0025
0.46	4.92 $\pm$ 0.11	33.4	45.4	3.64	0.893	0.899	-0.0219 $\pm$ 0.0019	-0.0245 $\pm$ 0.0022
0.41	5.94 $\pm$ 0.09	33.6	45.3	4.56	0.901	0.903	-0.1255 $\pm$ 0.0021	-0.1391 $\pm$ 0.0024
0.37	6.94 $\pm$ 0.08	33.7	45.4	5.46	0.905	0.907	-0.1875 $\pm$ 0.0021	-0.2069 $\pm$ 0.0023
0.34	7.94 $\pm$ 0.07	33.9	45.4	6.34	0.905	0.905	-0.2169 $\pm$ 0.0020	-0.2394 $\pm$ 0.0022
0.33	8.50 $\pm$ 0.07	33.9	45.4	6.84	0.908	0.908	-0.2329 $\pm$ 0.0019	-0.2563 $\pm$ 0.0021
0.31	8.95 $\pm$ 0.06	33.9	45.4	7.24	0.909	0.910	-0.2396 $\pm$ 0.0018	-0.2636 $\pm$ 0.0020
0.30	9.45 $\pm$ 0.06	34.0	45.5	7.68	0.897	0.905	-0.2387 $\pm$ 0.0040	-0.2652 $\pm$ 0.0045
0.28	10.46 $\pm$ 0.06	34.0	45.4	8.57	0.907	0.912	-0.2604 $\pm$ 0.0048	-0.2865 $\pm$ 0.0052
0.27	10.96 $\pm$ 0.06	34.0	45.4	9.02	0.907	0.913	-0.2614 $\pm$ 0.0042	-0.2874 $\pm$ 0.0046
0.26	11.46 $\pm$ 0.05	34.0	45.4	9.44	0.907	0.912	-0.2487 $\pm$ 0.0039	-0.2735 $\pm$ 0.0043
0.26	11.95 $\pm$ 0.05	34.0	45.3	9.91	0.901	0.900	-0.2430 $\pm$ 0.0037	-0.2699 $\pm$ 0.0042
Repeat Measurements								
0.16	2.01 $\pm$ 0.13	30.9	45.1	1.06	0.903	0.911	0.4125 $\pm$ 0.0035	0.4539 $\pm$ 0.0056
0.15	2.26 $\pm$ 0.11	31.6	45.2	1.28	0.904	0.908	0.4270 $\pm$ 0.0032	0.4707 $\pm$ 0.0036
0.62	2.91 $\pm$ 0.17	32.6	45.5	1.86	0.899	0.902	0.2515 $\pm$ 0.0019	0.2791 $\pm$ 0.0022
0.53	3.90 $\pm$ 0.13	33.1	45.3	2.75	0.900	0.902	0.0932 $\pm$ 0.0018	0.1034 $\pm$ 0.0020
0.26	11.95 $\pm$ 0.05	34.0	45.3	9.91	0.897	0.888	-0.2460 $\pm$ 0.0037	-0.2752 $\pm$ 0.0042

a) ΔE is the energy loss (MeV) in the entrance foil to the tritium gas cell.

b) Proton lab energy (MeV) at the tritium gas cell center.

c) $\frac{1}{2} \Delta E_p$ is the half energy loss (MeV) in the tritium gas cell.

d) θ_L = neutron lab emission angle in degrees; θ_{cm} = center-of-mass angle in degrees.

e) Neutron lab energy in MeV.

f) Errors are statistical only expressed as standard deviations. Estimated systematic error of 0.005 for all measurements.

For cases where target empty spectra were taken as a measure of background neutrons the analyzing power was calculated from

$$A_y = \frac{(N_+ - N_B^+) - (N_- - N_B^-)}{p_- (N_+ - N_B^+) + p_+ (N_- - N_B^-)} , \quad (5-3)$$

where $N_{\pm}$ is the number of neutrons detected with the incident beam polarization parallel (+) or antiparallel (-) to the normal to the reaction plane and the target full; $N_B^{\pm}$ is the number of neutrons detected with the beam polarization $\pm$ and the target empty. In this case the error ΔA_y was taken as the quadratic combination of the errors in the same manner as Eq. 5-2.

Also included in the data tables for comparison purposes are three asymmetries e_M , e_B , and e , and the average beam polarization p_+ and p_- . The measured asymmetry e_M was calculated from the expression

$$e_M = \frac{N_+ - N_-}{N_+ + N_-} . \quad (5-4)$$

The background asymmetry e_B was calculated from the expression

$$e_B = \frac{N_B^+ - N_B^-}{N_B^+ + N_B^-} . \quad (5-5)$$

The final corrected asymmetry e was calculated from the expression

$$e = \frac{(N_+ - N_B^+) - (N_- - N_B^-)}{(N_+ - N_B^+) + (N_- - N_B^-)} . \quad (5-6)$$

For cases where the background was negligible and was not measured,

$$e_M = e . \quad (5-7)$$

The errors in all three asymmetries, e_M , e_B , and e , are statistical only and were obtained by calculating an error expression for each in the same manner as was done for A_y . Also included in the data tables is the background fraction f . The fraction is defined by the expression³⁷

$$e = (1+f) e_M - f e_B . \quad (5-8)$$

In terms of the measured numbers

$$f = \frac{N_B^+ + N_B^-}{N_+ + N_- - [N_B^+ + N_B^-]} . \quad (5-9)$$

The fraction f is the ratio of background events to good events.

5.3 Least Squares Analysis of Analyzing Power Data

A least squares analysis was made of the angular distribution data at 6.00, 9.96, and 13.55 MeV, by fitting³³ the data to the expression³⁸

$$k^2 \frac{d\sigma}{d\Omega} A_y = \sum_{\ell=1}^{\ell_{\max}} A_{\ell} P_{\ell}^1(\cos \theta) . \quad (5-10)$$

In the expression $d\sigma/d\Omega$ is the unpolarized center-of-mass differential cross section, k is the magnitude of the center-of-mass wave vector in the initial channel, and $P_{\ell}^1(\cos \theta)$ are the associated Legendre polynomials. The constants A_{ℓ} were those that minimized χ^2 .

$$\chi^2 = \sum_{i=1}^N \left[\frac{Y(\theta_i) - Y_{\text{cal}}(\theta_i)}{\Delta Y(\theta_i)} \right]^2, \quad (5-11)$$

where

N = number of data points

$$Y(\theta_i) = k^2 \frac{d\sigma(\theta_i)}{d\Omega} A_y(\theta_i)$$

$$\Delta Y(\theta_i) = \text{error in } k^2 \frac{d\sigma(\theta_i)}{d\Omega} A_y(\theta_i)$$

$$Y_{\text{cal}}(\theta_i) = \sum_{\ell} A_{\ell} P_{\ell}^1(\cos \theta_i).$$

The values for $k^2(d\sigma/d\Omega)$ were obtained from the Legendre coefficients of McDaniels et al.³⁴ A linear interpolation was made between the coefficients at 13 and 14 MeV to obtain the coefficients at 13.55 MeV. Their coefficients at 6 and 10 MeV were used for the 6.00 and 9.96 MeV analyzing power data. The error in $k^2(d\sigma/d\Omega)$ was calculated from the expression

$$\left(\Delta k^2 \frac{d\sigma}{d\Omega} \right)^2 = \sum_i \left(\frac{\partial k^2 \frac{d\sigma}{d\Omega}}{\partial B_i} \Delta B_i \right)^2, \quad (5-12)$$

where ΔB_i are the errors in the Legendre coefficients. The error in $k^2(d\sigma/d\Omega)$ was then combined in quadrature with the statistical error in A_y to obtain ΔY .

The weighted variance (χ^2 per degree of freedom) was used as the criterion for determining the best fit to the data. The number of

coefficients $l_{\max}$ was varied from one to five and a fit to the data was calculated for each value of $l_{\max}$. For each fit the weighted variance was calculated. It was observed that the weighted variance decreased as the number of parameters was increased from one to three but that no significant decrease in the weighted variance was obtained for values of $l_{\max}$ greater than three.

The results of the least squares analysis of the data is tabulated in Table IV for an $l_{\max}$ of 2 and 3. At 13.55 MeV the data are equally well fit with two or three coefficients; therefore, for simplicity the coefficients for $l_{\max} = 2$ are preferred. At 6.00 and 9.96 MeV better fits to the data are obtained with three coefficients so that at these energies the coefficients for $l_{\max} = 3$ are preferred.

Table XIV

Associated Legendre Coefficients Obtained
From Least Squares Fit to A_y Data

$E_p^a)$ (MeV)	$WV^b)$	$l_{\max} = 2$		WV	$l_{\max} = 3$		
		$A_1(A)$	$A_2(A)$		$A_1(A)$	$A_2(A)$	$A_3(A)$
6.00	15.5	0.0117 ± 0.0017	-0.0412 ± 0.0015	1.0	0.0142 ± 0.0004	-0.0429 ± 0.0004	0.0041 ± 0.0003
9.96	19.2	-0.0264 ± 0.0019	-0.0478 ± 0.0014	1.1	-0.0261 ± 0.0005	-0.0496 ± 0.0004	0.0045 ± 0.0003
13.55	2.6	-0.0424 ± 0.0010	-0.0470 ± 0.0008	2.5	-0.0423 ± 0.0010	-0.0472 ± 0.0008	0.0007 ± 0.0007

a) Proton lab energy at tritium cell center.

b) WV = weighted variance (χ^2 per degree of freedom).

CHAPTER VI

DISCUSSION OF RESULTS AND COMPARISON TO R-MATRIX CALCULATIONS

6.1 R-Matrix Analysis

R-matrix theory² has provided a powerful technique for analyzing nuclear scattering and reaction data.³⁹ When experimental data are analyzed within the R-matrix formalism the analysis yields a set of energy levels and widths for the intermediate nucleus formed. The levels possess definite total angular momentum, or spin, and parity (J^π) and isotopic spin. In general, the energy levels and widths are treated as phenomenological³⁹ parameters and their usefulness lies in being able to parameterize a large amount of experimental data. In the case of ${}^4\text{He}$, the levels have a more physical interpretation. The levels that result from the R-matrix analysis are interpreted as excited states of ${}^4\text{He}$.³ In 1968 Werntz and Meyerhof performed an R-matrix analysis of differential cross section and polarization data from the $T(p,n){}^3\text{He}$ reaction; this analysis resulted in two solutions, both of which gave equally good fits to the data available at that time. Their level structure of ${}^4\text{He}$ is shown in Fig. 13. In this figure the energy values are plotted vertically in MeV based on the ground state as zero. In the figure the energy of each level is indicated along with its spin, parity, and isotopic spin. Also indicated for reference purposes are the excitation energies in ${}^4\text{He}$ corresponding to two or more

Fig. 13. R-Matrix Levels .

particles separated at rest. For example, the total binding energy of ${}^4\text{He}$ is 28.3 MeV, thus two neutrons and two protons separated and at rest correspond to an excitation energy of 28.3 MeV. The two solutions of WM denoted as I and II are characterized by a common set of isotopic spin zero ($T = 0$) levels but differ in the ordering of the isotopic spin one ($T = 1$) levels.

An R-matrix code entitled Energy Dependent Analysis (EDA) has been written by Don Dodder⁴⁰ of LASL; when the WM levels of ${}^4\text{He}$ are used as input to this code predictions for any observable in the $T(p,n){}^3\text{He}$ reaction can be calculated. The calculation procedures differ slightly from WM in treating threshold effects more accurately, but this does not significantly affect the results.⁴ The code EDA has been used to calculate predictions for all the observables measured and these will be presented in the sections that follow.

6.2 Analyzing Power and Polarization Results

6.2a Comparison of Experimental Values of A_y and P_y ,

If time reversal invariance of nuclear forces is assumed, then for elastic scattering the polarization P_y , and the analyzing power A_y are equal.⁴¹ The reaction $T(p,n){}^3\text{He}$ is not elastic scattering; however, if charge dependent and Coulomb effects are ignored, one might expect the neutron polarization P_y , with incident proton beam unpolarized to be equal to the analyzing power A_y when the reaction is initiated with a polarized proton beam. In order to compare the experimental values of P_y , and A_y , the least squares coefficients obtained from the associated Legendre polynomial fits to the angular

distributions (see Chapters 4 and 5) can be compared. For comparison the coefficients are presented in Table X. For proton energies of 6.0 MeV the P_y and A_y coefficients agree within the errors for both $\ell_{\max} = 2$ and $\ell_{\max} = 3$. Comparing the coefficients at 9.96 MeV (for a similar weighted variance) for an $\ell_{\max} = 3$, one notes that the $A_1(A)$ and $A_1(P)$ coefficients differ by about 2.4 standard deviations, and the $A_2(A)$ and $A_2(P)$ coefficients agree within the errors. The $A_3(A)$ and $A_3(P)$ coefficients also agree within the errors. At 13.55 MeV the data are equally well fit for $\ell_{\max} = 2$ or $\ell_{\max} = 3$. Comparing the coefficients for $\ell_{\max} = 2$, one notes that the $A_1(A)$ and $A_1(P)$ coefficients differ by about 1.8 standard deviations, and the $A_2(A)$ and $A_2(P)$ coefficients agree within the errors. From the comparison we conclude that the data are consistent with $A_y = P_y$ at these energies.

In the R-matrix analysis of $T(p,n)^3\text{He}$ differential cross section and polarization data performed by Werntz and Meyerhof, they presented associated Legendre coefficients obtained from a least squares analysis of then existing polarization data. These coefficients and coefficients obtained from fitting differential cross section were in turn used to obtain the R-matrix parameters. In private communication with R. C. Haight⁴², Werntz has stated that the expression for the $A_2(P)$ coefficient of WM is in error. See Eq. 6-8 of this chapter for the correct expression. In the WM expression for $A_2(P)$ (Eq. 20g of Ref. 3) the last three terms containing the spin flip amplitude $U_{11,10}^1$ should be multiplied by $1/\sqrt{2}$. It is the understanding of the author that this error propagated through the entire analysis of WM. How this affected

Table XV

Associated Legendre Coefficients

$E_p^{a)}$ (MeV)	Fit to	WV ^{b)}	$l_{max} = 2$		WV	$l_{max} = 3$		
			A_1	A_2		A_1	A_2	A_3
6.00	Ay	15.5	0.0117±0.0017	-0.0412±0.0015	1.0	0.0142±0.0004	-0.0429±0.0004	0.0041±0.0002
5.97	Py'	1.4	0.0101±0.0045	-0.0446±0.0040	2.1	0.0120±0.0085	-0.0466±0.0083	0.0015±0.0052
9.96	Ay	19.2	-0.0264±0.0019	-0.0478±0.0014	1.1	-0.0261±0.0005	-0.0496±0.0040	0.0045±0.0003
9.87	Py'	1.2	-0.0203±0.0037	-0.0479±0.0025	0.7	-0.0192±0.0029	-0.0528±0.0028	0.0053±0.0022
⊗ 13.55	Ay	2.6	-0.0424±0.0010	-0.0470±0.0008	2.5	-0.0423±0.0010	-0.0472±0.0008	0.0007±0.0007
13.55	Py'	1.3	-0.0352±0.0040	-0.0456±0.0034	1.6	-0.0355±0.0045	-0.0450±0.0042	-0.0011±0.0036

a) Proton lab energy at the tritium cell center.

b) WV = weighted variance (χ^2 per degree of freedom).

the resulting R-matrix parameters is not clear.

In Figs. 14 and 15 the associated Legendre coefficients obtained from fitting our polarization data with $l_{\max} = 2$ are plotted as solid dots. Plotted as open circles are the associated Legendre coefficients that WM obtained for $l_{\max} = 2$ by fitting polarization data available at that time. Also plotted are the associated Legendre coefficients that WM calculated from their R-matrix parameters. These calculated coefficients were read from graphs and, as such, are subject to a reading error. The coefficients calculated from WMI are plotted as open inverted triangles, those calculated from WMII are plotted as closed triangles. In Fig. 14 is shown the $A_1(P)$ coefficient. The points at 6.0 MeV have been displaced slightly in the figure to make the overlap discernible. The A_1 coefficients obtained from fitting the data agree quite well. The A_1 coefficient calculated from WMI and II agrees very well at 6 MeV and is within three standard deviations at 9.95 MeV. At 13.55 MeV the calculated A_1 coefficient is too low in magnitude.

In the same private communication with R. C. Haight⁴², Werntz has also stated that the $A_2(P)$ coefficient that WM calculated and then plotted is not that which would be obtained by calculating the coefficient correctly from the WM parameters. The effect of properly calculating A_2 is to increase its magnitude where A_2 is less than zero. In Fig. 15 the $A_2(P)$ coefficient is plotted as a function of proton energy. The notation is the same as in Fig. 14. The values for the coefficient obtained by fitting the data differ by about one and one-

Fig. 14. Associated Legendre Coefficient $A_1(P)$. Dots: from Fit to Our P_y Data with $\ell_{\max} = 2$, Open Circles: WM Fit to P_y Data with $\ell_{\max} = 2$, Closed Triangles: Calculated from WMI and Read from Graph, Open Triangles: Calculated from WMII and Read from Graph.

Fig. 15. Associated Legendre Coefficient $A_2(P)$. Dots: from Fit to Our P_y Data with $\ell_{\max} = 2$, Open Circles: WM Fit to P_y Data with $\ell_{\max} = 2$, Closed Triangles: Calculated from WMI and Read from Graph, Open Triangles: Calculated from WMII and Read from Graph.

half standard deviations at 6.0 MeV. The WM coefficient at 12.0 MeV obtained from fits to data differs considerably from the general trend of $A_2(P)$ established by our more recent polarization data. At 6.0, 9.96, and 13.55 MeV the calculated $A_2(P)$ coefficient does not agree with the experimental values, being too small in magnitude.

6.2b Comparison of A_y and $P_{y'}$ with R-matrix Calculations

The expression for the analyzing power and polarization in terms of the M-matrix is

$$A_y = \frac{\text{Tr}[M(\sigma_y \otimes I)M^\dagger(I \otimes I)]}{\text{Tr}MM^\dagger} \quad (6-1)$$

$$P_{y'} = \frac{\text{Tr}[M(I \otimes I)M^\dagger(\sigma_y \otimes I)]}{\text{Tr}MM^\dagger}$$

where $\text{Tr}MM^\dagger = 4k^2 I_0$.

Substituting the expressions given in Chapter II for the M-matrix and the operators one obtains

$$4k^2 I_0 A_y = 2\sqrt{2} \text{Im}[M_{SS}^* M_{S1}^* + M_{LS}^* (M_{11}^* + M_{1-1}^*) + M_{10}^* M_{11} + M_{1-1}^* M_{10} + M_{00}^* M_{01}]$$

$$4k^2 I_0 P_{y'} = 2\sqrt{2} \text{Im}[M_{SS}^* M_{LS} + M_{S1}^* (M_{11} + M_{1-1}) + M_{11}^* M_{01} + M_{01}^* M_{1-1} + M_{10}^* M_{00}]$$

$$4k^2 I_0 = 2|M_{11}|^2 + 2|M_{1-1}|^2 + 2|M_{01}|^2 + 2|M_{10}|^2 + 2|M_{LS}|^2 + 2|M_{S1}|^2 + |M_{00}|^2 + |M_{SS}|^2. \quad (6-2)$$

In order to indicate the contribution of the various angular moment configurations one could substitute for the M-matrix elements the expansions in terms of the collision amplitudes that are given in

Chapter II. The expansions are infinite sums over the orbital angular momentum and unless some simplifying assumptions are made the mathematical manipulation of the sums becomes unwieldy. In the analysis of $T(p,n)^3\text{He}$ by Werntz and Meyerhof, they imposed the following restrictions on the collision amplitudes: ℓ and $\ell' \leq 2$, $J \leq 2$, S or $S' \neq 1$ if ℓ or $\ell' = 2$. Under these restrictions the expressions for the M-matrix elements reduce to

$$M_{SS} = \frac{1}{2} P_0 U_{00,00}^0 + \frac{3}{2} P_1 U_{10,10}^1 + \frac{5}{2} P_2 U_{20,20}^2$$

$$M_{S1} = -\frac{3}{4} P_1 U_{10,11}^1$$

$$M_{1S} = \frac{3}{4} P_1 U_{11,10}^1$$

$$M_{01} = \frac{1}{4} P_1^1 \left[-\frac{3}{\sqrt{2}} U_{11,11}^1 + \frac{3}{\sqrt{2}} U_{11,11}^2 \right] \quad (6-3)$$

$$M_{10} = -\frac{1}{2\sqrt{2}} P_1^1 \left[-U_{11,11}^0 + U_{11,11}^2 \right]$$

$$M_{00} = \frac{1}{2} P_0 U_{01,01}^1 + P_1 \left[\frac{1}{2} U_{11,11}^0 + U_{11,11}^2 \right]$$

$$M_{11} = \frac{1}{2} P_0 U_{01,01}^1 + \frac{3}{4} P_1 \left[U_{11,11}^1 + U_{11,11}^2 \right]$$

$$M_{1-1} = 0 .$$

Substituting these restricted sums for the M-matrix elements, one obtains

$$4k^2 I_{OY} A_y = \sum_{\ell=1}^3 A_{\ell} (A) P_{\ell}^1 (\cos \theta) ; \quad (6-4)$$

$$4k^2 I_{O P_y} = \sum_{\ell=1}^3 A_{\ell}(P) P_{\ell}^1 (\cos \theta) \quad (6-5)$$

where

$$A_1(A) = \frac{1}{16} \text{Im} \left[-5U_{01,01}^1 U_{11,11}^{2*} + 3U_{01,01}^1 U_{11,11}^{1*} + 2U_{01,01}^1 U_{11,11}^{0*} \right. \\ \left. - 3\sqrt{2} U_{01,01}^1 U_{11,10}^{1*} - 3\sqrt{2} U_{00,00}^0 U_{10,11}^{1*} + 3\sqrt{2} U_{20,20}^2 U_{10,11}^{1*} \right] \quad (6-6)$$

$$A_2(A) = \frac{1}{16} \text{Im} \left[-3U_{11,11}^1 U_{11,11}^{2*} - 2U_{11,11}^0 U_{11,11}^{2*} - \frac{3\sqrt{2}}{2} U_{11,11}^2 U_{11,10}^{1*} \right. \\ \left. - 3\sqrt{2} U_{10,10}^1 U_{10,11}^{1*} - \frac{3\sqrt{2}}{2} U_{11,11}^1 U_{11,10}^{1*} \right] \quad (6-7)$$

$$A_3(A) = \frac{1}{16} \text{Im} \left[-3\sqrt{2} U_{20,20}^2 U_{10,11}^{1*} \right] \quad (6-8)$$

The expressions for the coefficients $A_{\ell}(P)$ describing $4k^2 I_{O P_y}$, are obtained by interchanging the subscripts ℓS and $\ell'S'$ on the expressions for $A_{\ell}(A)$ in Eqs. 6-6 through 6-8. Thus, under the WM restrictions on S , ℓ , and J , A_y is different from P_y , only if $U_{11,10}^1 \neq U_{10,11}^1$.

The experimental values for A_y and P_y , and the R-matrix calculations based on WMI and II are presented in Figs. 16 through 18. In these figures the analyzing power data are plotted as closed circles and the errors are the size of the circles, the polarization data are plotted as open circles. The data at 13.55 MeV is somewhat high in energy for a comparison to WM since their analysis included polarization data only up to 12.2 MeV. However, both the analyzing power and polarization do not change rapidly with energy above about 8 MeV, so

Fig. 16. Analyzing Power and Polarization Data at 13.55 MeV.

Fig. 17. Analyzing Power and Polarization Data at 9.96 MeV.

Fig. 18. Analyzing Power and Polarization Data at 6.00 MeV.
 Triangles: Polarization Data from Ref. 43.

that on this basis the comparison at 13.55 MeV is reasonable. At 13.55 MeV both WMI and II differ little from each other and both predict $A_y \approx P_y$, which is consistent with experiment. The calculations predict the qualitative shape of the data but quantitative agreement is lacking. Essentially the same conclusions can be drawn from the comparison at 9.96 MeV. At 6.00 MeV one would expect the calculations to provide a reasonably good description of the polarization since actual data at this energy (obtained from Ref. 43) was used by WM. In Fig. 18 the polarization data from Ref. 43 is plotted as closed triangles. The agreement with the present polarization data is reasonable. The calculations based on WMI deviate considerably from the data predicting the wrong sign for P_y , from about 0° to 50° . The calculations based on WMII are in somewhat better agreement predicting the qualitative shape of the data but quantitative agreement is lacking.

It is also interesting to compare the calculations with differential cross section data since differential cross section data were used by WM in their analysis. In Fig. 19 we compare $T(p,n)^3\text{He}$ differential cross section data at 6.00 MeV (obtained from Ref. 34) with the R-matrix calculations. Both WMI and II describe the angular distribution reasonably well. Recall that neither WMI or II described the polarization data at 6.00 MeV.

In Fig. 20 we compare the R-matrix calculations with the absolute zero degree lab differential cross section (data from Refs. 34 and 44). Both WMI and II account well for the location of the maximum in the cross section and qualitatively for the complete excitation function.

Center of Mass Cross Section (mb/sr)

Fig. 19. $T(p,n)^3\text{He}$ Differential Cross Section at 6.00 MeV. Data from Ref. 34.

Fig. 20. $T(p,n)^3\text{He}$ Zero Degree Laboratory Differential Cross Section. Closed Triangles: Data from Ref. 44, Dots: Data from Ref. 34.

Figure 21 shows the values of A_y near 45° c.m. as a function of proton energy. The solid line connecting the analyzing power data was drawn as a guide to the eye. The polarization data for the figure was obtained from the literature. Both the polarization and analyzing power have similar features, the experimental maxima at about 2.2 MeV in both A_y and P_y , is due to the interference^{3,38,50} between the 0^- and 2^- ($T = 0$) states in ^4He . The fact that the maxima occur at the same energy is a qualitatively different effect from the final-state interaction observed in the $D(d,n)^3\text{He}$ and $D(d,p)^3\text{T}$ polarization measurements⁵¹ where the nucleon polarization is the same at the same relative kinetic energies differing by about 764 keV in the ^4He system. In the energy range 1.7 to 4 MeV, A_y differs experimentally from P_y , by about 17% relative; terms that make $P_y \neq A_y$ are therefore relatively small. The R-matrix calculations performed with either WMI or II account well for the location of the maxima and qualitatively for the complete excitation function. However, the experimental results indicate that $P_y \neq A_y$ in the region 1.7 to 4 MeV where many polarization data exist. In this region A_y is higher than P_y , by about 17% relative which is significantly larger than the quoted errors. It is conceivable that this difference relates to the existence of unknown systematic errors. With respect to the neutron polarization data, this possibility seems reduced because of the consistency of several different experiments. The magnitude of the estimated systematic error in the analyzing power is much smaller than the observed difference. The calculations of both WMI and II predict P_y and A_y equal to within 0.004 below 6.5 MeV. A

Fig. 21. Analyzing Power and Polarization Data near 45° C.M. as a Function of Proton Lab Energy. Data Obtained from the Literature with: Diamonds, Ref. 45, 31.6° Lab; Inverted Closed Triangles, Ref. 46, 45° C.M.; Upright Closed Triangles, Ref. 47, 33° Lab; Squares, Ref. 43, 45° C.M.; Asterisks, Ref. 48, 40° Lab; Open Triangles, Ref. 49, 47° C.M.; Crosses, Ref. 8, 30° Lab.

modification of the WM parameters might account for the apparent difference between P_y and A_y . Under the WM restrictions A_y is different from P_y only if $U_{11,10}^1 \neq U_{10,11}^1$. In the WM parametrization the $T = 1, 1^-$ states which give singlet-triplet mixing are at equivalent proton energies of about 7.5 and 10.9 MeV or well above the 1.7-4 MeV interval. If the WM restrictions on S , l , and J are retained, then the magnitudes of $U_{10,11}^1$ and $U_{11,10}^1$ must be increased and their differences magnified. For example, to maximize the singlet-triplet mixing in the 1^- states, one could put the mixing parameter χ equal to -1 instead of -0.3 or -3.3 as in WM. Werntz has suggested this possibility to describe the experimentally determined $A_1(P)$ coefficient better.³⁸ The result is to increase the magnitudes of $U_{10,11}^1$ and $U_{11,10}^1$ each by a factor of about 2 which is entirely inadequate to account for the apparent difference between P_y and A_y between 1.7 to 4 MeV. Two other ways to increase the singlet-triplet mixing in this energy region might be to move the $T = 1, 1^-$ states down in energy or to increase their widths. These possibilities do not seem acceptable since the $T = 1, 1^-$ states were chosen by WM to give a good description of p - ^3He elastic scattering, which probably would not be described well with a large change in the $T = 1$ parameters of WM. Since the calculated differences between P_y and A_y are small even near the position of the $T = 1, 1^-$ states, this indicates that rather drastic modifications of the charge-independent parameters of WM will be necessary if the apparent 17% difference is to be reproduced from 1.7 to 4.0 MeV.

6.3 Longitudinal Polarization Transfer Data $K_z^{z'}$

The measurements of the polarization transfer observable $K_z^{z'}$ reported in this thesis were the first measurements of this observable in a nuclear reaction and the first measurements of any type at Van de Graaff energies. $K_z^{z'}$ is equivalent to the Wolfenstein A' parameter for nucleon-nucleon scattering and previous measurements of A' for proton-proton scattering have been reported by Roth⁵² and Limon⁵³ at 430 MeV and by Carithers⁵⁴ at 1.9 GeV.

6.3a Comparison to R-Matrix Calculations

The general expression for $K_z^{z'}$ may be obtained from the expressions given in Chapter II; at zero degrees the M-matrix becomes diagonal

$$M(0^\circ) = \begin{pmatrix} M_{SS} & 0 & 0 & 0 \\ 0 & M_{11} & 0 & 0 \\ 0 & 0 & M_{00} & 0 \\ 0 & 0 & 0 & M_{11} \end{pmatrix} \quad (6-9)$$

and the expression for $K_z^{z'}$ simplifies to

$$K_z^{z'}(0^\circ) = \frac{2\text{Re}[M_{SS}^* M_{00}] + 2|M_{11}|^2}{4k^2 I_0(0^\circ)} \quad (6-10)$$

Substituting for the M-matrix elements the restricted collision amplitudes and noting that for both WMI and WMII $U_{01,01}^1 = 0$, one obtains

$$\begin{aligned}
4k^2 I_0(0^\circ) K_z^{Z'}(0^\circ) = & \operatorname{Re} \left[\frac{1}{2} U_{00,00}^0 {}^* U_{11,11}^0 + U_{00,00}^0 {}^* U_{11,11}^2 \right. \\
& + \frac{3}{2} U_{10,10}^1 {}^* U_{11,11}^0 + 3 U_{10,10}^1 {}^* U_{11,11}^2 \\
& + \frac{5}{2} U_{20,20}^2 {}^* U_{11,11}^0 + 5 U_{20,20}^2 {}^* U_{11,11}^2 \left. \right] \\
& + \frac{9}{8} U_{11,11}^1 {}^* U_{11,11}^1 + \frac{9}{4} \operatorname{Re} \left[U_{11,11}^1 {}^* U_{11,11}^2 \right] \\
& + \frac{9}{8} U_{11,11}^2 {}^* U_{11,11}^2 \quad (6-11)
\end{aligned}$$

The experimental values of $K_z^{Z'}$ at zero degrees as a function of proton energy are shown in Fig. 22; also shown in the figure are the R-matrix calculations based on WMI and II. The experimental values of $K_z^{Z'}$ increase from about 0.3 at 3 MeV to 0.9 at 9 MeV and then decrease to 0.5 at 15 MeV. Both solutions of WM reproduce the qualitative shape of the data. In the expression giving $K_z^{Z'}$ in terms of the collision amplitudes the terms which involve the interference between the 1^- level with the 0^- and 2^- levels $\left(U_{10,10}^1 {}^* U_{11,11}^0 \text{ and } U_{10,10}^1 {}^* U_{11,11}^2 \right)$ contribute over 50% to the total value of $K_z^{Z'}$ at 9 MeV. As is shown in Fig. 13, both WMI and II have 0^- , 1^- , and 2^- levels near 27 MeV excitation energy which is equivalent to a proton lab energy of about 9.6 MeV. The peak in the experimental data appears to peak around a proton energy of 9 MeV which is close to the position of these levels.

The angular distribution of $K_z^{Z'}$ at 10 MeV is shown in Fig. 23. The calculations reproduce the shape of the angular distribution relatively well from 0° to 50° lab; beyond 50° both solutions deviate from the experimental data.

Fig. 22. Polarization Transfer Data $K_z^{z'}$ at 0° .

Fig. 23. $K_z^{z'}$ at 10.00 MeV.

6.3b The $T(\vec{p}, \vec{n})^3\text{He}$ Reaction at 0° as a Source of Longitudinally Polarized Neutrons

Simmons et al.⁵⁵ have recently pointed out that the polarization transfer reactions $T(\vec{p}, \vec{n})^3\text{He}$, $D(\vec{d}, \vec{n})^3\text{He}$, and $T(\vec{d}, \vec{n})^4\text{He}$ at 0° are superior sources of polarized neutrons compared to these reactions initiated with unpolarized beams. This arises because the figure of merit⁵⁶ for a polarized neutron source involves the neutron polarization squared times the differential cross section. At 0° the neutron polarization resulting from polarization transfer is large and this, coupled with the large 0° differential cross section, results in an appreciably larger figure of merit than when the reaction is initiated with an unpolarized beam. In the neutron energy range from 2 to 7 MeV the $T(\vec{p}, \vec{n})^3\text{He}$ reaction has an especially large figure of merit and on this basis alone is an excellent polarized neutron source. The figure of merit⁵⁶ for a polarized neutron source is given by

$$\text{Figure of Merit} = \frac{[p_{k'}^{\text{max}}]^2 I(\theta)}{S} \quad (6-12)$$

$p_{k'}^{\text{max}}$ = maximum neutron polarization in the k' direction

$I(\theta)$ = differential cross section at the angle θ

S = atomic stopping cross section

For the $T(\vec{p}, \vec{n})^3\text{He}$ reaction at zero degrees the neutron polarization with the incident proton beam polarized in the y and z directions is given by

$$p_{y'} = p_y K_y^{y'}(0^\circ) , \quad (6-13)$$

$$p_{z'} = p_z K_z^{z'}(0^\circ) ; \quad (6-14)$$

also

$$K_x^{x'}(0^\circ) = K_y^{y'}(0^\circ) . \quad (6-15)$$

The maximum neutron polarization is obtained if the incident proton beam is 100% polarized; for this case

$$p_{y'}^{\max} = K_y^{y'}(0^\circ) , \quad (6-16)$$

$$p_{z'}^{\max} = K_z^{z'}(0^\circ) . \quad (6-17)$$

In Fig. 24 the figure of merit for the reaction $T(\vec{p}, \vec{n})^3\text{He}$ at 0° as a source of transversely and longitudinally polarized neutrons is plotted as a function of neutron laboratory energy. The smooth curve through the points was drawn to guide the eye. Also plotted in this figure is the figure of merit for the $D(\vec{d}, \vec{n})^3\text{He}$ transfer reaction and the $T(\vec{p}, \vec{n})^3\text{He}$ reaction at 45° c.m. The curve labeled T indicates the $T(\vec{p}, \vec{n})^3\text{He}$ reaction as a source of transversely polarized neutrons and the curve labeled L indicates the longitudinal case. Below 7 MeV the transverse case has a higher figure of merit than the longitudinal case but above 7 MeV the longitudinal case is higher. Above 8 MeV the $D(\vec{d}, \vec{n})^3\text{He}$ reaction as a source of transversely polarized neutrons has a higher figure of merit than for either case with $T(\vec{p}, \vec{n})^3\text{He}$.

Fig. 24. Comparison of the Figure of Merit for the Reaction $T(\vec{p}, \vec{n}) {}^3\text{He}$. The Curve Labeled T Indicates the $T(p, n) {}^3\text{He}$ Reaction at 0° as a Source of Transversely Polarized Neutrons and the Curve Labeled L Indicates the Longitudinal Case.

In addition to the higher figure of merit the transfer reactions have another attractive advantage in that the neutron polarization is reversed when the incident beam polarization is reversed. In many experiments this is a distinct advantage over the unpolarized incident beam case where the neutron polarization direction is fixed.

6.4 The Polarization Transfer Coefficients $K_x^{x'}$, $K_z^{x'}$, and $K_y^{y'}$

6.4a Comparison of $K_x^{x'}$ with Calculations

The $K_x^{x'}$ data and the calculations based on WMI and II are shown in Figs. 25 and 26. Figure 25 shows the results at 9.94 MeV. At this energy the prediction of WMI is especially in disagreement with experiment. Figure 26 shows the results at 5.97 MeV. At this energy both WMI and II reproduce the qualitative shape of the data.

6.4b Comparison of $K_z^{x'}$ with Calculations

The $K_z^{x'}$ data and the calculations are shown in Figs. 27 and 28. Figure 27 shows the results at 9.94 MeV and Fig. 28 shows the results at 5.97 MeV. The calculations reproduce the qualitative shape of the data at both energies. At 5.97 MeV WMI and II give almost the same result.

6.4c Comparison of $K_y^{y'}$ with Calculations

The $K_y^{y'}$ data and the calculations based on WMI and II are shown in Figs. 29 and 30. Figure 29 shows the results at 9.87 MeV; at this energy WMII reproduces the general shape of the angular distribution but quantitative agreement is lacking. WMI deviates considerably from the data for angles less than 50° . Figure 30 shows the results at 5.97 MeV; at this energy both WMI and II reproduce the shape of the angular distribution.

Fig. 25. $K_X^{x'}$ at 9.94 MeV.

Fig. 26. $K_x^{x'}$ at 5.97 MeV.

Fig. 27. $K_z^{x'}$ at 9.94 MeV.

Fig. 28. $K_z^{x'}$ at 5.97 MeV.

Fig. 29. $K_y^{y'}$ at 9.87 MeV.

Fig. 30. $K_y^{y'}$ at 5.97 MeV.

6.5 EDA R-Matrix Analysis of ${}^4\text{He}$

An attempt was made by the author to analyze experimental data on the 4-nucleon system with the R-matrix code EDA. A large body of experimental data from the following reactions and scattering in the compound system ${}^4\text{He}$ was compiled: D(d,d)D , D(d,p)T , $\text{D(d,n)}{}^3\text{He}$, T(p,p)T , $\text{T(p,n)}{}^3\text{He}$, and ${}^3\text{He(n,n)}{}^3\text{He}$, for proton, neutron, and deuteron energies from 1 to 18 MeV. The data included differential cross section, polarization, analyzing power, and polarization transfer measurements. A number of searches over the entire data set were attempted using the levels of WMII as starting parameters. The EDA code was set up to search over the data and then generate a new set of parameters that reduced χ^2 . The new parameter set was then used as the starting parameters for the next search. The code was slow to reduce χ^2 requiring about 8 minutes of CDC-7600 computer time to perform six to eight searches over the data. In order to obtain an estimate of how well the data were being fit, the code calculated the weighted variance (χ^2 divided by the number of data points minus the number of adjustable parameters) with a good fit to the data being obtained when a weighted variance of one was achieved. After about 80 minutes of running time on the CDC-7600 computer the weighted variance was reduced from over 1000 to about 350; however, the code was very slow in reducing the weighted variance below 400 and the final generated parameter set was in doubt. It was felt that in order to successfully analyze ${}^4\text{He}$ the code EDA should be run on ${}^3\text{He(p,p)}{}^3\text{He}$ to determine the isotopic spin-1 ($T=1$) levels of ${}^4\text{He}$ and then to fix the $T=1$ levels and resume the

search over the extended data set of scatterings and reactions to determine the $T=0$ levels. This is a very ambitious project and the estimated amount of time required to complete it was sufficiently long so that no further effort was made to analyze the data.

In conclusion, some of the measurements have shown large effects. The polarization transfer observables $K_y^{y'}$ and $K_z^{z'}$ are measured to be about 80% of their maximum value. This indicates a large transfer of polarization from the incident proton to the outgoing neutron. A comparison of the experimental values of the analyzing power and polarization indicates that at 6.00, 9.96, and 13.55 MeV the data are consistent with $A_y = P_y$. Near 2.2 MeV the difference between them is about 17% relative. The data have been compared to R-matrix calculations based on the current level structure of ${}^4\text{He}$. The calculations reproduce qualitative aspects of the data but quantitative agreement is lacking. In some cases the calculations deviate considerably from the experimental data. The comparison indicates that changes in the current level structure of ${}^4\text{He}$ will be necessary to describe the data and a need for a reanalysis of the problem. The new $T(p,n){}^3\text{He}$ data reported here will be important in any reanalysis of the 4-body system.

APPENDIX A

PARITY OPERATOR

The matrix form of the parity operator given in Chapter II may be obtained as follows. Under the parity operation the unit vectors $\hat{x}$, $\hat{y}$, and $\hat{z}$, which define the coordinate system, transform as

$$\begin{aligned}\hat{x} &\xrightarrow{P} -\hat{x} \\ \hat{y} &\xrightarrow{P} \hat{y} \\ \hat{z} &\xrightarrow{P} -\hat{z} .\end{aligned}\tag{A-1}$$

These transformation properties follow since the vectors $\hat{x}$ and $\hat{z}$ are polar vectors and under parity change sign, whereas the axial vector or pseudovector $\hat{y}$ (defined by the incident wave vector $\vec{k}$ crossed into the final wave vector $\vec{k}'$) does not. The transformation of the spinors in the singlet-triplet representation under the parity operation is then seen to be

$$\begin{aligned}x_0^0 &\xrightarrow{P} x_0^0 \\ x_1^1 &= -\frac{1}{\sqrt{2}} (x_x + ix_y) \xrightarrow{P} -\frac{1}{\sqrt{2}} (-x_x + ix_y) = x_1^{-1} \\ x_1^0 &= x_z \xrightarrow{P} -x_z = -x_1^0 \\ x_1^{-1} &= \frac{1}{\sqrt{2}} (x_x - ix_y) \xrightarrow{P} \frac{1}{\sqrt{2}} (-x_x - ix_y) = x_1^1 .\end{aligned}\tag{A-2}$$

In matrix form one can express the parity operation as

$$P \begin{pmatrix} x_0^0 \\ x_1^1 \\ x_1^0 \\ x_1^{-1} \end{pmatrix} = \begin{pmatrix} x_0^0 \\ x_1^{-1} \\ -x_1^0 \\ x_1^1 \end{pmatrix} \quad (\text{A-3})$$

where P is a 4 by 4 matrix. If the matrix P is to give the desired result, P must have the form

$$P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad (\text{A-4})$$

APPENDIX B

CALIBRATION OF DIPOLE SPIN PRECESSION MAGNET

The integrated field $\int \mathbf{B} \cdot d\mathbf{l} = B\ell$ required for 90° precession may be obtained by integrating the Larmor precession frequency⁵⁷

$$\omega = \frac{g\mu_N}{\hbar} B. \quad (\text{B-1})$$

The result is

$$B\ell = \frac{h\nu}{4g\mu_N} = 2571.6\beta \text{ Kilo Gauss-cm} \quad (\text{B-2})$$

v = neutron velocity

$$h = 6.6256 \times 10^{-27} \text{ erg-sec}$$

$$g = 3.826$$

$$\mu_N = 5.0505 \times 10^{-24} \text{ erg/Gauss}$$

$$\beta = \frac{v}{c}.$$

Equation B-2 has been used to calculate $B\ell$ as a function of neutron energy. Some of the results are given in Table XVI.

During the course of an experiment the current flowing through the magnet was monitored by remote read-out. In order to obtain the correspondence between current and integrated field the following procedure was followed. The magnetic field at the center of the dipole was measured as a function of current. The results are shown in Fig. 31. A field profile measurement was performed with a current of 160 amps. The field profile is shown in Fig. 32. From the field profile at 160 amps the integrated field was determined to be 301.8 Kilo Gauss-cm. A current of 160 amps corresponded to a 5.1 Kilo Gauss field at the center of the dipole. The integrated field length of 301.8 Kilo

TABLE XVI

Integrated Transverse Field Required
for 90° Spin Precession

<u>En(MeV)</u>	<u>$\beta = V/C$</u>	<u>Integrated Field (KG-cm)</u>
2.22	0.069	176.3
3.22	0.083	212.4
4.22	0.095	243.1
5.23	0.105	270.2
6.23	0.115	294.7
7.23	0.123	317.2
8.23	0.131	338.2
9.23	0.139	357.8
10.23	0.146	376.5
11.23	0.153	394.1
12.23	0.160	411.0
13.23	0.166	427.1
14.23	0.172	442.6

Fig. 31. Central Field vs Current .

Fig. 32. Field Profile for $I = 160$ Amps.

Gauss-cm was then divided by the 5.1 Kilo Gauss field at the center to obtain the effective length of the field. The effective length was then multiplied by the field measured at the center of the dipole to obtain the integrated field necessary for 90° precession.

The calibration was checked by measuring the observable $K_x^{Z'}$ at zero degrees. At zero degrees $K_x^{Z'}$ is zero; as a result, if the dipole is energized with the correct current for 90° precession, no asymmetry should be measured. The current required for 90° precession was obtained as described. The current was then set at about 35 amps above and below this value and an asymmetry was measured for the two currents. The two asymmetries, which were of opposite sign, were plotted as a function of current. A linear interpolation was made between the two asymmetries. The intersection of the interpolated line with zero asymmetry yielded the current required for zero asymmetry or 90° precession. The current obtained from the interpolation agreed to within 1.7% of the current predicted from the calibration.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to all those people who contributed to the completion of this thesis. Special thanks are due to Dr. A. Raymond Kunselman of the University of Wyoming for guidance and counsel; to Dr. James E. Simmons of Los Alamos Scientific Laboratory and Dr. Robert C. Haight of Lawrence Livermore Laboratory for advice and wisdom in guiding the experimental work and the writing of the thesis; to Dr. Timothy R. Donoghue of Ohio State University for assistance with the analyzing power measurements; to Dr. Gerald G. Ohlsen and Dr. Gerald M. Hale of Los Alamos Scientific Laboratory for many helpful discussions concerning formalism and theory; to Mr. John Martin for valuable technical assistance, and to Mrs. Judy Elder, Mrs. Genevieve Dvorak, and Mrs. Elizabeth Fletcher for typing the manuscript.

Thanks are also due to the Department of Physics and Astronomy of the University of Wyoming, and the Associated Western Universities for financial assistance. Appreciation is due to Dr. Henry T. Motz for approving my appointment at LASL and to the Los Alamos Scientific Laboratory for use of its research facilities which enabled this thesis to be done.

Most of all the author wishes to thank his wife, Catherine, his children, John and Christine, and his parents for their love and encouragement during his graduate career.

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