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MEASUREMENT OF VECTOR AND TENSOR ANALYZING POWERS
FOR THE CHARGE SYMMETRIC $^2\text{H}(\vec{d},n)^3\text{He}$ AND $^2\text{H}(\vec{d},p)^3\text{H}$
REACTIONS, AND THE $^3\text{H}(\vec{d},n)^4\text{He}$ AND $^3\text{He}(\vec{d},p)^4\text{He}$
REACTIONS BELOW 6 MeV.

The Ohio State University, Ph.D., 1978

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$^3\text{H}(^1\text{d},n)^4\text{He}$ AND $^3\text{He}(^1\text{d},p)^4\text{He}$ REACTIONS BELOW 6 MeV

DISSERTATION

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

By
Lawrence J. Dries, B.S., M.S.

The Ohio State University
1978

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

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I would like to express my appreciation to my parents who gave me encouragement throughout the years of my education. And finally, I would like to thank my wife, Karen, whose encouragement, understanding, and infinite patience enabled me to complete this work.
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Publications (continued)


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CHAPTER I
INTRODUCTION

Charge independence of the nuclear interaction has been observed to hold to 1.5% or better in nucleon-nucleon scattering experiments when such interactions as the Coulomb force, which can effect a breaking of charge symmetry, are accounted for. This Coulomb interaction is quite small in nucleon-nucleon scattering and the required corrections to the interaction are fairly straightforward. One consequently can look at heavier mass systems to provide a further test of charge symmetry.

Comparison of mirror reactions has often been used as a test of charge independence of the nuclear force, but, generally, the conclusions from such experiments are hampered by difficulties in the calculation of the required Coulomb corrections. In light nuclei, however, Coulomb effects are small and the $^2\text{H}(d,p)^3\text{H}$ and $^2\text{H}(d,n)^3\text{He}$ reactions are a natural choice for this kind of test because of the identical particles in the entrance channel and mirror particles in the exit channel.

In previous comparisons of the polarizations of the outgoing protons and neutrons, Hardekopf et al.\textsuperscript{1,2)} have shown that, over the energy range of 3-10 MeV, the proton polarization is consistently larger than the neutron polarization. Above 10 MeV (10-14 MeV) this difference disappears and the magnitudes of the polarizations become
roughly constant with energy over the entire angular range. Hardekopf et al.\textsuperscript{1)} observed, however, that the polarizations for the two reactions were equal when they were compared at the same exit channel energies. Because very small analyzing powers have been measured for d+D elastic scattering, spin effects in the entrance channel were presumed small and the polarizations in the (d,n) and (d,p) reactions were presumed to be due to spin dependent effects in the exit channel alone. Hence, a comparison of the two reactions at equal exit channel energies was proposed as an ad hoc explanation of the measured results and the differences were attributed merely to Coulomb effects. This simple method brings the nucleons in the exit channel to the same energies but it does not properly account for Coulomb effects since measurements at different incident deuteron energies are being compared.

Comparisons of the vector and tensor analyzing powers for the two reactions have been made by various authors and some limited comparisons between the two have been made. Because of the experimental method of measuring the neutron analyzing powers by detecting the recoil $^3\text{He}$ ions was used, all of the comparisons were limited to back angles ($\theta_{\text{c.m.}} \gtrsim 90^\circ$).

The vector analyzing power, $t_{11}$, for both reactions was measured by Bernstein et al.\textsuperscript{3)} at 10 MeV, Gruebler et al.\textsuperscript{4)} at 10 and 11.5 MeV, Hilscher and Liers\textsuperscript{5)} at 10 MeV, and König et al.\textsuperscript{6)} from 4-11.5 MeV. Bernstein et al.\textsuperscript{3)} in a crude measurement, Gruebler et al.\textsuperscript{4)} and König et al.\textsuperscript{6)} all found the two reactions to be roughly identical when compared at equal deuteron energies, while Hilscher and Liers\textsuperscript{5)} found
significant differences (up to 20% in magnitude) between the two reactions.

Measurements of the tensor analyzing powers, $T_{20}$, $T_{21}$ and $T_{22}$, have been performed for both reactions by Gruebler et al. and König et al. covering the energy range 4-11.5 MeV. Their comparisons of the analyzing powers for the two reactions at equal deuteron energy show that $T_{20}$ differs most between the two reactions (up to 40% in magnitude) while $T_{21}$ and $T_{22}$ differ significantly but to a much smaller amount. Comparison at equal exit channel energies reduces the difference for $T_{20}$ but increases it for $T_{21}$ and $T_{22}$.

Other measurements of analyzing powers for these two reactions have been reported, though they afford no direct comparison. They include the data of Gruebler et al. who have measured all of the spin one analyzing powers for the $^2$H(d,p)$^3$H reaction for the energy ranges 3-11.5 MeV (ref. 7) and 1-2.5 MeV (ref. 8), though below 10 MeV, there is no equivalent (d,n) data for comparison. Other measurements of $^2$H(d,n)$^3$He analyzing powers include Salzman et al. who measured $A_y$, $A_{xx}$, $A_{yy}$, and $A_{zz}$ at 10 MeV for the $0^\circ$-$90^\circ_{\text{lab}}$ angular range; Simmons et al. who measured $A_{yy}(0^\circ)$ from 4-15 MeV [$A_{yy}(0^\circ) = \frac{1}{2}A_{zz}(0^\circ)$]; Salzman et al. who measured $A_{zz}(0^\circ)$ in 2 MeV steps from 3.3-14.9 MeV; and Lisowski et al. who measured $A_{zz}(0^\circ)$ in 500 keV steps from 1-15 MeV. The data of Simmons et al., Salzman et al. and Lisowski et al. for $A_{zz}(0^\circ)$ are in agreement above 6 MeV but differ substantially from each other below 6 MeV.
Higher order polarization observables, the polarization transfer coefficients, have been sparsely measured by several authors. Since these are difficult measurements to make, the experimental uncertainties are large. No appreciable difference between the (d,p) and (d,n) observables has been seen.

It is apparent from this summary of previously measured data that comparisons of the observables for the charge symmetric \( ^2\text{H}(d,n)^3\text{He} \) and \( ^2\text{H}(d,p)^3\text{H} \) reactions have produced uncertain results. These comparisons have been restricted to the back angles and, with the exception of the data of König et al.\(^6\), to energies of 10 MeV or higher. Data for these reactions over the entire angular range and for lower deuteron energies where the Coulomb effects will be more pronounced should provide a more conclusive study of the nature of the Coulomb correction that is required. It appears that the "ad hoc" comparison of the two reactions as proposed by Hardekopf et al.\(^1\) for the polarization data will not be of use in a comparison of the analyzing powers for the two reactions.

Unresolved uncertainties about the nature of the Coulomb interaction for the \( ^2\text{H}(d,n)^3\text{He} \) and \( ^2\text{H}(d,p)^3\text{H} \) mirror reactions are accompanied by uncertainty in the energy level structure of the d+D nuclear system, \(^4\text{He} \). Because it is the lightest mass nuclear system known to have excited states, \(^4\text{He} \) has been an obvious choice for model calculations, including shell model, cluster model and resonating group calculations.

Werntz and Meyerhof\(^13\) have reported what is generally accepted as the experimental level structure of \(^4\text{He} \) using principally cross
section and some polarization data for the $^3\text{H}(p,n)^3\text{He}$ reaction. In their analysis, they noted that two sets of levels could describe the data equally well. These two sets differed primarily in the ordering of the $T=1$ states between 25 and 30 MeV and correspond roughly to the two sets of phase shifts found by Morrow and Haeberli\textsuperscript{14} in their analysis of $p + ^3\text{He}$ scattering. Later measurements of analyzing power\textsuperscript{13} and polarization transfer\textsuperscript{16} data for the $^3\text{H}(p,n)^3\text{He}$ reaction show that neither set of levels can describe the data. The latest tabulation of the level structure of $^4\text{He}$, presented by Fiarman and Meyerhof\textsuperscript{17}, contains the set of $T=1$ levels known as Werntz-Meyerhof I, (WMI), and is shown in fig. I-1. Previous work at this lab has been motivated by the continuing uncertainty in the level structure of the four nucleon system: namely, $p + ^3\text{He}$ analyzing power measurements have been made\textsuperscript{19} to provide information on the $T=1$ levels, and $p + ^3\text{H}$ analyzing power and cross section measurements have been made\textsuperscript{19} to investigate the $T=0$ and $T=1$ levels. The present data for the $^2\text{H}(d,n)^3\text{He}$ and $^2\text{H}(d,p)^3\text{H}$ reactions will provide information on the $T=0$ states above the reaction threshold energy of 23.848 MeV in $^4\text{He}$ (fig. I-1).

In order to truly understand the energy level structure of this system, one must be able to describe all data on all open reaction channels simultaneously. To this end, a global, charge-independent $R$-matrix search has been in progress at Los Alamos.\textsuperscript{20} The requirement that all data sets being analyzing be fit simultaneously may help to resolve ambiguities which have resulted in previous analyses of much more restricted data sets, and may also act as a consistency check to
Fig. I-1 Isobar diagram, $A=4$, taken from Ref. 17.
point out any data points or sets which are inconsistent with data from other reaction channels.

In order to help resolve some of the ambiguities relating to the observed differences between the $^{2}$H(d,n)$^{3}$He and $^{2}$H(d,p)$^{3}$H reactions, as well as to provide new data to determine the $^{4}$He level structure, a pair of experiments was performed. These experiments were performed at low deuteron energy where the required Coulomb corrections for the comparison of the two reactions would be large and where the R-matrix analysis of the data should be the simplest because the three body break-up channel is not open.

The tensor analyzing power $A_{zz}$ was measured at $0^\circ$ for the $^{2}$H(d,p) and $^{2}$H(d,n) reactions for $E_{D} = 0.5-5.5$ MeV under nearly identical beam conditions so that any observed differences between the two reactions would be real and not an artifact of the experimental procedure. The analyzing power $A_{zz}(0^\circ)$ is a useful quantity to measure since at $0^\circ$ all of the other analyzing powers are zero and cannot interfere. Also, at $\theta=0^\circ$ many of the M-matrix elements, which relate the spin states of the entrance and exit channels of the reactions, do not contribute so that a few of these elements may be determined with high accuracy. Reliable information for these few M-matrix element may then be used as a basis for determining the other matrix elements by measuring the other analyzing powers away from $0^\circ$. The four spin 1 analyzing powers, $A_{y}$, $A_{xx}$, $A_{xz}$ and $A_{zz}$, were measured for the $^{2}$H(d,n) reaction in angular distributions ($0^\circ$-150$^\circ$ lab) for $E_{D} = 1.5-4.0$ MeV in 500 keV steps. Analyzing powers were measured by detecting the neutrons directly using NE213 scintillators which allowed standard n-$\gamma$ discrimination techniques
to be used. The quantity $A_{zz}$ was also measured by detecting the recoil $^3\text{He}$ ions at selected energies and angles to provide data via a different experimental technique to provide a check on the accuracy of the background subtraction techniques used in the neutron measurements. The $^3\text{He}$ recoil data were taken at far forward angles which correspond to neutron events at back angles where the background correction was the greatest.

The angular distributions of the $^2\text{H}(d,n)^3\text{He}$ measurements were then compared over the entire angular range with the published $^2\text{H}(d,p)^3\text{H}$ data of Gruebler et al.\textsuperscript{7,8} Because this comparison can now be made over the entire angular range and at lower energies where the sensitivity to Coulomb effects is larger, a more conclusive study of the nature of the Coulomb correction required by the data may be possible. The entire data set was made available to the Los Alamos R-matrix calculation effort.

The five nucleon system is also beset by uncertainties in its energy level structure. It is a fairly simple nuclear system which behaves to a large extent like an $\alpha$-particle core with a single nucleon attached to it, so this system, too, is the object of numerous model calculations. The latest energy level tabulation\textsuperscript{21} shows a relatively simple structure of two excited states at 16.7 and 20 MeV with $J^\pi$ of $\frac{3^+}{2}$ and $(\frac{3^+}{2}, \frac{5^+}{2})$ respectively as seen in fig. I-2. However, cluster model calculations by Heiss and Hackenbroich\textsuperscript{22} suggest six positive parity states in this region (15-25 MeV) along with a pair of negative parity states coupled to the first excited state of $^8\text{He}$ ($J^\pi=0^+$).
Fig. I-2 Isobar diagram, A=5, taken from Ref. 21.
Fig. I-2
Experiments by Schröder et al.\textsuperscript{23, 24}) suggest evidence for at least one of the odd parity states and the R-matrix calculation for the five nucleon system being carried out at Los Alamos\textsuperscript{20}) indicate that existing data may require some of these other states as well.

In order to provide information on this system, measurements of $A_{zz}(0^\circ)$ for the charge symmetric $^3\text{He}(d,p)^4\text{He}$ and $^3\text{H}(d,n)^4\text{He}$ reactions have been carried out over the 0.5-6.0 MeV energy interval in steps of 250 keV. The upper end of this energy range ($E_d = 5-6$ MeV) encompasses much of the region where the calculations suggest these states may exist.

A second goal of this set of measurements was to calibrate the $^3\text{He}(d,p)^4\text{He}$ reaction as a tensor polarization monitor to be used in other polarized deuteron experiments at this lab. To this end, an absolute measurement of the beam polarization was made using the $^{16}\text{O}(d,\alpha_1)^{14}\text{N}^*$ reaction\textsuperscript{25}) in conjunction with the measurement of $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)$ reaction at a selected energy. This measurement then provided an absolute normalization for the $^3\text{He}(d,p)$ analyzing power measurements.

Existing data for $A_{zz}(0^\circ)$ for the $^3\text{H}(d,n)$ reaction in this energy range is sparse and often contradictory. Broste et al.\textsuperscript{26}), Sunier et al.\textsuperscript{27}) and Lisowski et al.\textsuperscript{28}) have all measured $A_{zz}(0^\circ)$ at 7 MeV, but they differ from each other by up to 30%, having measured $A_{zz}(0^\circ) = 1.697$, 1.330, and 1.532, respectively. New, accurate data should help resolve this wide divergence and give proper guidance to the R-matrix search which has been guided principally by the data of Sunier et al.\textsuperscript{27}) at this energy.
The quantity $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)^4\text{He}$ reaction has been measured for $E_D = 0.34-11.6$ MeV by Schmelzbach et al.\textsuperscript{29) and calibrated with the absolute polarization measurement provided by the $^{16}\text{O}(d,\alpha)^{14}\text{N}$ reaction. However, the measurement was repeated in this experiment for three reasons. First, this measurement, along with the $^3\text{H}(d,n)^4\text{He}$ measurement of $A_{zz}(0^\circ)$ provided a comparison of the two charge symmetric reactions under nearly identical experimental conditions. Secondly, there is the possibility of depolarization of the deuteron beam in the residual gas in the high voltage terminal of a tandem accelerator as used by Schmelzbach et al.\textsuperscript{29} which would be most acute in the lower energy ranges corresponding to this experiment. A possible indication of this depolarization effect is the disagreement between the data of Schmelzbach et al.\textsuperscript{29} and the data of Simon et al.\textsuperscript{30} and Garrett and Lindstrom\textsuperscript{31} below 1 MeV. And thirdly, since this reaction was to be used as the tensor polarization monitor for all other polarized deuteron experiments at this lab, it was felt that an independent measurement of this quantity was warranted.

The purpose of this dissertation, then, is multifold. Charge symmetry in nuclear reactions was investigated for the $^3\text{He}(d,p)^4\text{He}$ and $^3\text{H}(d,n)^4\text{He}$ charge symmetric reactions and for the $^2\text{H}(d,p)^3\text{H}$ and $^2\text{H}(d,n)^3\text{He}$ charge symmetric reactions utilizing a method for measuring $A_{zz}(0^\circ)$ which was independent of accurate knowledge of the beam polarization. A beam polarization dependent comparison of the $^2\text{H}(d,n)^3\text{He}$ and $^2\text{H}(d,p)^3\text{H}$ reactions was made by measuring complete angular distributions of the four independent analyzing powers for the $^2\text{H}(d,n)$ reaction and comparing with published $^2\text{H}(d,p)$ data. Information on the energy level
structure of the four and five nucleon systems was gathered using these same reactions. And a tensor polarimeter was established and calibrated for the polarized deuteron experimental program at the Ohio State University Van de Graaff Laboratory.
CHAPTER II
EXPERIMENTAL APPARATUS AND PROCEDURE

II-A. INTRODUCTION

The deuteron beam used in this series of experiments was obtained from the Ohio State University polarized ion source in conjunction with the CN model Van de Graaff accelerator. The ion beam was then magnetically focused and analyzed and directed to either a rotatable neutron detector table for neutron analyzing power measurements or a rotatable scattering chamber for charged particle work. Data was reduced on-line as it was acquired via computer programs which summed the spectra and computed preliminary values for the measured analyzing powers. The beam polarization was monitored using $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)$ reaction. This analyzing power was calibrated absolutely in this work using the isospin forbidden $^{16}\text{O}(d,\alpha_1)^{14}\text{N}^*$ reaction.

II-B. POLARIZED SOURCE

The Ohio State University polarized ion source is described in some detail by Regner$^{32}$ and Donoghue et al.$^{33}$ It is a ground state, atomic beam source capable of producing polarized protons and deuterons, and is operated inside the pressurized high voltage terminal of the 7 MV Van de
Graaff accelerator. This location places severe size and power constraints on the polarized source. The whole assembly plus associated electronics must fit inside the high voltage dome, 1.7 m high by 0.9 m in diameter, where the available power for the electronics is limited to the 4 kW provided by the 400 Hz alternator in the terminal. The polarized source which has evolved over the past eight years is the result of various compromises made on some of the design parameters in order to accommodate these constraints.

Briefly, the source consists of the following components:

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

2. A 13.3 cm long sextupole magnet which produces a Stern-Gerlach separation of the hyperfine states of the atomic beam. This length, though not sufficient to produce a complete separation of these states, is the longest permissible size due to space limitations.

3. The RF transitions unit\(^3\) which houses the following:
   
   i) A 348 MHz oscillator loop in a magnetic field of uniform gradient (97-113 G) which inverts the populations of states 3 and 5 in the hyperfine structure of atomic deuterium. This transition produces a polarized deuteron beam with a theoretical maximum polarization of \(p_{zz} = -1\) and \(p_z = 1/3\).

   ii) An 8 MHz oscillator loop in a magnetic field of uniform gradient (7.4-9.8 G) which follows the 348 MHz
transition unit and will interchange populations of states with equal $F$ and opposite $m_F$ quantum numbers. When used alone, this unit produces purely vector polarized deuterons (maximum $p_z = 2/3$, $p_{zz} = 0$) and when used with the 348 MHz unit on it will change the sign of the deuteron polarization.

iii) A 12 MHz oscillator loop which will interchange the populations of states with equal $F$ and opposite $m_F$ for an atomic hydrogen beam. This will result in a polarized proton beam with a theoretical maximum polarization $p_y = 1$.

4. A strong field (~ 1000 gauss) ionizer based on the designs of Glavish\(^3\) which strips the electron from the atomic deuterium (hydrogen) beam and forms the ion beam.

5. An extractor voltage of 5 kV is applied to the ionizer assembly. This voltage accelerates the ion beam from the ionizer into a three element einzel lens which focuses the beam in the center of the spin precession unit which follows.

6. A spin precession unit, or Wien filter, which consists of crossed E and B fields and is capable of rotating the spin vector of 5 keV deuterons by $\pm 110^\circ$ (protons by $\pm 360^\circ$).

7. An electrostatic main lens element (0-70 kV) to match the ion source optics to the accelerator optics.

The polarized ion source is physically divided into four separate vacuum chambers. Chamber #1, which houses the dissociator bottle
assembly, operates at a relatively high pressure ($\sim 5 \times 10^{-5}$ torr) since there is a large gas flow from the dissociator bottle which must be pumped away. Chambers #1 and 2 are separated by an interface plate with a small hole ($\sim 1$ cm diameter) to provide a large pumping impedance between the chamber. This allows chamber 2 to operate at a pressure of $\sim 1 \times 10^{-6}$ torr. Chamber 2 houses the 6-pole separation magnet followed by the RF transition units. Another small hole ($\sim 8$ mm diameter) separates the RF units and the ionizer assembly which is located in chamber 3. This provides further isolation of the ionizer chamber vacuum (typically $\leq 1 \times 10^{-7}$ torr) from the higher pressure in chamber 1. This high vacuum is required in chamber 3 because any background hydrogen that exists in this chamber will be ionized and become an unpolarized component to the ion beam, thus diluting the beam polarization. Chamber 4 contains the extractor and einzel lens assembly and the Wien filter. This is followed by the main lens assembly which protrudes into the accelerator and is connected to the first three electrodes of the accelerator tube. Each vacuum chamber is pumped by a titanium sublimation pump (TSP). The TSP's in chambers 2 and 3 are used in conjunction with an ion pump. These pumping systems were developed at this lab and are described by McEver et al.\textsuperscript{36} This system provides high pumping speed for the hydrogen isotopes with relatively small power requirements ($\sim 200$-$300$ watts per TSP).

Several changes have been made by this author in the configuration of the polarized ion source since the report of Donoghue et al.\textsuperscript{33} in order to facilitate alignment of the source components and to enhance the polarization and intensity of the ion beam. This new configuration
is shown in fig. II-1 which depicts the atomic beam section of the polarized source where all of the design changes were made.

The vacuum chambers for the atomic beam part of the source (chambers 1 and 2) have been completely rebuilt. The new design consists of self-aligning cylindrical chambers which replaced the old system of square chambers dowel pinned together. The dissociator bottle assembly is also self-aligned to the vacuum chambers, replacing an adjustable system which was difficult to align. The new system was designed to maximize the figure of merit for the polarized source ($P^2I$) by placing the dissociator nozzle the optimum distance from the entrance to the 6-pole magnet (~ 7.5 cm as determined from test bench operation of the source). In addition, the port connecting vacuum chamber #1 with its TSP was enlarged from a 10 cm to a 14 cm diameter hole. This reduced the pumping impedance for this pump by 50% and allowed larger gas loads to be run in the dissociator bottle, resulting in more intense beams.

A major change in configuration was made on the RF transitions portion of the polarized ion source. The RF magnets and loops were moved outside the source vacuum so that test bench optimization of the magnetic field conditions necessary for the transitions could be achieved with much greater certainty and convenience. This change was accomplished by designing a structure to house the RF magnets and loops as well as a length of quartz tubing (8 mm I.D. x 12 mm O.D. x 20 cm long) which passes through the RF loops and contains the source vacuum inside. Quartz is transparent to the RF fields used here so the transitions are performed on the atomic beam as it passes through the tubing.
Fig. II-1  Diagram of the atomic beam section of the polarized ion source.
Fig. II-1
This design also allows for better vacuum isolation of chamber #3 from chamber #2 due to the greater pumping impedance through the quartz tubing than existed in the earlier design.

Finally, a remotely operated motor driven rotation system was devised for the Wien filter. This mechanism allows the E and B field plates of the Wien filter to be rotated about the beam axis. This feature is useful in aligning $\phi$-angle orientation of the Wien filter (sec. II-I) and in aligning the spin vector of the beam in any desired orientation at the target.

II-C. ION BEAM TRANSPORT

A diagram of the beam line components as used in this series of experiments is shown in fig. II-2 which displays the relative positions of the focusing and steering magnets used as well as some beam diagnostic tools and the target areas.

Efficient transport of the ion beam from the polarized source to the target is very important due to the characteristics of the polarized beam. The accelerated ion beam from the polarized ion source is somewhat larger in size than the beam from the standard ion source, due primarily to the size of the anode structure in the ionizer where the ion beam is formed. Also, the beam intensity from the polarized source is much lower (~ 200 nA at the analyzing magnet) than the standard source. To maximize beam transmission to the target a quadrupole doublet focusing magnet was installed at the exit of the Van de Graaff prior to the analyzing magnet. The magnetic center of this quadrupole is movable by unbalancing the fields of the individual coils and is
Fig. II-2  Diagram of the beamline components, showing slits, focussing and steering components, and detector areas.
made to coincide with the ion beam axis. This procedure minimizes any steering effects and maximizes the focusing.

The accelerated deuteron beam can be contaminated with a beam of singly ionized molecular hydrogen (\(^1\text{H}_2^+\)) which will pass through the analyzing magnet just as the deuteron beam (\(^2\text{H}^+\)) does because it has the same charge to mass ratio. Not only does the contaminant beam adversely affect the accurate charge integration which is required for these experiments, it also adds other charged particle and neutron groups to the observed spectra. To alleviate this problem, a wheel with apertures for sixteen thin (10 \(\mu\)g/cm\(^2\)) carbon foils is also located above the analyzing magnet. These foils may be moved into the beam path as needed to eliminate the molecular hydrogen beam while the deuteron beam passes through relatively unaffected except at lower energies (< 2 MeV) where some attenuation occurs.

The energy control slits are located at the entrance and exit to the analyzing magnet which was calibrated using the \(^7\text{Li}(p,n)^7\text{Be}\) threshold reaction at \(E_p = 1.88\) MeV.

Other steering and quadrupole magnets used in transmitting the beam to the target areas are as shown in fig. II-2. The beam profile was monitored at several locations along the beam line using NEC beam scanners.

The target areas which include the scattering chamber and the neutron table will be discussed in the next section.
II-D. PARTICLE DETECTION APPARATUS

As shown in fig. II-2, there are two detector areas on the experimental beamline. They are the neutron table which is used for neutron detection experiments and the scattering chamber which is used for charged particle detection experiments.

II-D-1. Neutron Detection

Neutron detection experiments are performed using the neutron table at the end of the beamline as shown in fig. II-2. This table is shown in more detail in fig. II-3 and consists of two movable detector holder arms which pivot about the center of the table where the target is placed. Used in symmetric pairs, the neutron detectors could be placed at any angle from 15° to 155°. Angles scribed on the table surface in 1° increments enable the reaction angle to be set with an uncertainty less than 0.25°. Typically, the neutron detectors used with this apparatus were placed 35 cm from the target to provide a reaction half-angle of 4°. The table itself can be oriented in either the vertical or the horizontal plane so that measurements of all of the spin one analyzing powers can be made conveniently. For these measurements, the incident beam is defined by a pair of slit boxes located at 75 cm and 100 cm in front of the target. They both were set to have square apertures with 3.8 mm on each side of the square. The slits were also aligned to be centered about the rotation axis of the neutron table to within 0.1 mm. Current integration for this apparatus was accomplished by completely stopping the incident beam in the backing of the target being used. The backing materials used were tantalum.
Fig. II-3  Diagram of rotatable neutron detector table. The table can be fixed in either the horizontal or the vertical plane.
and platinum. In addition, an electron suppressor ring with a 6.4 mm diameter hole and biased at +300V was located 13 cm in front of the target.

The neutron detectors used for these experiments were 5 x 5 cm NE213 bubble free scintillators\textsuperscript{37} optically coupled to 56DVP photomultiplier tubes.\textsuperscript{38} Neutrons and gamma rays produce light pulses in NE213 with different decay characteristics so that standard n-\(\gamma\) discrimination techniques may be performed using the ORTEC 458 Pulse Shape Analyzer (PSA) module. The electronics required for this circuit are shown in fig. II-4. The dynode pulses from the ORTEC 269 photomultiplier tube base are sent to an ORTEC 113 preamplifier and then to an ORTEC 460 amplifier in the control room. The unipolar output of the amplifier is fed to the PSA which produces a time spectrum of the neutron and gamma ray events from differences in the fall time of the scintillator pulse (fig. II-5). A single channel analyzer internal to the PSA allows an electronic window to be set around the neutron portion of the time spectrum. The PSA produces a logic pulse for each event in this window, and this pulse is used to gate the neutron spectrum from the ORTEC 460. In this fashion, gamma ray events detected by the NE213 are eliminated from the spectrum and only neutron events are counted. The gamma ray rejection efficiency of this system was measured to be 500:1 by using a \(^{22}\text{Na}\) gamma ray source and counting events for the amplifier gated and ungated.

For each detector, four spectra are collected and stored on disk in order to monitor the n-\(\gamma\) separation. These spectra are:
Fig. II-4  Diagram of the n-γ discrimination electronics for the neutron detectors.
Fig. II-5 Diagram of the linear output of the ORTEC 458 PSA Module for the $^3\text{H}(\vec{d},n)^4\text{He}$ reaction neutrons at $E_D = 3.18$ MeV. The spectrum on the left is the ungated time spectrum showing both neutron and gamma ray events as the two peaks. The spectrum on the right shows the same time spectrum with the gamma ray events gated out.
Fig. II-5
(ungated) pulse height spectrum, the time spectrum from the PSA showing both the neutron and gamma ray peaks, the gated time spectrum and the scintillator pulse height spectrum gated by the neutron pulses from the PSA. This last spectrum is the one that is used for determining the neutron yield for the analyzing power measurements.

The signals from the electronics set-up were sent to a Tennelec PACE system which has eight stretchers feeding a single very fast analog-to-digital converter, thus enabling eight spectra to be acquired without the use of routing pulses. Deadtime in each of the stretchers was monitored with a system consisting of a fast (8 MHz) clock which produced dc NIM levels. When a stretcher is busy (i.e., when it has received a signal) it produces a dc level. When these two levels are in coincidence they trigger an AND logic gate which sends a pulse to a 100 MHz scaler. The ratio of busy pulses to clock pulses is then a measure of the deadtime in a stretcher. Each of the eight stretchers are monitored for deadtime independently. The PACE ADC fed the signals to the in-house IBM 1800 computer in add-one-to-storage mode. The spectra were displayed on a storage oscilloscope in a real time display. At the end of each data run, the spectra of interest were stored on permanent disk for on-line analysis and further analysis at a later date.

II-D-2. Charged Particle Detection

Charged particle detection for several parts of these experiments was performed in the cylindrical rotatable scattering chamber as shown in fig. II-6. It is supported at both the entrance and exit ports by
Fig. II-6  Diagram of the rotatable charged particle scattering chamber. The thin nickel and Havar foils at the entrance and exit to the chamber allow it to be used as a gas scattering chamber. They are easily removable for experiments using solid targets.
DELRIN-INSULATOR
HAVAR EXIT FOIL
ANTI-SCATTERING
SNOOT
FRONT SLITS
REAR SLITS
40 cm
FARADAY CUP
REAR ROTATABLE SEAL
NICKEL ENTRANCE FOIL
FRONT SLITS
FRONT ROTATABLE SEAL
SCATTERING CHAMBER
DETECTOR BLOCKS
Fig. II-6
ball bearings which allow it to rotate with precision about the beam axis. The target rod is mounted in the center of one of the end plates (5 cm thick Al) and is precision aligned to be in the center of the cylinder. The detector assembly is mounted on the other end plate and consists of two detector blocks which are each independently rotatable about the central axis of the scattering chamber. Each detector block is capable of housing four silicon surface barrier detectors and collimating telescopes separated by 10°. The blocks are rotatable from outside the vacuum system and their position is determined to within 0.1° by a vernier scale scribed on the outside of the detector lid. Beam defining slits (up-down-left-right) are located at both the entrance and exit ports of the chamber. These slits are optically aligned to be centered about the rotation axis of the chamber to within 0.1 mm. The slits are isolated from ground so that each slit current may be monitored independently. This allows the beam to be guided through the center of the chamber at all times merely by balancing the beam current on all of the slits. A faraday cup is mounted behind the exit slits. The current from the faraday cup plus the four exit slits are added together for charge integration purposes. The rotation of the scattering chamber about the beam axis is monitored by an incremental optical shaft encoder which is accurate to within 0.1°.

For experiments using a gas target, a pair of slit blocks have been designed by this author which allow the entire volume of the scattering chamber to be isolated from the beamline vacuum system. The electrical connection for monitoring slit currents are vacuum tight
and the slit blocks have a provision for installing foil holders on them. A 1.25 µm thick nickel foil is used for the entrance window of the chamber and a 2.5 µm thick Havar foil is used as the exit window. The exit window is itself electrically isolated so that a bias may be applied to it to keep electrons from the foil from reaching the slits and faraday cup used for charge integration.

Particle detection using the scattering chamber is relatively straightforward. Under normal operating conditions, eight silicon surface barrier detectors (typically 500 µm thick) are mounted in the chamber as four pairs of detectors at symmetric angles for efficient measurement of polarization observables. The electronics required for this set-up are displayed in Fig. II-7. The signal from the detector is pre-amplified (ORTEC 109A) and sent to an ORTEC 460 amplifier in the control room where the spectra are sent to the Tennelec PACE system as described earlier and stored on permanent disk for analysis.
Fig. II-7  Electronics setup for up to eight charged particle detectors in the scattering chamber.
Scattering Chamber.

Ortec 109A

Pre-amp

Ortec 460

Tennelec Pace

Amplifier

IBM 1800

Fig. II-7
II-E. METHOD OF MEASUREMENT

The measurement of spin one analyzing powers can be quite complicated since there are four different independent analyzing powers. Various techniques for performing these measurements are discussed by Ohlsen and Keaton. However, for these measurements a method discussed by König et al. was chosen and is described below.

The O.S.U. polarized ion source has two RF transition units available for deuteron beams: a 348 MHz oscillator which induces transitions between states 3 and 5 in the hyperfine structure of atomic deuterium in a strong magnetic field (SF), and a 8 MHz oscillator which follows the SF unit and inverts the populations of the hyperfine states with the same quantum number \( F \) and opposite \( m_F \) in a weak magnetic field (WF). When used in conjunction with the SF transition, the WF unit reverses the beam polarization produced by the SF unit, and when used alone produces a purely vector polarized beam. The maximum vector and tensor beam polarizations \( (p_z \) and \( p_{zz} \)) which can be produced by these transitions is summarized in the following table:

<table>
<thead>
<tr>
<th>SF</th>
<th>WF</th>
<th>( p_z )</th>
<th>( p_{zz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>off</td>
<td>off</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>off</td>
<td>on</td>
<td>-2/3</td>
<td>0</td>
</tr>
<tr>
<td>on</td>
<td>off</td>
<td>1/3</td>
<td>-1</td>
</tr>
<tr>
<td>on</td>
<td>on</td>
<td>-1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

Due to incomplete separation of the electronic states in the sextupole magnet, the maximum beam polarizations obtainable with the O.S.U. source are \(~80\%\) of these values.
The yield for a reaction initiated by a spin 1 incident beam is given by:

\[ \sigma = \sigma_0 [1 + \frac{3}{2} p_y A_y + \frac{2}{3} p_{xz} A_{xz} + \frac{1}{3} p_{xx} A_{xx} + \frac{1}{3} p_{yy} A_{yy} + \frac{1}{3} p_{zz} A_{zz}] \]  

(1)

where the A's are the analyzing powers to be measured, the p's are the beam polarization components, \( \sigma \) is the yield with a polarized beam, and \( \sigma_0 \) is the yield with an unpolarized beam. This expression includes five analyzing powers even though there are only four independent ones. The redundancy is removed by the identity:

\[ A_{xx} + A_{yy} + A_{zz} = 0 \]  

(2)

Similarly

\[ P_{xx} + P_{yy} + P_{zz} = 0 \]

Using these two conditions it can be shown that:

\[ \frac{1}{3} p_{xx} A_{xx} + \frac{1}{3} p_{yy} A_{yy} + \frac{1}{3} p_{zz} A_{zz} = \frac{1}{6} (p_{xx} - p_{yy})(A_{xx} - A_{yy}) + \frac{1}{2} P_{zz} A_{zz} \]  

(3)

The polarized beam produced in the source is axially symmetric due to the solenoidal field in the ionizer, so it can be described by a vector part \( p_z \) and a tensor part \( p_{zz} \). These polarization components are rotated in the Wien filter and in the accelerator's 90° analyzing magnet to produce a vector and tensor polarization in the target coordinate system as described below:
\[ p_y = \sin \beta \cos \phi p_z \]
\[ p_{xz} = -\frac{3}{2} \sin \beta \cos \beta \sin \phi p_{zz} \]
\[ p_{xx} - p_{yy} = -\frac{3}{2} \sin^2 \beta \cos 2\phi p_{zz} \]
\[ p_{zz} = \frac{1}{2}(3 \cos^2 \beta - 1)p_{zz} \] \hspace{1cm} (4)

where \( \beta \) and \( \phi \) are the angles indicated in fig. II-8.

Combining equations 1, 3, and 4 results in an expression for reaction yield in terms of the reaction analyzing powers (A's) and the beam polarization from the source (magnitudes \( p_z \) and \( p_{zz} \) with orientation \( \beta, \phi \) at the target).

\[
\sigma = \sigma_0 [1 + \frac{3}{2} p_{zz} A_y \sin \beta \cos \phi - \frac{1}{2} p_{zz} A_{xz} \sin 2\beta \sin \phi - \frac{1}{4} p_{zz} (A_{xx} - A_{yy}) \sin^2 \beta \cos 2\phi + \frac{1}{4} p_{zz} A_{zz} (3 \cos^2 \beta - 1)]
\] \hspace{1cm} (5)

Now define:

- \( L_1 \) = yield in left (\( \phi=0^\circ \)) detector with 348 MHz on
- \( R_1 \) = yield in right (\( \phi=180^\circ \)) detector with 348 MHz on
- \( L_2 \) = yield in left (\( \phi=0^\circ \)) detector with 348 MHz + 8 MHz on
- \( R_2 \) = yield in right (\( \phi=180^\circ \)) detector with 348 MHz + 8 MHz on \hspace{1cm} (6)
- \( U_1 \) = yield in up (\( \phi=270^\circ \)) detector with 348 MHz on
- \( D_1 \) = yield in down (\( \phi=90^\circ \)) detector with 348 MHz on
- \( U_2 \) = yield in up (\( \phi=270^\circ \)) detector with 348 MHz + 8 MHz on
- \( D_2 \) = yield in down (\( \phi=90^\circ \)) detector with 348 MHz + 8 MHz \hspace{1cm} (7)

Now, if left and right detectors only are used (\( \phi=0^\circ, 180^\circ \)) then equations 5 and 6 yield:
Fig. II-8 The coordinate system used for the analyzing power measurements.
Fig. II-8
\[ L_1 = \sigma_0 [1 + \frac{3}{2}p_z A_y \sin \beta - \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta + \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1)] \]

\[ L_2 = \sigma_0 [1 - \frac{3}{2}p_z A_y \sin \beta + \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta - \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1)] \]

\[ R_1 = \sigma_0 [1 - \frac{3}{2}p_z A_y \sin \beta - \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta + \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1)] \]

\[ R_2 = \sigma_0 [1 + \frac{3}{2}p_z A_y \sin \beta + \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta - \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1)] \quad (8) \]

Further, define the quantities \( L \) and \( R \) as below using equation (8):

\[ L = \frac{L_1 - L_2}{L_1 + L_2} \quad \text{such that:} \]

\[ L = \frac{3}{2}p_z A_y \sin \beta - \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta + \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1) \]

\[ R = -\frac{3}{2}p_z A_y \sin \beta - \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta + \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1) \quad (9) \]

In exactly the same manner, the quantities \( U_1, U_2, D_1 \) and \( D_2 \) can be combined to yield:

\[ U = \frac{U_1 - U_2}{U_1 + U_2} \quad \text{and} \quad D = \frac{D_1 - D_2}{D_1 + D_2} \]

\[ D = \frac{1}{2}p_{zz}A_{xz} \sin 2\beta + \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta + \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1) \]

\[ U = \frac{1}{2}p_{zz}A_{xz} \sin 2\beta + \frac{1}{4}p_{zz}(A_{xx} - A_{yy}) \sin 2\beta + \frac{1}{4}p_{zz}A_{zz}(3 \cos 2\beta - 1) \quad (10) \]

Suitable choices of \( \beta \), then, will isolate any of the four analyzing powers as described below:
For $\beta=0^\circ$:

\[ L+R = U+D = p_{zz}^{A}zz \]  
\[ L-R = U-D = 0 \]

For $\beta=45^\circ$:

\[ U-D = p_{zz}^{A}xz \]

For $\beta=90^\circ$:

\[ L-R = 3p_{zz}^{A}y \]
\[ L+R = -\frac{1}{2}p_{zz}(A_{xx}-A_{yy})-\frac{1}{2}p_{zz}^{A}zz \]
\[ U+D = \frac{1}{2}p_{zz}(A_{xx}-A_{yy})-\frac{1}{2}p_{zz}^{A}zz \]
\[ U-D = 0 \]

Using equation (2) reduces (13) to:

\[ L+R = p_{zz}^{A}yy \]
\[ U+D = p_{zz}^{A}xx \]

Other combinations of $L$, $R$, $U$, $D$ do not yield maximal expressions for the analyzing powers. The conditions where $L-R = U-D = 0$ for $\beta=0^\circ$ and $U-D = 0$ for $\beta=90^\circ$ can be used as consistency checks on the data to ensure that charge integration has been accurate. Because of the construction of these expressions, all of them are dependent upon accurate charge integration and accurate determination of the $\beta$, $\phi$ angles as will be discussed later. However, they are totally independent of the ratios of the solid angles of both detectors. This method
also relies upon performing a proper spin flip as discussed by Ohlsen and Keaton\textsuperscript{40}, and which is accomplished here by completely reversing the beam polarization with the WF transition. This is the "spin-flip normalization" method.

One can calculate, in a similar fashion, the quantity \( pA \) for the spin one analyzing powers using an "unpolarized beam normalization" procedure as described below. Two data runs are taken: one with a polarized beam (using either the SF or the SF+WF transitions), and one run with an unpolarized beam.

\[
\begin{align*}
L_p &= \text{yield in left (} \phi=0^\circ \text{)} \text{ detector with polarized beam} \\
R_p &= \text{yield in right (} \phi=180^\circ \text{)} \text{ detector with polarized beam} \\
U_p &= \text{yield in up (} \phi=270^\circ \text{)} \text{ detector with polarized beam} \\
D_p &= \text{yield in down (} \phi=90^\circ \text{)} \text{ detector with polarized beam}
\end{align*}
\]

Define the following quantities:

\[
\begin{align*}
L &= \frac{L_p}{D_o} = 1 + 3p_z A_y \sin \beta - \frac{1}{4}p_{ZZ}(A_{xx}-A_{yy}) \sin^2 \beta + \frac{1}{4}p_{ZZ} A_{zz}(3 \cos^2 \beta - 1) \\
R &= \frac{R_p}{D_o} = 1 - 3p_z A_y \sin \beta - \frac{1}{4}p_{ZZ}(A_{xx}-A_{yy}) \sin^2 \beta + \frac{1}{4}p_{ZZ} A_{zz}(3 \cos^2 \beta - 1) \\
D &= \frac{U_p}{D_o} = 1 - \frac{1}{2}p_{ZZ} A_{xz} \sin 2\beta + \frac{1}{4}p_{ZZ}(A_{xx}-A_{yy}) \sin^2 \beta + \frac{1}{4}p_{ZZ} A_{zz}(3 \cos^2 \beta - 1) \\
U &= \frac{D_p}{D_o} = 1 + \frac{1}{2}p_{ZZ} A_{zz} \sin 2\beta + \frac{1}{4}p_{ZZ}(A_{xx}-A_{yy}) \sin^2 \beta + \frac{1}{4}p_{ZZ} A_{zz}(3 \cos^2 \beta - 1)
\end{align*}
\]

As before, appropriate choices for \( \beta \) will isolate each of the analyzing powers:
For $\beta=0^\circ$:

\[ L + R = U + D = 2 + p_{zz} A_{zz} \]
\[ L - R = U - D = 0 \]

For $\beta=45^\circ$:

\[ U - D = p_{zz} A_{xz} \] (17)

For $\beta=90^\circ$:

\[ L - R = 3 p_{zz} A_y \]
\[ L + R = 2 + p_{zz} A_{yy} \]
\[ U + D = 2 + p_{zz} A_{yy} \]
\[ U - D = 0 \]

These expressions for the analyzing powers, just as the spin flip normalization expressions, are dependent upon accurate charge integration and accurate determination of the $\beta$, $\phi$ angles. The measurement is also independent of the ratios of the solid angles of both detectors.

To summarize, the four independent analyzing powers measured in this experiment can be obtained as described in the following table:

Spin-flip normalization:

<table>
<thead>
<tr>
<th>$\beta$ $\phi$</th>
<th>$\beta$ $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>$90^\circ, 90^\circ, 270^\circ$</td>
</tr>
<tr>
<td>$p_{zz} A_{zz} = L+R$</td>
<td>$p_{zz} A_{xx} = U+D$</td>
</tr>
<tr>
<td>$45^\circ, 90^\circ, 270^\circ$</td>
<td>$p_{zz} A_{xz} = U-D$</td>
</tr>
<tr>
<td>$90^\circ, 0^\circ, 180^\circ$</td>
<td>$p_{zz} A_y = (L-R)/3$ (18)</td>
</tr>
</tbody>
</table>
Unpolarized beam normalization:

\[ \beta = 0^\circ \quad P_{zz} A_{zz} = L + R - 2 \]

\[ \beta = 90^\circ, \phi = 90^\circ, 270^\circ \quad P_{zz} A_{xx} = U + D - 2 \]

\[ \beta = 45^\circ, \phi = 90^\circ, 270^\circ \quad P_{zz} A_{xz} = U - D \]

\[ \beta = 90^\circ, \phi = 0^\circ, 180^\circ \quad P_{z} A_{y} = (L - R) / 3 \]  \hspace{1cm} (19)

The statistical uncertainty in the measured analyzing power is computed in the usual fashion.

\[ \Delta f(x_1, x_2, \ldots, x_n) = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial f}{\partial x_i} \right)^2 (\Delta x_i)^2} \]  \hspace{1cm} (20)

Using this expression, we can see that

\[ \Delta pA = \Delta (L - R) = \Delta (L + R) = \sqrt{(\Delta L)^2 + (\Delta R)^2} \]  \hspace{1cm} (21)

For the spin-flip normalization, this becomes:

\[ \Delta pA = \sqrt{(\frac{2L_2}{(L_1 + L_2)^2})^2 (\Delta L_1)^2 + (\frac{2L_1}{(L_1 + L_2)^2})^2 (\Delta L_2)^2 + (\frac{2R_2}{(R_1 + R_2)^2})^2 (\Delta R_1)^2} \]

\[ + (\frac{2R_1}{(R_1 + R_2)^2})^2 (\Delta R_2)^2 \]  \hspace{1cm} (22)

A similar expression for \( \Delta (U + D) \) is obtained if

\[ L_1 + U_1 \]
\[ L_2 + U_2 \]
\[ R_1 + D_1 \]
\[ R_2 + D_2 \]
For the unpolarized beam normalization the $\Delta pA$ is seen to be:

$$\Delta pA = \sqrt{\left(\frac{1}{L_0}\right)^2 (\Delta L_p)^2 + \left(\frac{L_p}{L_0}\right)^2 (\Delta L_0)^2 + \left(\frac{1}{R_0}\right)^2 (\Delta R_p)^2 + \left(\frac{R_p}{R_0}\right)^2 (\Delta R_0)^2}$$  \hspace{1cm} (23)

The uncertainties in the yields to the reactions $\Delta L_1$, $\Delta L_2$, $\Delta R_1$, $\Delta R_2$, etc., include a contribution from the background subtraction as indicated:

$$\Delta L_1 = \sqrt{L_1 + 2B}$$

where $B$ is the number of background counts subtracted from the total yield to give the number $L_1$.

So far we have calculated uncertainties in $pA$. To obtain an expression for $\Delta A$, merely apply the same equation (20) to get:

$$\Delta A = \Delta(pA_p) = \sqrt{\left(\frac{1}{p}\right)^2 (\Delta pA)^2 + \left(\frac{pA}{p^2}\right)^2 (\Delta p)^2}$$  \hspace{1cm} (24)

Contributions to the uncertainty in the analyzing powers for this method are second order in both $\beta$ and $\phi$, except for $A_{xz}$ which has a first order $\phi$ dependence. These contributions are summarized below where the quantity $\frac{1}{2}(A_{xx}-A_{yy})$, which is the generally reported analyzing power as opposed to $A_{xx}$, is computed from $A_{xx}$ and $A_{zz}$ to be (using $A_{xx} + A_{yy} + A_{zz} = 0$)

$$\frac{1}{2}(A_{xx} - A_{yy}) = A_{xx} + \frac{1}{2}A_{zz}$$  \hspace{1cm} (25)
The uncertainties due to $\beta$ and $\phi$ imprecision are:

$$
\Delta A_y = \frac{1}{2}[(\Delta \beta)^2 + (\Delta \phi)^2]A_y
$$

$$
\Delta A_{zz} = (\Delta \beta)^2 [\frac{1}{2}(A_{xx} - A_{yy})] + \frac{3}{2}(\Delta \beta)^2 A_{zz}
$$

$$
\Delta A_{xz} = \sqrt{2} [\Delta \phi + \Delta \beta \Delta \phi]A_y - [2(\Delta \beta)^2 + \frac{1}{2}(\Delta \phi)^2]A_{xz}
$$

$$
\frac{1}{2}(A_{xx} - A_{yy}) = \frac{3}{2}(\Delta \beta)^2 A_{zz} - \frac{1}{2}[(\Delta \beta)^2 + 2(\Delta \phi)^2]A_{xz}
$$

$$
(26)
$$

For these experiments $\beta$ and $\phi$ were determined from calibration of the Wien filter (sec. II-I) to be $\Delta \beta = 3^\circ$, $\Delta \phi = 1^\circ$. The resulting uncertainties in the analyzing powers measured in this experiment were at worst:

$$
\Delta A_y = 0.002
$$

$$
\Delta A_{zz} = 0.001
$$

$$
\Delta A_{xz} = 0.006
$$

$$
\frac{1}{2}(A_{xx} - A_{yy}) = 0.003
$$

A special case of the formalism derived so far is the determination of $A_{zz}(0^\circ)$. In order to measure $A_{zz}$ we set $\beta = 0^\circ$. This eliminates contributions from all other polarization components, since they all have sin $\beta$ or sin $2\beta$ factor. Additionally, rotation invariance requires that $A_y$, $A_{xz}$ be odd functions of $\theta$, so they vanish at $\theta = 0^\circ$. Also, at $\theta = 0^\circ$ there is no definable x or y axis so $A_{xx} = A_{yy}$. Thus, the term $A_{xx} - A_{yy}$ vanishes at $\theta = 0^\circ$ as well. Equation (5) then reduces to:

$$
\sigma(0^\circ) = \sigma_0(0^\circ) (1 + \frac{1}{2}P_{zz}A_{zz})
$$

(27)
The spin-flip normalization expression for pA is thus:

\[ P_{zz}^{Az} = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} \tag{28} \]

where \( \sigma_1, \sigma_2 \) are yields for the two orientations of the spin vector.

The unpolarized beam normalization expression for pA is:

\[ P_{zz}^{Az} = 2\left(\frac{\sigma_p}{\sigma_0} - 1\right) \tag{29} \]

where \( \sigma_p, \sigma_0 \) are the yields for a polarized and unpolarized beam.

Statistical uncertainties in these calculations are again defined by equation (20) as:

\[
\text{spin-flip} \quad \Delta P_{zz}^{Az} = \sqrt{\left(\frac{2\sigma_2}{(\sigma_1 + \sigma_2)^2}\right)^2 (\Delta \sigma_1)^2 + \left(\frac{2\sigma_1}{(\sigma_1 + \sigma_2)^2}\right)^2 (\Delta \sigma_2)^2}
\]

\[
\text{unpolarized normalization} \quad \Delta P_{zz}^{Az} = 2\sqrt{\left(\frac{1}{\sigma_0}\right)^2 (\Delta \sigma_p)^2 + \left(\frac{\sigma_p}{\sigma_0}\right)^2 (\Delta \sigma_0)^2}
\]

(30)
A reliable and efficient polarimeter for a tensor polarized deuteron beam is a necessity for the performance of this series of experiments. As discussed in Chapter I, the \(^3\)He(d,p) reaction has been shown to be an excellent choice for this purpose since at \(0^\circ\) the tensor analyzing power \(A_{zz}\) is quite large and smoothly varying over the entire energy range of the accelerator. In order to establish the absolute scale of this analyzing power, however, the beam polarization must be known with high accuracy. This is best done using the \(^{16}\)O(d,\(\alpha_1\))\(^{14}\)N* reaction.

Jacobsohn and Ryndin\(^{29}\) have shown that due to the spin structure of the particles and states involved in the \(^{16}\)O(d,\(\alpha_1\))\(^{14}\)N* reaction, \(J^\pi (1^+ + 0^+ + 0^+ + 0^+)\), the tensor analyzing power \(A_{zz}\) is identically equal to one (\(A_{zz} \equiv 1\)) independent of energy and angle. The other analyzing powers are shown to be \(A_{xz} \equiv A_{yz} \equiv 0\) and \(A_{xx} - A_{yy} \equiv 3\), also independent of energy and angle. Substituting these numbers into the general equation describing the yield for a deuteron induced reaction (sec. II-E) gives:

\[ \sigma = \sigma_0 [1 - \frac{3}{4} P_{zz} \sin^2 \beta \cos 2\phi + \frac{1}{4} P_{zz} (3 \cos^2 \beta - 1)] \]

where \(\beta\) and \(\phi\) are the angles describing the orientation of the beam spin vector with respect to the target reference frame (fig II-8). If the beam spin vector is aligned parallel to its momentum vector (\(\beta = 0^\circ\)),...
the above equation reduces to the simple expression:

\[ \sigma = \sigma_0 (1 + 0.5 p_{zz}) \]

Thus the beam polarization can be measured absolutely by measuring yields of the \( \alpha_1 \) group when the reaction is initiated first with a polarized beam and then an unpolarized beam.

There are several features of the reaction, however, that make it unattractive as a general use polarimeter. Because the reaction is isospin forbidden the yield is too low to be practical. The differential cross section is almost always less than 1 mb/sr. The \(^{16}\)O + d reaction also produces several other alpha particle, deuteron, and proton groups which are much more intense on a relative basis and almost completely obscure the low yield from the \( \alpha_1 \) group. Thus, special measures were required to detect and identify the \( \alpha_1 \) group.

The purpose of this measurement, then, was to make a careful determination of the beam polarization using the \(^{16}\)O(d,\( \alpha_1 \)) reaction at a single energy with a statistical accuracy of \( \Delta p_{zz} = 0.01 \) or better and to use this result to calibrate \( A_{zz}(0^\circ) \) for the secondary standard \(^3\)He(d,p) reaction. The \(^3\)He(d,p) reaction would then serve as the polarimeter for this series of experiments and for other planned deuteron experiments at this lab.

To perform this measurement the scattering chamber described earlier (sec. II-D-2) was set up as a gas cell with the detectors immersed in the gas. A single detector telescope was used, consisting of a pair of 15 \( \mu \)m thick transmission (\( \Delta E \)) detectors mounted back
to back and located 10 cm from the center of the chamber. Since A_{zz}
for the reaction is independent of reaction angle, a large solid angle
can be used to increase the counting rate. In this case a half-angle
of 11° was produced by a pair of 6.4 mm diameter collimators separated
by 3.2 cm. The measurement was performed at a reaction energy of 3.9
MeV and at \( \theta_{\text{lab}} = 50° \) where the cross section rises to \( \sim 1 \text{ mb/sr} \).
This produced alpha particles with energy \( E_{\alpha_1} = 4 \text{ MeV} \) (the ground state
group had \( E_{\alpha_0} = 6 \text{ MeV} \)). The method described below was designed to
provide a detector spectrum which has the \( \alpha_1 \) group completely isolated
from all other charged particle groups.

For the detector geometry used here, the alpha particles of in­
terest will lose \( \sim 10 \text{ keV/torr} \) of \( \text{O}_2 \) gas in the chamber as determined
by observing the 5.5 MeV alpha particles from an \( ^{24}\text{Am} \) source. The
gas pressure was then adjusted so that the \( \alpha_1 \) group from the \( ^{16}\text{O}(d,\alpha) \)
reaction was completely stopped in the first detector (95 Torr). As
seen in fig. II-9(a), the spectrum from this detector contains the \( \alpha_1 \)
group as the highest energy peak, the \( \alpha_0 \) group which passes through
the detector and deposits less energy in the detector, and all of the
other proton, deuteron, and alpha groups that lose even less energy
in this thin detector. Clearly the separation between the two alpha
groups is quite good, but there is a measurable background between them
that may be due to tailing of the \( \alpha_0 \) peak underneath the \( \alpha_1 \) peak.
Since the measurement is very sensitive to background effects, the
following method was devised to eliminate the \( \alpha_0 \) peak. The \( \alpha_0 \) group
particles which pass through the front detector are stopped in the
Fig. II-9

a) Diagram showing the $\alpha_1$ and $\alpha_0$ groups from the $^{16}\text{O}(d,\alpha)^{14}\text{N}$ reaction.

b) Diagram showing the same spectrum with the $\alpha_0$ group gated out of the spectrum.
Fig. II-9
back detector. Using the electronics set up shown in fig. II-10, the pulses from the rear detector were used to gate the front detector spectrum in an anti-coincidence requirement. The resulting gated spectrum from the front detector, shown in fig. II-9(b), clearly has the $\alpha_0$ group almost completely gated out. The $\alpha_1$ peak stands alone with no interference from other peaks and with no background and can be used reliably for the beam polarization measurement.

The apparatus for measuring $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)$ reaction was mounted inside the scattering chamber on the movable target holder rod. The gas cell and detector assembly are shown in fig. II-11. The gas cell consists of a 1.25 cm long chamber filled with 1.5 atm of $^3\text{He}$. The entrance window to the cell was a 2.5 $\mu$m thick Havar foil and the exit window was a 0.25 mm thick tantalum disk. This exit window was thick enough to stop the incident deuteron beam for accurate charge integration while the energetic reaction protons (~20 MeV) could pass through the tantalum disk to be stopped in a 1500 $\mu$m thick surface barrier detector. The detector was collimated by a pair of 3.2 mm diameter collimators separated by 4.4 cm to subtend a half-angle of 4°. The electronics used here are also shown in fig. II-11 and simply produce a linear pulse height spectrum from the detector. Any other charged particle groups that may be produced in the target cannot penetrate the tantalum exit window, so the proton group from the $^3\text{He}(d,p)$ reaction is well isolated, as shown in fig. II-12.

Data was acquired for both experiments using a three run technique: a run with an unpolarized beam, a run with the 348 MHz strong field
Fig. II-10  Electronics setup for the $^{16}\text{O}(d,\alpha_1)^{14}\text{N}^*$ experiment to gate out the ground state alpha particle group.
Fig. II-10

α-PARTICLES

ORTEC 109A

ORTEC 460

LINEAR GATE

PULSE INHIBIT

GATE AND DELAY GENERATOR

ORTEC 426

ORTEC 416A

15μM SILICON SURFACE BARRIER DETECTORS

PRE-AMP

AMPLIFIER

TIMING SCA

ORTEC 455

IBM 1800
Fig. II-11  Gas cell and detector used for the $^3\text{He}(d,p)^4\text{He}$ reaction measurement of $A_{zz}(0^\circ)$, including the electronics used.
Fig. II-11

- ORTEC
- TENNELEC
- PACE
- IBM 1800
- AMP
- Fig. 11-11
- $1500_{\mu}M$
- SURFACE BARRIER DETECTOR
- 0.25 mm TANTALUM BEAM STOP
- GAS CELL
  - 1.5 ATM $^3$HE
  - 1.5 ATM $^3$HE
- TENNELEC PACE + IBM 1800
- ORTEC 460 AMP
- ORTEC 109A PRE-AMP
Fig. II-12  Typical spectrum for the $^3$He(d,p)$^4$He reaction measurements at $\theta = 0^\circ$ ($E_D = 2.75$ MeV).
transition (SF) on, and a run with both the 348 MHz and the 8 MHz weak field transitions (SF+WF) on. This technique allows the asymmetry \( p_{zz}^A_{zz} \) to be calculated for both transition schemes using an unpolarized beam normalization (section II-E) so that the efficiency of the weak field transition polarization reversal can be determined as well.

Due to the low yield of the \(^{16}\text{O}(d,\alpha_1)\) reaction, thirty sets of data (three runs/set) were acquired over a 12 hour period. After each group of ten sets of \(^{16}\text{O}(d,\alpha_1)\) data, the chamber was evacuated, the \(^3\text{He}\) cell lowered into the beam path, and a set of \(^3\text{He}(d,p)\) data was acquired. During the twelve hours of the experiment, the polarization was seen to be constant and the weak field reversal of the polarization was virtually 100%, as summarized below:

<table>
<thead>
<tr>
<th>Group of 10 sets of (^{16}\text{O}(d,\alpha_1))</th>
<th>Beam Polarization, ( p_{zz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-SF)</td>
</tr>
<tr>
<td>1</td>
<td>(-0.657\pm0.012)</td>
</tr>
<tr>
<td>2</td>
<td>(-0.670\pm0.012)</td>
</tr>
<tr>
<td>3</td>
<td>(-0.678\pm0.012)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(^3\text{He}(d,p)) sets</th>
<th>( p_{zz}^A_{zz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(SF)</td>
</tr>
<tr>
<td>1</td>
<td>1.087\pm0.012</td>
</tr>
<tr>
<td>2</td>
<td>1.038\pm0.012</td>
</tr>
<tr>
<td>3</td>
<td>1.051\pm0.012</td>
</tr>
</tbody>
</table>

Since the polarization reversal was 100%, a proper spin flip was achieved, so the beam polarization over the duration of the experiment can be calculated using the spin-flip normalization (sec. II-E) to be:

\[
p_{zz} = -0.669\pm0.005
\]
The result of the $^3$He(d,p) experiment, also using the spin-flip calculation is:

$$A_{zz}(0^\circ) = -1.591 \pm 0.011 \text{ at } 3.79 \text{ MeV}$$

The quoted energy, 3.79 MeV, is the energy of the deuteron beam in the center of the $^3$He gas cell. This measurement established the absolute calibration of the $^3$He(d,p) reaction which was used as the secondary standard polarimeter in the course of the experiments discussed in the following sections.
II-G. DATA COLLECTION

There were three distinct experiments performed in this project. They consist of the following: the measurement of $A_{zz}(0°)$ for the charge symmetric $^3\text{He}(\vec{d},p)^4\text{He}$ and $^3\text{H}(\vec{d},n)^4\text{He}$ reactions, the measurement of $A_{zz}(0°)$ for the charge symmetric $^2\text{H}(\vec{d},p)^3\text{H}$ and $^2\text{H}(\vec{d},n)^3\text{He}$ reactions, and the measurement of angular distributions of the four independent analyzing powers, $A_y$, $A_{xx}$, $A_{xz}$ and $A_{zz}$, for the $^2\text{H}(\vec{d},n)^3\text{He}$ reaction. The method for measuring these analyzing powers was discussed in sec. II-E. The targets and measurement techniques will be discussed here.

II-G-1. Measurement of $A_{zz}(0°)$ for the $^3\text{He}(\vec{d},p)$ and $^3\text{H}(\vec{d},n)$ Reactions

As discussed earlier (Chapter I), the purpose of this experiment was to establish the $^3\text{He}(\vec{d},p)$ reaction as a polarization monitor in a careful measurement at this laboratory and to measure the quantity $A_{zz}(0°)$ for these two charge symmetric reactions.

To permit the nearly simultaneous measurement of $A_{zz}(0°)$ for both reactions a combination gas cell and target holder was constructed as shown in fig. II-13. It consisted of a short path length (6.4 mm long) gas cell with a 2.5 μm thick Havar foil entrance window to contain 1.5 atm. $^3\text{He}$ gas. The exit window of the cell consisted of a titanium-tritium target evaporated onto a 0.25 mm thick platinum disk. Platinum was chosen as the backing material in order to reduce the background neutron flux from $(d,n)$ reactions on the backing material to less than 1%. The thickness of the platinum was chosen so that the incident deuteron beam could be completely stopped in the target for accurate
Fig. II-13 Diagram of target and detector arrangement used for the measurement of $A_{zz}(0^\circ)$ for the $^3\text{H}(d,n)^4\text{He}$ and $^3\text{He}(d,p)^4\text{He}$ reactions.
1500Å thick surface barrier detector

1.3 atm He gas cell

0.9 mg/cm² titanium-tritium target

0.25mm platinum backing

Fig. II-13
charge integration as required by the experimental method, while the energetic protons (~ 20 MeV) from the $^3$He(d,p) reaction could pass through the disk to a surface barrier detector located behind the target. The half-thickness ($\Delta E$) of the $^3$He target ranged from 10 keV for 6 MeV deuterons to 60 keV for 500 keV deuterons. The titanium thickness was 900 $\mu$g/cm$^2$ and the tritium activity was 3.9 Ci on a 2.5 cm diameter active area. The energy thickness of the tritium target ($\Delta E$) ranged from 30 keV at 6 MeV to 130 keV at 300 keV.

The $^3$He(d,p) reaction protons passed through the tritium target and backing and into a 1500 $\mu$m thick surface barrier detector operated in air 5 cm behind the target. The detector was collimated by a pair of 3.2 mm diameter collimators separated by 4 cm to subtend a half angle of 4°. Additional absorbers of 125 $\mu$m thick aluminum were placed in front of the detector as needed at higher machine energies to ensure the protons were completely stopped in the detector. A typical spectrum from this apparatus was shown in the previous section (fig. II-12), and clearly shows that the peak of interest is well isolated with no significant background.

The proton detector was removed for a $^3$H(d,n) reaction measurement to eliminate attenuation of the neutron flux (measured to be ~ 15%). The neutron detector was a 5x5 cm NE213 scintillator with electronics for standard n-\gamma discrimination techniques as described earlier (sec. II-D-1). This system was located 35 cm behind the target to subtend a half-angle of 4°. The gated neutron spectra (fig II-14) consisted of the neutrons of interest plus neutrons from other (d,n) reactions from
Fig. II-14  

a) Typical linear spectrum for the $^3\text{H}(d,n)^4\text{He}$ reaction ($E_D = 2.75$ MeV) without gating the $\gamma$-rays out.

b) The same spectrum using $n-\gamma$ discrimination to gate out the $\gamma$-ray events.
Fig. II-14
various materials that the beam hits, but since the $^3\text{H}(d,n)$ neutrons are so energetic ($Q = 17.59$ MeV) they were easily the highest energy neutrons detected. Thus, no background correction was required.

Data were acquired using the same three-run procedure described earlier (sec. II-F). Namely, the spin vector was aligned parallel to the beam momentum direction ($\beta = 0^\circ$) and three data runs were taken: one run with the strong field (SF) transition on, one run with the combined strong field and weak field (SF+WF) transitions on, and one run with an unpolarized beam. This procedure allows two calculations of the measured analyzing power to be made with an unpolarized beam normalization method (sec. II-E). Since the WF reversal of the beam polarization produced by the SF transition has been shown to be virtually 100%, the two unpolarized beam normalization measurements of $A_{zz}$ should be exactly equal in magnitude and opposite in sign. If this condition was met to within the accuracy of the counting statistics (1-2 standard deviations) the data point was accepted as valid. If not, the data point was rejected. This method provides a useful check on the accuracy of the beam charge integration. At most, ~5% of the data points measured were rejected by this procedure. Data for both reactions were acquired so that the statistical uncertainty of the measured $P_{zz}A_{zz}$ using the spin flip normalization was typically $\Delta P_{zz}A_{zz} = 0.005$.

The beam polarization was measured absolutely at 3.9 MeV using the $^{16}\text{O}(d,\alpha_1)$ reaction (sec. II-F) so that for $E = 3.79$ MeV in the $^3\text{He}$ cell $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)$ reaction was $A_{zz}(0^\circ) = -1.596$. For the
present experiment this point at 3.79 MeV for $^3$He(d,p) was re-measured at regular intervals (approximately twice a day) to confirm that the beam polarization was not changing with time. The polarization was measured to be constant to within 0.01 over the four days' duration of these measurements ($p_{zz} = -0.760\pm0.010$). Beam intensities on target ranged from 10 nA at 1 MeV to 100 nA at 6 MeV, the difference due to better focusing characteristics of the beam and better transmission properties for higher machine energies.

II-G-2. Measurement of $A_{zz}(0^\circ)$ for the $^2$H(d,p)$^3$H and $^2$H(d,n)$^3$He Reactions

The tensor analyzing power $A_{zz}(0^\circ)$ was also measured for the charge symmetric $^2$H(d,n) and $^2$H(d,p) reactions using a procedure similar to that describe in the preceeding section.

To insure that the measurements for both reactions were made under nearly identical beam conditions, the gas cell described in the previous section was modified by replacing the titanium-tritium target exit window with a thin (12.5 μm) tantalum foil (fig. II-15). Extra tantalum foils were added as needed so that at each energy, there were enough foils to completely stop the incident deuteron beam for the required accuracy charge integration. This procedure allowed the exit window of the gas cell to remain as thin as possible so the $^2$H(d,p) reaction protons ($Q=4.03$ MeV) could exit the cell and pass through the air to a surface barrier detector mounted at 0° behind the target. The capability of adding and removing these tantalum foils enabled the
Fig. II-15 Diagram of target and detector arrangement for the measurement of $A_{zz}(0^\circ)$ for the $^2\text{H}(d,n)^3\text{He}$ and $^2\text{H}(d,p)^3\text{H}$ reactions.
GAS CELL
500μM OR 1500μM
SURFACE BARRIER DETECTOR

56 DVP
PM TUBE
NE 213

GAS CELL
0.5 ATM D₂
+ 1.5 ATM Ne

VARIABLE NUMBER OF
13μM THICK
TANTALUM FOILS

INCIDENT
BEAM
Σ112, θ=0°

Fig. II-15
beam to be stopped and the reaction protons to be detected over the entire energy range of the experiment (0.5-5.5 MeV). The gas cell contained a gas mixture of 0.5 atm D₂ and 1.5 atm ³He.

For a measurement of $A_{zz}(0°)$ for the $^2$H(d,p) reaction, the protons passed through the exit foil and were stopped in a 500 μm thick surface barrier detector collimated to subtend a half-angle of 4°. A typical spectrum for this reaction is shown in fig. II-16 and shows the dominant proton peak of interest along with some other very low yield (d,p) groups which did not interfere with the $^2$H(d,p) peak. The peak from the $^3$He(d,p) reaction is also apparent in this spectrum though was not used to measure the beam polarization because it was not a background free spectrum and because it may be contaminated with low energy (d,p) protons from contaminant reactions.

The proton detector assembly was removed for a measurement of the $^2$H(d,n) analyzing powers to allow the neutrons to pass unattenuated to a 5x5 cm NE213 scintillator which also subtended a half-angle of 4°. Standard n-γ discrimination techniques (sec. II-D-1) were applied. Typical neutron spectra, gated and ungated, are shown in fig. II-17. The Q value for the $^2$H(d,n) reaction is 3.27 MeV, so that low energy neutrons from other reactions could provide a background problem. This background was measured to be < 1% and was ignored.

The $^3$He(d,p) reaction was used as a polarization monitor for these measurements. The reaction protons easily passed though the exit window of this cell and were slowed by a 1 mm thick aluminum absorber foil in front of a 1500 μm thick detector mounted at 0° behind the target. The analyzing powers $A_{zz}(0°)$, as determined in the experiment
Fig. II-16 Typical charged particle spectrum for the measurement of $A_{zz}(0^\circ)$ for the $^2\text{H}(d,p)^3\text{H}$ reaction. ($E_D = 2.75 \text{ MeV}$)
Fig. II-16

D(D,p) SPECTRUM
\[ \theta = \text{zero deg} \]

PROTONS FROM D\(^+\)D\(^-\)

PROTONS FROM D\(^+\)HE
Fig. II-17 Typical gated and ungated spectra for the $^2\text{H}(d,n)^3\text{He}$ reaction at $\theta = 0^\circ$. ($E_D = 2.75$ MeV)
GATED AND UNGATED SPECTRA
(110,111 AT ZERO DEG)

Fig. II-17
described in the previous section (II-G-1), were used to measure the beam polarization at every energy that data was taken.

The data for the measurement of $A_{zz}(0^\circ)$ for both reactions as well as the polarimeter measurement were acquired using the same procedure described previously (sec. II-F). The beam spin vector was aligned so that $\beta = 0^\circ$ and three data runs were acquired: one run with the SF transition on, one run with the combined SF+WF transitions on, and one run unpolarized. Data was acquired in 250 keV steps from 0.5 to 5.5 MeV.

For the duration of the experiment (4 days) the polarization was measured to be constant at $P_{zz} = -0.790 \pm 0.010$. The various polarization measurements fluctuated about this value with a standard deviation of 0.012. Beam intensities on target ranged from 10 nA at 1 MeV to 90 nA at 5 MeV.

II-G-3 Measurement of Angular Distributions of the Four Independent Analyzing Powers, $A_y$, $A_{xx}$, $A_{xz}$, $A_{zz}$

The four independent vector and tensor analyzing powers, $A_y$, $A_{xx}$, $A_{xz}$ and $A_{zz}$, for the $^2$H($d, n$)$^3$He reaction were measured in 15° steps over the 0°-150° angular range in 500 keV steps from 1.5 to 4.0 MeV.

The target consisted of a cylindrical gas cell 6.4 mm long with a 2.5 μm thick Havar entrance foil and a 250 μm thick tantalum disk exit window. This exit window was thick enough to completely stop the incident deuteron beam for charge integration purposes without attenuating the neutron flux to any appreciable extent.
The side walls of the gas cell were 500 μm thick stainless steel. The gas cell contained 1.5 atm of D₂ gas and was located at the center of the neutron detector table as described in sec. II-D-1.

The detectors consisted of a pair of 5 x 5 cm NE213 scintillators mounted at symmetric angles with respect to the target. Each detector subtended a half-angle of 4.25°. Standard n-γ discrimination techniques (sec. II-D-1) were used. Typical gated neutron spectra obtained at selected angles and energies are shown in fig. II-18. The background contribution to these spectra is appreciable away from a reaction angle of 0° where it is negligible (less than 1%). This is due to the abundance of low energy neutrons produced by other (d,n) reactions on contaminants along the beam line and in the target, as well as low energy breakup neutrons from the beam. At angles away from 0° the cross section for the $^2$H(d,n) reaction drops sharply (by a factor of 10' at 85° lab, 3 MeV) as does the energy of the neutrons so the foreground/background ratio also drops at large reaction angles.

For beam energies up to 3 MeV these background neutrons account for less than 10% of the total detected neutrons, as measured with a target full/target empty procedure. In order to make a background subtraction for energies from 1.5-3.0 MeV, a background ratio measurement was performed at several angles to establish the background percentage as a function of angle. This background percentage was then subtracted from each data run with deuterium in the gas cell. Above 3 MeV, the background contribution rose sharply so that it exceeded 30% of the total counts at the back angles. For these energies, a target-full/target-empty determination of the background was made for each
Fig. II-18  Typical gated neutron spectra for the $^2\text{H}(d,n)^3\text{He}$ reaction at $\theta = 45^\circ$, $90^\circ$ and $135^\circ$ at $E_D = 3$ MeV.
Fig. II-18
data run so that a direct run-for-run background subtraction could be made.

To determine each of the four analyzing powers with a minimum of interference from the other three, appropriate choices must be made for the orientation of the beam with respect to the target coordinate system as described in sec. II-E. These choices for the various analyzing powers are summarized below:

<table>
<thead>
<tr>
<th>Analyzing Power</th>
<th>( \beta )</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_y )</td>
<td>90°</td>
<td>0°,180°</td>
</tr>
<tr>
<td>( A_{zz} )</td>
<td>0°</td>
<td>arbitrary</td>
</tr>
<tr>
<td>( A_{xz} )</td>
<td>45°</td>
<td>90°,270°</td>
</tr>
<tr>
<td>( A_{xx} )</td>
<td>90°</td>
<td>90°,270°</td>
</tr>
</tbody>
</table>

These orientations are accomplished by setting the detector table (sec. II-D-1) and the Wien filter appropriately. When the detector table is horizontal, the pair of detectors (left-right) correspond to \( \phi=0°,180° \). When the table is vertical, the pair of detectors (up-down) correspond to \( \phi=270°,90° \). The \( \beta \)-angle is set with the Wien filter located in the polarized source.

Once the appropriate \( \beta,\phi \) combination had been set, the three tensor analyzing powers were measured using the three data run technique described previously, along with the background determination. In order to completely eliminate any possible interference from the tensor analyzing powers, the vector analyzing power was measured using a two run, polarization on-off technique with the 8 MHz weak field (WF) transition. This transition produces a purely vector polarized
beam with $p_z = \frac{2}{3}p_{zz}$ where $p_{zz}$ is the tensor polarization produced by
the 348 MHz strong field (SF) transition. This feature was verified
using $d-\alpha$ elastic scattering to be discussed in sec. II-I. The
formalism for this unpolarized normalization technique is described
in sec. II-E.

The $^3$He($d,p$) reaction at 0° was used as the polarimeter for these
measurements, using the analyzing powers $A_{zz}(0°)$ determined earlier.

The $^3$He gas cell was mounted on the target rod in the scattering cham­
ber so that it could be inserted into the beam path whenever a polariza­

tion measurement was required. The $^3$He gas was not mixed with the $D_2$
gas for this experiment because more $D_2$ gas was necessary for these
measurements due to the lower reaction cross sections, and the gas
cell could not stand the extra pressure of the $^3$He gas. The $^3$He gas
cell and detector were as described in sec. II-F. This polarimeter
monitors only the tensor component of the beam polarization, $p_{zz}$.

The vector polarization was inferred from this number as will be shown
in sec. II-I.

In addition to the measurement of analyzing powers for the neutrons
directly, measurements of $A_{zz}$ for the $^2$H($d,n$) reaction were also per­
formed by detecting the recoil $^3$He nuclei at selected energies and
angles. These measurements were made inside the gas scattering chamber
(sec. II-D-2) filled with 125 Torr of $D_2$ gas. The detectors were
symmetric pairs of 500 μm thick surface barrier detectors placed at
$\theta_{lab} = 18°, 28°, 38°$, and collimated to subtend a half-angle of 2.5°.

A typical spectrum is shown in fig. II-19. The charged particle
Fig. II-19  Typical spectrum for the $^3$He recoil measurement of $A_{zz}$ for the $^2\text{H}(d,n)^3\text{He}$ reaction, showing the $^3$He peak, the proton and recoil triton peaks from the $^2\text{H}(d,p)^3\text{H}$ reaction, and the elastically scattered deuterons from the d+d scattering process.
Fig. II-19
groups seen were the elastically scattered deuterons, the recoil $^3$He nuclei, and both the protons and the recoil $^3$H nuclei form the $^2$H(d,p) reaction.

Analyzing powers were measured using the usual three run method after setting $\beta=0^\circ$. Data were collected at 2.5, 3.0, 3.5, and 4.0 MeV. Because particles from the $^2$H(d,p) reaction were also observed, direct information was obtained in a truly simultaneous measurement of differences between the (d,p) and (d,n) reactions. The recoil $^3$He data also served as a check on the accuracy of the background subtraction method used for the neutron measurements. The forward angle recoils correspond to neutron events at the back angles where the background neutron contribution was largest.

The polarized beam characteristics for the angular distribution measurements were again quite constant. Beam intensities ranged from 15 nA at 1.5 MeV to 50 nA at 4.0 MeV. For the data taken in the 1.5-3.0 MeV range the average polarization was $P_{zz} = -0.775\pm0.010$. Actual measurements of the polarization fluctuated about this value with a standard deviation of 0.012. For the 3.5-4.0 MeV data, which was taken at a later date, the average polarization was $P_{zz} = -0.728\pm0.010$ where fluctuations about this point had a standard deviation of 0.005.
II-H. DATA REDUCTION

The pulse height spectra obtained during this series of experiments were reduced with the aid of a modified version of the FORTRAN code SOUTH. Two versions of this program exist for summing spectra for either charged particles or neutrons.

The version for charged particle peak summation was described by Regner. The program allows the operator to pick four channels in the spectrum. The second and third channels define the peak location and the first and fourth are used for a background determination. The program then integrates the channels between the peak defining points and subtracts a linear background determined by the average counts/channel between points 1 and 2 and the average counts/channel between points 3 and 4. The program prints out the integrated peak minus the background, the background amount, and the statistical uncertainty in the integrated counts (including the background uncertainty contribution).

The version of SOUTH used for summing neutron spectra is described by Doyle. The operator picks one channel of the gated neutron spectrum (typically half-way down the Compton edge). The program then integrates all counts in the spectrum starting at 40, 50, 60, 70, and 80% of the channel picked up to the end of the spectrum (channel 256 for this experiment). The different bias levels calculated allow the experimenter to choose as much of the neutron spectrum as possible without counting low energy neutron contamination events which would start to appear at the lower bias levels. The 80% bias level was used
almost exclusively in this series of experiments in order to eliminate this contamination which would result in an inaccurate analyzing power measurement. This program does not perform a background subtraction, so this must be done as a separate procedure as described in section II-G-3.

All of the data taken was reduced on-line as it came in to ensure that any problem in the equipment could be found as rapidly as possible. To assist in this on-line reduction, several short programs were written to calculate the measured asymmetry for each analyzing power using each method possible in the three-run data acquisition technique: the SF/unpolarized, SF+WF/unpolarized, and SF/SF+WF calculations. If the two unpolarized normalization calculations were not identical to within two standard deviations of the counting statistics, that set of three runs was rejected. Rejection of a measurement occurred only about 5% of the time.

A further correction was made to the analyzing powers in off-line analysis of the data in addition to the background subtraction for the $^2\text{H}(d,n)$ angular distribution measurements. The Tennelec PACE system produces a pulse every time it interrogates a stretcher and finds a count in it. This busy output, together with a timer, is a dead time monitor for each of the stretchers in the system. Dead times of up to 2% were observed during the experiment. The effect of these corrections on the data was larger than the statistical uncertainty only for the very large analyzing powers measured in the $^3\text{He}(d,p)$ and $^3\text{H}(d,n)$ experiments, but the correction was applied to all of the data.
II-I. PRE-EXPERIMENT MEASUREMENTS

Two different calibration procedures were performed before the experiments described in the previous sections could be conducted. These were the $\beta$ and $\phi$ angle calibration of the Wien filter in the polarized ion source, and the calibration of the vector polarization produced by the weak field transition with the tensor polarization produced by the strong field transition.

II-I-1 Wien Filter Calibration

The measurement of spin one analyzing powers requires that the orientation of the spin vector of the beam polarization ($\beta$ and $\phi$ angles as shown in fig. II-8) be accurately known. Large uncertainties in $\beta$ and $\phi$ will introduce contributions of other unwanted analyzing powers into the measurement.

The spin precession unit (Wien filter) in the polarized source consists of crossed E and B fields normal to the beam momentum direction which allow the spin vector to be rotated in the plane perpendicular to the $\vec{B}$ field. The Wien filter may also be rotated as a unit about the beam axis. The combination of these two features allows the beam spin vector to be oriented in any arbitrary direction in the target coordinate system. The goals of the Wien filter calibration are to make the rotation plane in the Wien filter correspond to the $y$-$z$ plane in the target coordinate system so that $\phi = 0^\circ(180^\circ)$ for the left (right) detector, and to calibrate the $\beta$ angle as a function of the Wien filter parameters monitored on the polarized source.
To perform the $\beta,\phi$ calibration the $\vec{p}^+\text{He}$ elastic scattering process was used. The target was 0.5 atm of $^4\text{He}$ contained in a rectangular gas cell 1.6 cm long by 1 cm wide with 2.5 $\mu$m thick Havar entrance and exit window foils. The target was mounted in the rotatable scattering chamber (sec. II-D-2). The Wien filter was set so that its rotation plane was approximately coincident with the $y$-$z$ plane at the target.

The left and right detector blocks in the scattering chamber differed in $\phi$ by $180^\circ$, so for the left detector $\phi=0^\circ$ and for the right detector $\phi=180^\circ$. The yield for a spin $\frac{1}{2}$ beam is given by:

$$\sigma = \sigma_0(1 + pA \sin\beta \cos\phi)$$

$\sigma =$ yield with a polarized beam
$\sigma_0 =$ yield with an unpolarized beam
$p =$ beam polarization
$A =$ analyzing power for $p-\alpha$ scattering at this $E,\theta$

By making two runs, one with the scattering chamber in one position and another with the chamber rotated by $180^\circ$, a measurement independent of charge integration and detector solid angle can be made. With this procedure, a proper spin flip is made as defined by Ohlsen and Keaton$^{40}$. Defining a geometric mean of the yields in the left and right detectors as $L=\sqrt{L_1L_2}$ and $R=\sqrt{R_1R_2}$, the observed asymmetry will be:

$$pA \sin\beta \cos\phi = \frac{L-R}{L+R}$$

The strengths of both the $E$ and $B$ fields in the Wien filter are monitored remotely by digital voltmeters, but since there is the
possibility of hysteresis in the B field, only the E field reading was used for calibration purposes. The asymmetry in p-α elastic scattering as a function of the meter reading for the E field for both polarities of the Wien filter is plotted in fig. II-20. The solid line is a fit to the data of the form:

\[ y = A_1 \sin(A_2 + A_3x + A_4x^2) \]

where

- \( y \) = measured asymmetry
- \( x \) = E field reading

The least squares fit to the data yielded the parameters:

- \( A_1 = -0.5673 \)
- \( A_2 = 0.3265 \)
- \( A_3 = 0.0352 \)
- \( A_4 = 0.0000 \)

This indicates the expected result that the rotation of the spin angle (\( \beta \)) is linear with E field strength since the asymmetry is described by a purely sinusoidal function characterized by an amplitude \( (A_1) \), a phase \( (A_2) \), and a frequency \( (A_3) \). The non-linear term \( (A_4) \) is not required. Since the elastic scattering asymmetry is sensitive only to the component of the spin normal to the scattering plane, a \( y=y_{\text{max}} \) point corresponds to \( \beta=90^\circ \) and a \( y=0 \) point corresponds to \( \beta=0^\circ \).

The \( \beta \) calibration for deuterons can be inferred from these results so that actual measurement is not necessary. However, to verify this result a deuteron \( \beta \) angle calibration was performed using the \( ^3\text{He}(\alpha,p) \) reaction at \( 0^\circ \). At \( \theta=0^\circ \), the yield for this reaction is given by:

\[ \sigma = \sigma_0 \left(1 + \frac{1}{4}(3\cos^2\beta - 1) \right) p_{zz} A_{zz} \]
Fig. II-20  Plot of $p_yA_y$ vs. E-field setting on the Wien filter for a calibration of the $\beta$-angle using $p+^3$He elastic scattering. The resulting sine curve indicates a linear relation between $\beta$ and the E-field setting.
Measurement of the asymmetry with a polarized/unpolarized method again showed that \( \beta \) is linear with the E field reading and produced essentially identical results to the p-\( \alpha \) scattering calibration of \( \beta \).

In order to perform the \( \phi \) angle calibration, the p-\( \alpha \) elastic scattering process was used again. The \( \beta \) angle was set to 90° and the up-down (\( \phi=270°,90° \)) asymmetry as opposed to the left-right asymmetry was measured as function of the position of the rotatable scattering chamber. This position was monitored by an optical shaft encoder which was geared to the chamber and monitored its position to within 0.1°. The observed asymmetry (for \( \beta=90° \)) will be:

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

The Wien filter will be in the correct position if the observed up-down asymmetry is zero (\( \phi=90°,270° \)) when the scattering chamber is at 90° which means that the scattering plane is coincident with the deflection plane of the 90° analyzing magnet for the accelerator, and the detectors are truly up and down geographically. This is accomplished by rotating the Wien filter about the beam axis in the polarized source until the observed up-down asymmetry is zero for the chamber at 90°. A plot of the measured asymmetry for the final position of the Wien filter as a function of chamber position is shown in fig. II-21. The solid line is least squares linear fit to the data and shows that the asymmetry is zero for a chamber position of 89.9°±1.0°, so the \( \phi \) angle orientation is known quite well.
Fig. II-21  Plot of effective beam polarization ($p_y \cos \theta$) vs. scattering chamber position ($\phi$) for the $\phi$-angle calibration of the Wien filter. The solid line is a least squares linear fit to the data and passes through the horizontal axis at 89.9°.
Fig. II-21
II-I-2 Calibration of the $^3$He(d,p) Reaction as a Vector Polarization Monitor

In order to perform the vector analyzing power measurements for the $^2$H(d,n) reaction (sec. II-G-3) a reliable vector polarimeter is required. No convenient reaction or scattering process exists in the energy range of this experiment for which analyzing powers are well known, so a calibration of the vector polarization produced by the weak field transition to the tensor polarization produced by the strong field transition was performed.

The maximum polarization obtainable from the transitions used in the O.S.U. polarized ion source are summarized in sec. II-E. Actual measured polarizations will be smaller due to incomplete Stern-Gerlach separation of the hydrogen hyperfine states in the short sextupole magnet used in the source and to any unpolarized background component to the deuteron beam.

The strong field (SF) 348 MHz transition produces a maximum polarization of $p_{zz}=-1$ and $p_z=1/3$. The vector component will thus always be one third of the tensor part in magnitude. The weak field (WF) transition produces a purely vector polarized beam ($p_{zz}=0$) with a maximum polarization of $p_z=-2/3$. Therefore, if both transition probabilities are essentially 100% the vector polarization produced by the WF transition alone will be exactly equal to two-thirds of the tensor polarization produced by the SF transition alone, and the $^3$He(d,p) tensor polarimeter can also be used as a vector polarimeter.

To verify this relation, d-α elastic scattering was performed in the gas scattering chamber (sec. II-D-2) filled with 1/3 atm of $^4$He.
The \( \beta \) angle was set to \( \beta=90^\circ \) and left-right yields \( (\phi=0^\circ,180^\circ) \) were obtained. The yield for this situation is described by the equation (sec. II-E):

\[
\sigma = \sigma_0 (1 + \frac{3}{2} p_{Z\alpha} \cos \phi - \frac{3}{4} p_{ZZ} A_{zz})
\]

For the left detector \( (\phi=0^\circ) \) yield \( L \), and the right detector \( (\phi=180^\circ) \) yield \( R \), this expression reduces to:

\[
L = L_0 (1 + \frac{3}{2} p_{Z\alpha} - \frac{3}{4} p_{ZZ} A_{zz})
\]

\[
R = R_0 (1 - \frac{3}{2} p_{Z\alpha} - \frac{3}{4} p_{ZZ} A_{zz})
\]

This yields the result that:

\[
p_{Z\alpha} = \frac{2}{3} \left( \frac{L}{L_0} - \frac{R}{R_0} \right)
\]

The asymmetry \( p_{Z\alpha} \), was measured for the two conditions: SF on/off and WF on/off at \( \theta_{lab}=60^\circ \) at an energy of \( E=5.32 \text{ MeV} \). The results of this measurement are:

<table>
<thead>
<tr>
<th>Method</th>
<th>( p_{Z\alpha} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF on/off</td>
<td>( 0.124\pm0.005 )</td>
</tr>
<tr>
<td>WF on/off</td>
<td>( -0.244\pm0.005 )</td>
</tr>
</tbody>
</table>

Since the magnitude of \( p_z \) due to the WF transition is exactly equal to twice the \( p_z \) due to the SF transition to within the counting statistics, it will be equal to two-thirds the value of \( p_{ZZ} \) due to the SF transition. Thus the \(^3\text{He}(d,p)\) reaction at \( 0^\circ \) may also be used as a vector polarimeter for the polarized beam produced by the O.S.U. polarized ion source assuming only that \( p_z = -p_{ZZ}/3 \) for the SF transition.
CHAPTER III
PRESENTATION AND DISCUSSION OF DATA

III-A. Introduction

The data measured in this series of experiments is presented in this section. Contributions to the experimental uncertainty in the measurements as well as measured corrections applied to the data are discussed. Comparisons with existing, overlapping data are made, and comparison between the \( (d,p) \) and \( (d,n) \) analyzing powers are made for the \( ^3\text{He}(d,p)^4\text{He} \) and \( ^3\text{H}(d,n)^4\text{He} \) charge symmetric reactions, and for the \( ^2\text{H}(d,p)^3\text{H} \) and \( ^2\text{H}(d,n)^3\text{He} \) charge symmetric reactions for the quantity \( A_{zz}(0^\circ) \). Legendre polynomial fits to the angular distributions for the \( ^2\text{H}(d,n) \) analyzing power data have been made, and comparisons with published \( ^2\text{H}(d,p) \) analyzing powers and Legendre polynomial fit parameters are made.

III-B. \( A_{zz}(0^\circ) \) for \( ^3\text{He}(d,p)^4\text{He} \) and \( ^3\text{H}(d,n)^4\text{He} \)

The analyzing power \( A_{zz}(0^\circ) \) for the two reactions of interest are plotted in figs. III-1 and III-2 as a function of average deuteron energy in the center of the target. This energy is different for the two reactions since the deuterons for the \( ^3\text{H}(d,n) \) experiment had to
Fig. III-1  Plot of $A_{zz}(0^\circ)$ for the $^3\text{He}(^3\text{He},p)^4\text{He}$ reaction, including data of other authors.
Fig. III-2  Plot of $A_{zz}(0^\circ)$ for the $^3\text{H}(\tilde{d},n)^4\text{He}$ reaction including data of other authors.
PRESENT WORK

The figure shows a graph of $A_{zz}(0^\circ)$ versus $E_0$ (MeV) for the reaction $^3\text{H}(d,n)^4\text{He}$. The graph includes data points for:

- PRESENT WORK
- LISOWSKI
- BROSTE
- SUNIER
- GRUNDER

Fig. III-2
traverse the second half of the $^3$He gas cell and get to the center of
the titanium tritium target:

$$<E_D>_{^3He} = E_{VDG} - \Delta E_{foil} - \frac{1}{2} \Delta E_{gas\ cell}$$

$$<E_D>_{^3H} = <E_D>_{^3He} - \frac{1}{2} \Delta E_{gas\ cell} - \frac{1}{2} \Delta E_{Ti}$$

The range and stopping power tables of Northcliffe and Schilling were used for the energy loss calculations. Energies below 1 MeV have been corrected for the large variation of the cross section over the target energy spread and include straggling effects. The uncertainties for the $A_{zz}$ data reported here include both statistical uncertainties (typically ±0.005) and beam polarization uncertainties (estimated $\Delta p_{zz} = 0.010$). The quoted uncertainties in the tabulations of data from other laboratories do not contain the latter contribution to uncertainty in $A_{zz}$.

The data for $A_{zz}(0^o)$ for the $^3$He(d,p) reaction are shown in fig. III-1 along with the data of several other authors. Schmelzbach et al. measured this quantity over the entire range of this experiment and their data are in general agreement with the data reported here. Small differences in magnitude between their data and the data reported here are seen above 4 MeV and a relatively larger difference is seen below 1.5 MeV where the data of Simon et al. and Garrett and Lindstrom are more coincident with the present data. This disagreement with the data of Schmelzbach et al. may be a reflection of depolarization of the beam in a tandem accelerator as discussed in Chapter I. The Garrett and Lindstrom data set was extracted from
Legendre polynomial fits to their measurements of angular distributions of $A_{zz}$.

The $^3\text{H}(d,n)$ $A_{zz}(0^\circ)$ data is plotted in fig. III-2. Overlapping data from other authors are scarce in this energy region. The data of Grunder et al.\textsuperscript{45}, extracted from Legendre polynomial fits to their angular distribution data, show good agreement with the data reported here below 1 MeV but significant disagreement at 1 MeV. At the high end of the energy range, the data of Broste et al.\textsuperscript{26} and Sunier et al.\textsuperscript{27} and Lisowski et al.\textsuperscript{28}, all acquired in experiments at Los Alamos show significant and rather startling differences among themselves as highlighted by their commonly measured data point at 7 MeV where differences of up to 30% are seen. The data of Broste et al.\textsuperscript{26} was extracted from their measurement of $A_{yy}(0^\circ)$ which is equal to $-0.5 A_{zz}(0^\circ)$ since $A_{xx}+A_{yy}+A_{zz} = 0$ and $A_{xx} = A_{yy}$ at $\theta = 0^\circ$.

Unfortunately, the data reported here could not be extended to cover this energy due to limitations of the accelerator. The data measured in this experiment extend up to 6 MeV. The data of Lisowski et al.\textsuperscript{28} show fair agreement with the present data, though their data are consistently smaller in magnitude in the area of overlap.

Fig. III-3 shows a comparison of the charge symmetric $^3\text{He}(d,p)$ and $^3\text{H}(d,n)$ reaction data for $A_{zz}(0^\circ)$. The solid and dashed lines are drawn as a guide to the eye. The structure of the two curves is clearly similar, though large differences below 2 MeV and above 3.5 MeV are present. The value of $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)$ reaction is always larger in magnitude than the value for the $^3\text{H}(d,n)$ reaction. The difference in $A_{zz}(0^\circ)$ for the two reactions at low energies ($E_D < 2$ MeV)
Fig. III-3  Plot of the $A_{zz}(0^\circ)$ data for both the $^3\text{He}(\vec{d},p)^4\text{He}$ and $^3\text{H}(d,n)^4\text{He}$ reactions as measured in this experiment. The solid and dashed lines are a guide to the eye.
may be due to the fact that the $J^\pi = \frac{3^+}{2}$ resonance which dominates the reaction at low energies occurs at different energies for the two reactions: 107 keV for the $^3$H(d,n) reaction and 430 keV for the $^3$He(d,p) reaction. Also at low energies, the difference in the Coulomb wave functions for the outgoing proton and neutron will contribute to the observed difference in $A_{zz}$. At high energies ($E_D > 3.5$ MeV), the difference between the two reactions is not as readily understood, and an explanation of the difference must await the results of the Los Alamos R-matrix calculations in progress.

III-C. $A_{zz}(0^\circ)$ for $^2$H(d,p)$^3$H and $^2$H(d,n)$^3$He

The data for $A_{zz}(0^\circ)$ for the $^2$H(d,n) and $^2$H(d,p) reactions are plotted in figs. III-4 and III-5 as a function of average deuteron energy at the center of the target. The energy loss tables of Northcliffe and Schilling$^{11}$ were used for this calculation. The uncertainties for the present $A_{zz}(0^\circ)$ data include both statistical uncertainties (typically 0.005) and beam polarization uncertainties (estimated $\Delta p_{zz} = 0.01$). The solid lines through the data points are drawn to serve as a guide to the eye for comparison with other data sets.

The $^2$H(d,n) data are plotted in fig. III-4 together with the data of Lisowski et al.$^{12}$, Salzman et al.$^{11}$, and Simmons et al.$^{10}$) The data of Lisowski et al.$^{12}$ agree with the present data set quite well above 3 MeV, but below 3 MeV there is a significant difference between the two sets. This may be due in part because of the experimental
Fig. III-4  Plot of $A_{zz}(0^\circ)$ for the $^2$H(d,n)$^3$He reaction including data of other authors. The dashed line is a guide to the eye.
Fig. III-4
Fig. III-5  Plot of $A_{zz}(0^\circ)$ for the $^2H(d, p)^3H$ reaction including data of other authors. The solid line is a guide to the eye.
$^2\text{H}(d,p)^3\text{He}$

**PRESENT WORK**

GRÜEBLER et al. (I) $\theta_{\text{LAB}}=7.5^\circ$

GRÜEBLER et al. (II) $\theta_{\text{LAB}}=7.5^\circ$

PETITTJEAN et al.

---

**Fig. III-5**

$A_{22}(0^\circ)$ vs $E_D$ (MeV)
procedure required for the measurements using the tandem accelerator at TUNL.

Because of poor tandem accelerator performance at low energies, relatively thick absorbers were required to bring the deuteron energy in the target to the desired value for target energies below 3 MeV. This introduces the possibility of large uncertainty in the average target energy. Also, beam intensities for the lowest reported energies were not measurable so that charge integration was impossible and time integration was substituted. As at other facilities using a Lamb-shift type polarized ion source, the quench ratio method was used to monitor the beam polarization. As discussed in the previous section relating to the data of Schmelzbach et al.29) this method is perhaps not exact, especially at low energies due to the possibility of depolarization of the deuteron beam in the residual gas of the high voltage terminal in a tandem accelerator. The data reported here were taken using a polarimeter located in close proximity to the target and using analyzing powers carefully measured in a separate experiment (sec. II-F and II-G-1), and are thus immune from such a problem. The data of Salzman et al.10) are in agreement with the present data and the earlier data of Simmons et al.10) are not, including a point at 4 MeV with $A_{22} = -0.368$ not shown here. Overlap with these two sets is small, however.

The data for the $^2H(d,p)$ reaction are plotted in fig. III-5. Grübler et al.7,8) have measured angular distributions of all the analyzing powers for the $^2H(d,p)$ reaction, and their data at $\theta_{\text{lab}} = 7.5^\circ$ are also plotted in fig. III-5. There is good agreement between their data and the present data although there is some scatter between the
two different data sets reported by Gruebler et al.\textsuperscript{7,8}) Also shown is a single point at 460 keV by Petitjean et al.\textsuperscript{4,7})

Fig. III-6 shows a comparison of the values of $A_{zz}(0^\circ)$ for both reactions as measured in this experiment. There is a clear difference between the two curves over the entire energy range of the experiment. It is also clear that simple energy shift due to the different $Q$-values of the two reactions as was done for the comparison of the polarization data\textsuperscript{1}) would not alleviate the difference, since the two curves appear to be reaching a plateau at different magnitudes of $A_{zz}$. Furthermore, the energy shift proposed by Hardekopf et al.\textsuperscript{1}) for the polarization data would shift the $(d,p)$ data up in energy, whereas any shift in this data would require the $(d,p)$ data to be moved down in energy to bring about more agreement between the $(d,p)$ and $(d,n)$ analyzing powers.

III-D. Angular Distributions of all Spin 1 Analyzing Powers for the $^2H(d,n)^3He$ Reaction

The data for all four independent analyzing powers for the $^2H(d,n)$ reaction are shown in figs. III-7, III-8, III-9, and III-10 for $A_y$, $A_{zz}$, $A_{xz}$, and $A_{xx}$ respectively. Data were acquired typically in $15^\circ$ intervals over the range $\theta_{lab} = 0^\circ-150^\circ$. As stated in previous sections, the analyzing powers have been corrected for background and deadtime. The uncertainties in the analyzing powers include contributions from uncertainty in the beam polarization ($\Delta p_{zz} = 0.01$), uncertainty in $\beta$ and $\phi$ (estimated $\Delta \beta = 3^\circ$, $\Delta \phi = 1^\circ$), the statistical counting uncertainty, and an additional uncertainty of $\Delta A = 0.005$
Fig. III-6 Plot of the $A_{zz}(0^\circ)$ data for both the $^2\text{H}(\vec{d},n)^3\text{He}$ and $^2\text{H}(\vec{d},p)^3\text{H}$ data as measured in this experiment. The dashed and solid lines are as in Figs. III-4, 5 and serve as an aid for comparison of the values of $A_{zz}(0^\circ)$ for the two reactions.
Fig. III-6
Fig. III-7  Plot of the $A_Y$ angular distribution data for the $^2H(d,n)^{\alpha}He$ reaction.
Fig. III-7
Fig. III-8  Plot of the $A_{zz}$ angular distribution data for the $^2\text{H}(d,n)^3\text{He}$ reaction, including the recoil $^3\text{He}$ data shown as crosses at 2.5, 3.0, 3.5, and 4.0 MeV.
Fig. III-8
Fig. III-9  Plot of the $A_{xz}$ angular distribution data for the $^2H(d,n)^3He$ reaction.
Fig. III-9
Fig. III-10  Plot of the $A_{XX}$ angular distribution data for the $^2\text{H}(\vec{d},n)^3\text{He}$ reaction.
Fig. III-10
which includes charge integration uncertainty and uncertainty in the
detector angle, \( \theta \), etc. In addition, the analyzing powers have been
corrected for the finite solid angle of the neutron detectors (\( \Delta \theta_{\text{lab}} = 4^\circ \)) utilizing the computer program OMEGA\(^{16}\)), which numerically averages
over the shape of the analyzing power curve for the solid angle range
of the detector, calculates the effect of the finite detector solid
angle and adds the correction back in to the measured data. Correc­
tions of this type were less than 0.005 more than 80% of the time and
exceeded 0.01 for only a few of the data points.

A comparison with existing \(^2\text{H}(d,p)\) analyzing power data is
possible, as Gruebler \textit{et al.} \(^7,8\)) have measured these analyzing powers
at \( E_D = 1.5, 2.0, 2.5, 3.0 \) and 4.0 MeV overlapping the \(^2\text{H}(d,n)\) data
reported here. For purposes of comparison, the present \( A_{xx} \) data,
along with the \( A_{zz} \) data, was used to calculate the generally reported
quantity \( \frac{1}{2}(A_{xx} - A_{yy}) \) via the relation:

\[
\frac{1}{2}(A_{xx} - A_{yy}) = A_{xx} + 2A_{zz}
\]

which is an exact equality because the overcompleteness of the cartesian
analyzing powers\(^{49}\) requires that:

\[
A_{xx} + A_{yy} + A_{zz} = 0
\]

The \(^2\text{H}(d,p)\) data reported by Gruebler \textit{et al.} \(^7,8\)) was expressed in
terms of spherical basis tensors (\( i\text{T}_{11}, \text{T}_{20}, \text{T}_{21} \) and \( \text{T}_{22} \)) (ref. 49)
which are related to the cartesian tensors via the following relations:
\[
A_Y = \frac{2}{\sqrt{3}} i T_{11}
\]
\[
A_{zz} = \sqrt{2} T_{20}
\]
\[
A_{xz} = -\sqrt{3} T_{21}
\]
\[
\frac{1}{2}(A_{xx} - A_{yy}) = \sqrt{3} T_{22}
\]

The \((d,n)\) data was fit with a Legendre polynomial expansion as formulated by Seiler\(^{50,51}\) using the equation

\[
4\pi \left\{ \sum_{k=1}^{l} \sigma(T) \sum_{k=1}^{L} d_{kq}(L) P_L^q(\cos \theta) \right\}
\]

where differential and total cross section data \((\sigma(\theta) \text{ and } \sigma_T)\) were obtained from the review article of Liskien and Paulsen.\(^{52}\) The polynomial fit was accomplished using a modified version of the FORTRAN code LEPIT.\(^{53}\)

The \(^2\)H\((d,p)\) Legendre fit parameters were extracted from several sources. The data at 3 and 4 MeV use cross sections of Gruebler et al.\(^{7}\), while the data at 1.5, 2.0 and 2.5 MeV use analyzing powers from Gruebler et al.\(^{8}\) and cross sections of Brolley et al.\(^{54}\) and Schulte et al.\(^{55}\)

The resulting polynomial fits for both the \(^2\)H\((d,n)\) and \(^2\)H\((d,p)\) data are shown in figs. III-11, III-12, III-13 and III-14 along with the \(^2\)H\((d,n)\) data measured in this experiment. The quantities \(A_Y\) and \(\frac{1}{2}(A_{xx} - A_{yy})\) show no strong dependence on energy over the range of this experiment, while the quantities \(A_{xz}\) and \(A_{zz}\) show considerable change, especially at the forward angles. Similarly, a comparison of the \((d,p)\) fits with the \((d,n)\) fits reveals that they are roughly equivalent for the \(A_Y\) and \(\frac{1}{2}(A_{xx} - A_{yy})\) quantities (though significant differences
Fig. III-11 Plot of the $A_y$ angular distribution data for the $^2\text{H}(d,n)^3\text{He}$ reaction with the Legendre polynomial fit to the data as a solid curve and a fit to the $^2\text{H}(d,p)^3\text{H}$ data of Gruebler et al.\textsuperscript{6,7} shown as a dashed curve.
Fig. III-12  Plot of the $A_{zz}$ angular distribution data for the $^2\text{H}(d,n)^3\text{He}$ reaction with the Legendre polynomial fit to the data as a solid curve and a fit to the $^2\text{H}(d,p)^3\text{H}$ data of Gruebler et al.$^{6,7}$ shown as a dashed curve.
Fig. III-12
Fig. III-13  Plot of the $A_{xz}$ angular distribution data for the $^2\text{H}(d,n)^3\text{He}$ reaction with the Legendre polynomial fit to the data as a solid curve and a fit to the $^2\text{H}(d,p)^3\text{H}$ data of Gruebler et al.\textsuperscript{6,7} shown as a dashed curve.
Fig. III-14  Plot of the $\frac{1}{2}(A_{xx}-A_{yy})$ angular distribution data for the $^2\text{H}(\text{d},\text{n})^3\text{He}$ reaction with the Legendre polynomial fit to the data as a solid curve and a fit to the $^2\text{H}(\text{d},\text{p})^3\text{H}$ data of Gruebler et al.$^6,7$ shown as a dashed curve.
Fig. III-14
develop for $A_Y$ at low energies) while the $A_{zz}$ and $A_{xz}$ fits show substantial variations over the entire energy range. As in the comparison of the quantity $A_{zz}(0^\circ)$ for these two reactions, a comparison of the two reactions at equal exit channel energies will not resolve the differences. This comparison can be easily made by comparing the $(d,p)$ fits on the left side of the page where they are plotted with the $(d,n)$ fits on the right side of the page, an upward shift of ~ 1.5 MeV in the $(d,p)$ energy scale.

The difference between the two reactions is also evidenced in plots of the Legendre polynomial fit parameters, $d_{kq}(L)$ as shown in figs. III-15, III-16, III-17 and III-18. Significant differences are seen for the coefficients of all of the analyzing powers with the exception of $\frac{1}{2}(A_{xx} - A_{yy})$.

Some new data for the $^2H(d,p)$ and $^2H(d,n)$ reactions have recently been reported by König et al. Their comparison of the two reactions was performed at the back angles only ($\theta_{c.m.}$ $\leq 100^\circ$) for the only point of overlap (4 MeV) with the present $^2H(d,n)$ data, due to the experimental technique employed. Differences similar to those presented here are shown in their work, though, as seen in this experiment, the larger differences are observed in the forward angular region.
Fig. III-15  Plot of Legendre polynomial fit parameters for $A_y$
for the $^2\text{H}(\bar{d},n)^3\text{He}$ and $^2\text{H}(\bar{d},p)^3\text{H}$ reactions.
LEGENDRE POLYNOMIAL FIT
PARAMETERS FOR $A_\gamma$

Fig. III-15
Fig. III-16  Plot of Legendre polynomial fit parameters for $A_{zz}$ for the $^2H(d,n)^3He$ and $^2H(d,p)^3H$ reactions.
LEGENDRE POLYNOMIAL FIT
PARAMETERS FOR $A_{zz}$

Fig. III-16
Fig. III-17  Plot of Legendre polynomial fit parameters for $A_{xz}$ for the $^2\text{H}(\vec{d}, \text{n})^3\text{He}$ and $^2\text{H}(\vec{d}, \text{p})^3\text{H}$ reactions.
LEGENDRE POLYNOMIAL FIT
PARAMETERS FOR $A_{xz}$

Fig. III-17
Fig. III-18  Plot of Legendre polynomial fit parameters for $\frac{1}{2}(A_{XX}-A_{YY})$ for the $^2\text{H}(\vec{d},n)^3\text{He}$ and $^2\text{H}(\vec{d},p)^3\text{H}$ reactions.
LEGENDRE POLYNOMIAL FIT
PARAMETERS FOR $\frac{1}{2}(A_{xx} - A_{yy})$

$\omega H(d,n)$
$\times \omega H(d,p)$

Fig. III-18
 CHAPTER IV

SUMMARY

This set of experiments was performed in order to investigate differences in the polarization observables for charge symmetric reactions and to provide new information for the Los Alamos R-matrix searches for the energy level structure of the four and five nucleon systems. Because of the complexity and scope of the R-matrix calculation effort which is necessary to understand completely these nuclear systems, final results cannot be obtained here. Preliminary results will be presented and discussed in this chapter.

IV-A  Comparison of the Charge Symmetric $^2\text{H}(d,n)^3\text{He}$ and $^2\text{H}(d,p)^3\text{H}$ Reactions

Differences in the analyzing powers for the charge symmetric $^2\text{H}(d,n)^3\text{He}$ and $^2\text{H}(d,p)^3\text{H}$ reactions were presented in Chapter III by directly comparing the analyzing powers, and by comparing the Legendre polynomial fit parameters which include cross section information for the two reactions. The Legendre polynomial fit parameters show large differences between the two reactions for $A_{xz}$, less severe differences for $A_{zz}$, differences at energies below 3 MeV for $A_y$ and practically no differences for $\frac{1}{2}(A_{xx}-A_{yy})$. Because the observed differences are
generally due to magnitude rather than shape differences, it is quite clear that a simple ad hoc shift of the energy scale to make a comparison at equal exit channel energies as suggested by Hardekopf et al.\textsuperscript{1)} for the polarization data would not remove these differences.

In an attempt to understand the differences between $A_{zz}(0^\circ)$ for the \textsuperscript{2}H(d,n) and \textsuperscript{2}H(d,p) reactions Arnold\textsuperscript{56}) has suggested a simple spin transfer formalism which assumes that the reaction is basically a stripping process. This formalism reproduces the result that the ratio of the (d,p) and (d,n) analyzing powers is relatively constant over the entire energy range of this experiment but this calculated ratio differs by 10\% from the observed ratio.

The R-matrix analysis at Los Alamos, which has only recently been expanded to include reactions in the d+D entrance channel, has generated predictions for $A_{zz}(0^\circ)$ for these two reactions which essentially reproduce the ratio of the analyzing powers, but is seriously wrong about the magnitudes.

These experiments, then, have measured and compared the analyzing powers for two reactions where charge symmetry is expected to hold because Coulomb effects are small. The experiments were performed at low energies where Coulomb effects should have the greatest effect to see if the question of whether or not there is a breaking of charge symmetry can be resolved. The question will not be settled easily, however. The ultimate determination must await results of the charge independent R-matrix calculation to see if that can adequately describe the data from this experiment and from all other reaction channels with a consistent set of level parameters. Only if the data cannot be
described in this fashion can one say that there may be a violation of charge symmetry.

It is not possible therefore to say that the observed differences between the $^2\text{H}(d,n)$ and $^2\text{H}(d,p)$ analyzing powers are in fact a violation of charge symmetry in nuclear reactions. Different approaches to understanding these reactions indicate that the observables should, in fact, be different. The situation is as yet unresolved, and a final determination must await further results of the R-matrix calculations to see if they can reproduce the observed differences.

IV-B R-Matrix

As stated in the previous section, the four nucleon R-matrix search has only recently been expanded to include the d+D reactions. Initial attempts to fit cross section data for the $^2\text{H}(d,p)^3\text{He}$ and $^2\text{H}(d,n)^3\text{He}$ reactions at low energies have not been entirely successful. However, the R-matrix analysis has not included the $^2\text{H}(d,n)$ analyzing power data reported here. When the present data set is included in the analysis the expanded data base may provide enough information to produce better agreement with the observed results. An indication of the impact the data reported here will have on the R-matrix analysis can be seen in figs. IV-1 through IV-4 which show the $^2\text{H}(d,n)$ analyzing power data, Legendre polynomial fits to the data, and the R-matrix predictions\(^{20}\) for $A_y$, $A_{zz}$, $A_{xz}$ and $\frac{1}{2}(A_{xx}-A_{yy})$ respectively. The R-matrix predictions are only very preliminary calculations made without benefit of the present data set. The agreement with the $A_{xz}$ data is quite good, as is the agreement with the $A_y$ and $\frac{1}{2}(A_{xx}-A_{yy})$ data at
Fig. IV-1 \( A_y \) data for the \(^2H(\alpha,n)\)\(^3He\) reaction with R-matrix prediction.
$^2\text{H} (\bar{d}, n)^3\text{He}$

1.5 MeV
- $^2\text{H}(d, n)$
- $^2\text{H}(d, n)$
- $\text{R-MATRIX}$

2.0 MeV
- $^2\text{H}(d, n)$
- $^2\text{H}(d, n)$
- $\text{R-MATRIX}$

2.5 MeV
- $^2\text{H}(d, n)$
- $^2\text{H}(d, n)$
- $\text{R-MATRIX}$

3.0 MeV
- $^2\text{H}(d, n)$
- $^2\text{H}(d, n)$
- $\text{R-MATRIX}$

3.5 MeV
- $^2\text{H}(d, n)$
- $^2\text{H}(d, n)$
- $\text{R-MATRIX}$

4.0 MeV
- $^2\text{H}(d, n)$
- $^2\text{H}(d, n)$
- $\text{R-MATRIX}$

$\theta_{c.m.}$

Fig. IV-1
Fig. IV-2 $A_{zz}$ data for the $^2H(d,n)^3He$ reaction with R-matrix prediction.
Fig. IV-2
Fig. IV-3  \( A_{xz} \) data for the \(^2\text{H}(d,n)^3\text{He} \) reaction with R-matrix prediction.
$^3\text{H}(d,n)^3\text{He}$

1.5 MeV
$^3\text{H}(d,n)$
$\cdots$ R-MATRIX

3.0 MeV
$^3\text{H}(d,n)$
$\cdots$ R-MATRIX

2.0 MeV
$^3\text{H}(d,n)$
$\cdots$ R-MATRIX

3.5 MeV
$^3\text{H}(d,n)$
$\cdots$ R-MATRIX

2.5 MeV
$^3\text{H}(d,n)$
$\cdots$ R-MATRIX

4.0 MeV
$^3\text{H}(d,n)$
$\cdots$ R-MATRIX

Fig. IV-3
Fig. IV-4 \[ \frac{1}{2} (A_{xx} - A_{yy}) \] data for the \[^2\text{H}(\vec{d},n)^3\text{He}\] reaction with \(R\)-matrix prediction.
Fig. IV-4
lower energies. The predictions for the latter two analyzing powers deteriorate significantly at the energies above 2.5 MeV. The $A_{zz}$ predictions, however, differ dramatically from the measured data in both magnitude and shape at all energies. Clearly, the present data set will influence future analysis of the four nucleon system.

A separate R-matrix search for the $^5\text{He}$ and $^5\text{Li}$ five nucleon system level structures is also in progress at Los Alamos.\textsuperscript{20} Predictions for the tensor analyzing power $A_{zz}(0^\circ)$ for the $^3\text{He}(d,p)^4\text{He}$ and $^3\text{H}(d,n)^8\text{He}$ reactions are shown in figs. IV-5 and IV-6 respectively, along with the measured data.

The predictions for the $^3\text{He}(d,p)$ reaction have been influenced principally by the data of Schmelzbach \textit{et al.}\textsuperscript{29} Since the differences between their data and the data reported here are small, the inclusion of this new data in the analysis should have little effect except at energies below 2 MeV where possible depolarization problems in tandem accelerators, as discussed in Chapter I, may render the low energy data of Schmelzbach \textit{et al.}\textsuperscript{29} suspect.

The $^3\text{H}(d,n)$ R-matrix predictions, along with the measured data are shown in fig. IV-6. The R-matrix analysis has had less data to search on in this energy range and has been guided principally by the data of Sunier \textit{et al.} at 7 MeV, which consist of angular distributions of vector and tensor analyzing powers plus some polarization transfer coefficients. Inclusion of the data reported here as well as that of Lisowski \textit{et al.}\textsuperscript{28} should definitely affect the future analysis of this system.
Fig. IV-5 \( A_{zz}(0^\circ) \) for the \(^3\)He(\(d,p\))\(^4\)He reaction with R-matrix prediction.
$^3\text{He} (d, p)^4\text{He}$

**Fig. IV-5**

- **PRESENT WORK**
- **SCHMELZBACH**
- **SIMON**
- **GARRETT**

**LASL R-MATRIX**
Fig. IV-6 $A_{zz}(0^\circ)$ for the $^3H(\bar{d},n)^4He$ reaction with R-matrix prediction.
\[ ^3\text{H} (d,n) ^4\text{He} \]

Fig. IV-6

- PRESENT WORK
- LISOWSKI
- BROSTE
- SUNIER
- GRUNDER
- LASL R-MATRIX

\[ A_{zz}(0^\circ) \]

\[ E_d (\text{MeV}) \]
IV-C Conclusion

The new data provided by this experiment for the $^2$H(d,n)$^3$He reaction should greatly aid the understanding of the four nucleon system through the charge independent R-matrix calculation effort. The data will clearly have an impact on the calculations as is evident from the preliminary results presented in this chapter. The present understanding of the five nucleon systems will also be increased: the $^5$Li structure presently known is reinforced by the $^3$He(d,p)$^4$He data, and the $^5$He structure requires some modification due to the present $^3$H(d,n)$^4$He results. The question of whether the differences in the mirror or charge symmetric reactions can be explained as merely arising from Coulomb effects requires a complete R-matrix analysis. The magnitude of this calculation effort may best be characterized by the fact that for the four nucleon system there are 5000 data points to search on for $E_D < 5$ MeV, and for the five nucleon system there are 10,000 data points to search on for $E_D < 10$ MeV. The analysis routine makes full use of the entire core of the CDC 7600 computer at Los Alamos.

Finally, the $^3$He(d,p)$^4$He reaction has been calibrated as a secondary standard polarimeter for both the tensor and vector polarized deuteron beam from the O.S.U. polarized ion source. It is an excellent reaction for this purpose since it has a large, slowly varying analyzing power, $A_{zz}(0^\circ)$, over the entire energy range of the accelerator at this lab. The proton spectra are very clean because the high $Q$-value of the reaction effectively isolates the proton peak from any possible contaminant peaks in the spectrum. And the measurement is easily
performed with a single charged particle detector. This reaction, then will serve as the polarization monitor for the future experimental program at this lab using polarized deuterons.
LIST OF REFERENCES


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37. NE213 is a scintillator available from Nuclear Enterprises, Inc., San Carlos, California, and is especially suited for n-γ discrimination techniques.

38. 56DVP photomultiplier tubes are available from Amperex Corp., Hicksville, N.Y.

39. Havar is a trade name for a foil fabricated by the Hamilton Watch Co., Lancaster, Pa., and is a Co-Fe-Ni alloy.


48. R. Detomo, Jr., private communication.


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