Radiative Capture of Tensor and Vector Polarized Deuterons by Tritium at 8.6 MeV and 400 keV

by

John Charles Riley

Department of Physics
Duke University

Date: September 18, 1989

Approved:

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Henry R. Weller, Supervisor

Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics in the Graduate School of Duke University

1989
ABSTRACT

(Physics-Nuclear)

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Abstract

The $^3\text{H}(d,\gamma)^5\text{He}$ reaction was studied at 8.6 MeV and 400 keV using polarized and unpolarized beams to deduce the relative strengths of the $S = 3/2$ and $S = 1/2$ channels. The absolute differential cross section $\sigma(\theta)$, $A_\gamma(\theta)$, and $T_{20}(\theta)$ were measured at $E_d=8.6$ MeV and the differential cross section $\sigma(\theta)$, $A_\gamma(\theta)$, and $A_{\gamma\gamma}(\theta)$ were measured at 400 keV.

The $a_k$, $b_k$, and $c_k$ coefficients of Legendre polynomial expansions of the observables were extracted at both energies. A T-matrix analysis of the $E_d=400$ MeV data indicates 95% $S = 3/2$ (E1) strength, with 2.5% $S = 1/2$ (E1) and 2.5% M1 strength present.

A direct capture E1 calculation was performed at 8.6 MeV and was in good agreement with the experimentally determined coefficients when a spin-orbit interaction was included. The results of this comparison indicated that the ground state of $^5\text{He}$ consisted of 88-100% $S = 3/2$ strength. This result was also consistent with the 95% $S = 3/2$ (E1) strength found by the T-matrix analysis of the low energy data.
This dissertation is dedicated to
my family,
who always believed in me and encouraged me
in all my endeavors for these many years.
Thanks most of all to Dr. Grace Mendez, my wife, for all of the love and support she has given me over the last three years. Without her this dissertation could never have come to fruition.

I also thank my advisor, Dr. Henry R. Weller, for giving me a chance when others would not and standing by me in times of need. His support and contributions to my education have been tremendous and much appreciated.

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# Table of Contents

Abstract ................................................................. iii  
Acknowledgements ....................................................... v  
List of Figures ............................................................ vii  
List of Tables ............................................................. viii  
Chapter 1: Introduction ................................................. 1  
  2.1 Introduction .......................................................... 3  
  2.2 Beam ................................................................. 3  
  2.3 Detectors ............................................................. 7  
  2.4 Monitor Detectors .................................................... 12  
  2.5 Targets ............................................................... 15  
  2.6 Electronics ........................................................... 15  
  2.7 Measurement of Deuteron Energy at 400 kev .................. 19  
Chapter 3: Data Reduction .............................................. 29  
  3.1 Fitting and Summing Procedures ................................. 29  
  3.2 Scalar Corrections .................................................. 30  
  3.3 Corrected Data ....................................................... 31  
Chapter 4: Experimental Results ..................................... 46  
  4.1 $\sigma(\theta)$, $A_{1Y}(\theta)$, and $T_{20}(\theta)$ at 8.6 MeV .......... 46  
  4.2 $\sigma(\theta)$, $A_{1Y}(\theta)$, and $A_{2Y}(\theta)$ at 400 keV ............ 65  
Chapter 5: Transition Matrix Analysis of Data at $E_{d} = 400$keV .................. 81  
Chapter 6: Direct Capture Calculations at 8.6 MeV ............. 94  
Chapter 7: Conclusions .................................................. 106  
Appendix ........................................................................ 107  
List of References ....................................................... 108
List of Figures

2-1 Triangle Universities Nuclear Laboratory ........... 5
2-2 $E_d$ after degrading foils ............................ 9
2-3 Chamber used at low energies ....................... 11
2-4 NaI detector system ................................. 13
2-5 Electronics diagram .................................. 17
2-6 TAC spectrum ........................................ 21
2-7 NaI energy spectrum ................................... 23
2-8 $E_d$ after degrading foils ............................ 25
2-9 Polarization on target ............................... 28
4-1 Absolute cross section at 8.6 MeV ................. 52
4-2 $A_y$ at 8.6 MeV .................................... 54
4-3 $T_{20}$ at 8.6 MeV .................................... 56
4-4 Legendre polynomial fit to cross section ......... 58
4-5 Legendre polynomial fit to $A_y$ ..................... 61
4-6 Legendre polynomial fit to $T_{20}$ ................... 63
4-7 Unnormalized yield at 400 keV ..................... 68
4-8 $A_y$ at 400 keV ..................................... 69
4-9 $A_{yy}$ at 400 keV ................................... 72
4-10 Legendre polynomial fit to yield .................... 75
4-11 Legendre polynomial fit to $A_y$ .................... 77
4-12 Legendre polynomial fit to $A_{yy}$ .................. 79
5-1 Angular momentum coupling ......................... 83
5-2 TME fits to $\sigma(\theta)$, $A_y(\theta)$, $A_{yy}(\theta)$ at 400 keV........ 89
6-1 Direct capture calculation without spin-orbit .... 99
6-2 Direct capture calculation with spin-orbit ........ 104
List of Tables

3-1 Corrected sums for $\sigma(\theta)$ and $A_y(\theta)$ at 8.6 MeV..........32
3-2 Corrected sums for $T_{20}(\theta)$ at 8.6 MeV..................35
3-3 Corrected sums for $\sigma(\theta)$ at 400 keV......................38
3-4 Corrected sums for $A_y(\theta)$ and $A_{yy}(\theta)$ at 400 keV......40
4-1 $\sigma(\theta)$, $A_y(\theta)$ and $T_{20}(\theta)$ at 8.6 MeV.............57
4-2 Coefficients from Legendre polynomial expansion
               at 8.6 MeV...64
4-3 $A_y(\theta)$ and $A_{yy}(\theta)$ at 400 keV........................73
4-4 Coefficients from Legendre polynomial expansion at
               400 keV...80
5-1 Results of TME analysis.........................................87
5-2 Comparison of Legendre Coefficients.........................92
6-1 Optical Model parameters (no spin-orbit)...........97
6-2 Optical Model parameters (with spin-orbit)......101
Chapter 1

Introduction

The capture reaction $^3\text{H}(d,\gamma)^5\text{He}$ has been a largely unexamined reaction despite the relative simplicity of the $A=5$ system. Previous work on the reaction was performed with unpolarized beams measuring cross sections and $\sigma(d,\gamma)/\sigma(d,n)$ branching ratios below $E_d = 1$ MeV [Buss, 1963; Kosiara, 1970; Bezotsnyi, 1975; Cecil, 1985; Morgan, 1986] and cross section measurements for $E_d = 2-12$ MeV [Batay-Csorba, 1975]. Angular distributions have not been measured before. There have also been no previous studies of this reaction using polarized beams, a need which the present work attempts to fill.

$^3\text{H}(d,\gamma)^5\text{He}$ is a difficult reaction technically to make measurements on because of several factors. First, tritium is a highly radioactive gas that is difficult to make into a suitable target that can be safely handled and stored. The targets used in these experiments were tritiated titanium foils for ease of handling and to minimize safety concerns, although at the expense of having the spectra contaminated by background resulting from the titanium. Another difficulty in this experiment is the tremendous neutron flux produced in the $^3\text{H}(d,n)^4\text{He}$ reaction, especially at the lower energy measured here and at forward angles at 8.6 MeV. The techniques of handling this problem are addressed in Chapter 2.

Both polarized and unpolarized beams were used at 8.6 MeV and 400 keV to measure tensor and vector analyzing powers of the reaction, an absolute differential cross section at 8.6 MeV and a differential cross section at 400 keV. The objectives were to deduce how much strength was carried by each of the channels of the reaction and to gain
insight into the spin structure of the ground state of $^5\text{He}$. Polarized beams have proven themselves to be very powerful tools in investigating light nuclei, and made it possible to understand much about the $^3\text{H}(d,\gamma)^5\text{He}$ reaction.

This dissertation will describe the methods used to investigate the $^3\text{H}(d,\gamma)^5\text{He}$ reaction, present the results of this investigation, interpret those results, and draw conclusions from them.
Chapter 2

Experimental Techniques and Equipment

2.1 Introduction

The data in this thesis were taken at TUNL; a schematic diagram showing the layout of the laboratory is shown in Figure 2-1. Polarized and unpolarized deuterons incident on a tritiated Titanium foil were used to study the $^3\text{H}(d,\gamma)^5\text{He}$ reaction at $E_d = 8.6 \text{ MeV}$ and $400 \text{ keV}$. The absolute differential cross section, $T_{20}(\theta)$ and $A_y(\theta)$ were measured at seven angles in the experiment at $8.6 \text{ MeV}$. In the experiments at $400 \text{ keV}$, the differential cross section was measured at nine angles, and $A_{yy}(\theta)$ and $A_y(\theta)$ were measured at seven angles. Polarized deuterons were supplied by the TUNL Polarized Ion Source (PIS) and the unpolarized deuterons were supplied by the TUNL Direct Extraction Negative Ion Source (DENIS). The deuterons were accelerated by a Type FN Tandem Van de Graaff accelerator. The operation and characteristics of the ion sources and accelerators have been described in publications [Newson, 1974; Clegg, 1974]. The resulting $\gamma$-rays were detected by two $25.4 \text{ cm} \times 25.4 \text{ cm}$ cylindrical NaI detectors. The following sections of this chapter deal with the beam transportation, detectors involved, targets used, and electronic and software sorting techniques used to obtain the desired $\gamma$-ray spectra.

2.2) Beam

Both the unpolarized and polarized beams were pulsed prior to injection into the Tandem Van de Graaff. The unpolarized deuterons were passed through a radio frequency
Figure 2-1: Triangle Universities Nuclear Laboratory
Triangle Universities Nuclear Laboratory (TUNL)
chopper and a double drift buncher, producing a 2 ns beam burst with a repetition rate of 2 MHz. The polarized deuterons were ramped in the duoplasmatron of the source, then sent through a double drift buncher and a chopper (Wender, 1980), producing a beam burst of 2-3 ns at a repetition rate of 4 MHz. The beams were then accelerated through a model FN tandem Van de Graaff. After acceleration, the beam passed through a pair of 90 degree magnets used for energy analysis and a 30 degree switching magnet to get to target room 4 (Figure 2-1), where the experimental area was located. At a point just before the target chamber, the beam passed through a 7.6 cm long x 1.0 cm diameter copper tube serving as a capacitive pickup, providing a stop signal for a time-to-amplitude converter used for time-of-flight measurements. In the experiments done at 8.6 MeV, the beam then passed through a 0.25 cm diameter hole in a tantalum disk for collimation, passed through the target foil and into the tantalum Faraday cup, which was located 2 m behind the laboratory wall. The collimator current was minimized and usually kept in the 1 to 2 nA range. Beam currents on target ranged from 60 to 100 nA in the case of polarized beam, with a typical polarization of 60 %, measured by the quench-ratio method before the first 90 degree magnet. Beam current was limited to 140 nA in the case of unpolarized beam because of count rate limitations in the NaI spectrometers. The integrated beam currents were used for cross section determination and relative normalization.

In the low energy experiments, a 3.375 MeV beam was passed through the same system as in the 8.6 MeV experiment until after the capacitive pickup. The beam then passed through a 0.4 cm diameter hole in a tantalum collimator, an electron suppression ring, a 1 mil Havar energy degrading foil, and was finally stopped in the target foil. The beam
energy after the degrading foil was approximately 400 keV with an energy spread of 200 keV FWHM (Figure 2-2). The procedure for degrading the beam and determining its energy and energy spread is described in section 2.7). The collimator current was usually held to less than 1 nA. The electron suppression ring and a small 2" diameter chamber (Figure 2-3) allowed us to integrate the beam on target for the purpose of relative normalization. Typical beam currents were similar to that above for unpolarized beam, but only 60 nA for the polarized beam because of the lower transmission through the accelerator at lower terminal voltages.

2.3) Detectors

Two 25.4 cm x 25.4 cm cylindrical NaI scintillators surrounded by NE 110 plastic [Suffert, 1968] anti-coincidence shields were used to detect the γ-rays in this experiment. These detectors were surrounded by 20 cm of lithium carbonate doped paraffin (50 % by weight) and 10 cm of lead. The paraffin moderates the neutron flux which is then attenuated by the high cross section for the $^6\text{Li}(n,\alpha)$ reaction at thermal neutron energies. Both detectors also had a 0.6 cm thick sheet of boron carbide doped plastic (50 % by weight) between the paraffin and lead and the right detector had a 0.15 cm sheet of cadmium in front of the boron doped plastic. Both boron and cadmium have high cross sections for thermal neutron absorption and were used for thermal neutron attenuation, having an attenuation factor of 10$^{11}$. Each detector had a tapered lead collimator that illuminated the rear face of the NaI crystal which was positioned at a distance of 108 cm from the center of the target chamber. The
Figure 2-2: Solid state detector spectrum of elastically scattered deuterons after passing through the degrading foil.
$E_{\text{cent}} = 400 \text{ keV}$

$\text{FWHM} = 200 \text{ keV}$
Figure 2-3: Chamber used in experiments at 400 keV. The diameter of the chamber is two inches.
resolution of each of these systems was about 3% for the 16.8 to 22.4 MeV \( \gamma \)-rays in these experiments [Weller, 1980]. The detection system for the experiment at \( E_d = 8.6 \) MeV is shown in Figure 2-4. In the experiment at \( E_d = 400 \) keV, tungsten shadow bars were used to shield the detectors from the energy degrading foil.

2.4) Monitor detectors

A silicon surface barrier detector was used as a monitor in the \( E_d = 8.6 \) MeV experiments. It was placed at forward angles from 50 to 70 degrees from the beam direction. The detector thicknesses used varied from 500 to 1500 microns, depending on the beam energy. Elastically scattered deuterons from tritium and titanium as well as recoil tritons were observed. Tantalum collimators with small holes in them were placed 2.5 cm from and directly in front of the detector. In the low energy experiments, a NE213 scintillator with tapered copper collimators was placed 260 cm from the target along the direction of the beam (0°). Pulse-shape discrimination was used to separate neutrons from \( \gamma \)-rays, and a time-of-flight spectrum was produced, showing the neutrons from the \( ^3\text{H}(d,n) \) reaction. These monitors were used as a check on the reliability of the charge integration by comparing the counts in the monitor with the charge collected in each run. The neutron monitor was also used to check for possible depolarization of the beam in the degrading foil and target. This will be discussed in section 2.7) of this chapter.
Figure 2-4: NaI detector system. The target chamber set-up shown here was used in obtaining the 8.6 MeV data.
2.5) Targets

The targets used in this experiment were tritiated titanium foils manufactured at Oak Ridge National Laboratory. The tritium was deposited one for one with the titanium atoms in the foil while the foil was heated. The target used in the experiments at 8.6 MeV had a tritium thickness of 240 \( \mu g/cm^2 \) [Feldman, 1989]. The tritium thickness was obtained by comparing a measured elastic scattering cross section to the known value [Brolley, 1960]. The target was monitored by a solid-state detector for possible loss of tritium due to beam heating, and no effect was observed. The target used in the low energy experiments was approximately four times thicker. Subtraction of the background resulting from the titanium will be discussed in the next chapter.

2.6) Electronics

A schematic diagram of the electronics used in this experiment is shown in Figure 2-5. Light from events in the NaI were collected by six gain matched RCA 8575 photomultiplier tubes. The outputs of these tubes were mixed to form one signal which was clipped to 350 ns by a partially terminated coaxial cable of appropriate length. This signal was fanned out to a fast linear gate and a TD101 differential discriminator. The discriminator outputs were used for timing information (from a lower gate) and energy discrimination. The signal for energy discrimination was passed through a gate generator which held the fast linear gate open for 400 ns and then closed for 10 \( \mu s \) to reduce signal pileup from the NaI detector.
Figure 2-5: Electronics used in $^3$H(d,$\gamma$)$^5$He experiment.
The signal was then amplified and passed through a gain stabilizer. The gain stabilizer monitored an LED pulser in the NaI, compensating for any gain shifts that occurred. This LED was subsequently gated out by a linear gate before the signal was sent to an ADC, in order to avoid dead time which it might cause in the computer.

Signals from the plastic shield surrounding the NaI were sent through a variable gain amplifier and a fast discriminator. The output of the discriminator was sent to a coincidence box along with the output of the NaI differential discriminator. Signals from both within 60 ns of one another cause a coincidence output to be generated. This signal was sent to an ADC and used for software sorting of the NaI signal into accepted and rejected spectra. Cosmic rays and events not depositing their full energy into the NaI were removed using this technique. A second coincidence circuit was set up, identical to the first except that the NaI differential discriminator signal was delayed by 330 ns, allowing us to correct for accidental coincidences, which varied from 1% to 12%.

A high neutron production cross section exists in the d-³H reaction, especially at forward angles at 8.6 MeV and isotropically at the lower energies used, necessitating the use of a time-of-flight (TOF) discrimination to remove the neutrons from the γ-ray spectrum. The output of the NaI differential discriminator was used to start a time-to-amplitude converter (TAC) which was stopped by a signal from the capacitive pickoff placed before the target chamber. The output from the TAC was sent to an ADC. The resulting spectrum showed a clear separation in time of the neutron and γ-ray events in the NaI. A logical gate set around the γ-ray peak was used in the software sorting of the NaI energy signal to give a spectrum corresponding to γ-rays in
the NaI. Using this TOF requirement allowed us to
discriminate between γ-ray and neutron events in the NaI, as
well as to reduce background that is uncorrelated in time.
A typical spectrum for the NaI-TOF-TAC and the resulting NaI
spectrum after background subtraction are shown in figures
2-6 and 2-7 respectively.

2.7) Measurement of deuteron energy at 400 keV.

The energy of the degraded deuteron beam was measured
by scattering it off a thin (10 mg/cm²) carbon foil and
measuring the energy of the scattered particles with a
calibrated silicon surface barrier detector of 100 micron
thickness. The calibration was performed by elastically
scattering deuterons of known energy off of the carbon foil
at several energies. The measurement of the energy of the
degraded beam was done starting with an incident deuteron
beam of 4 MeV and lowering the energy until an optimum of
beam transmission through the degrading foil, energy loss in
the degrading foil, and resolution in beam energy of the
resulting beam was reached. This optimum was a subjective
judgement that we were as close to the fusion resonance
region as possible while maintaining a decent current for
count rate purposes and having reasonable definition of the
energy of the beam. An energy spectrum from the silicon
detector is shown in Figure 2-8. This corresponds to the
conditions used for the experiment: the incident beam had an
energy of 3.375 MeV before passing through Havar foils
having a thickness of 1 mil (0.001"). There was a concern
that depolarization of the deuteron beam might occur during
the energy degrading and stopping in the target, so a
Figure 2-6: TAC spectrum. The left peak is the n's, and the right is the γ-rays. The time resolution of the γ-ray peak is 5 ns.
Figure 2-7: Energy spectrum for the NaI detector after background subtraction.
Figure 2-8: Solid state detector spectrum of deuteron energy after the degrading foil.
$E_{\text{cent}} = 100 \text{ keV}$

FWHM = 200 keV
measurement of the polarization of the beam was performed via the known analyzing power of the $^3\text{H}(d,n)^4\text{He}$ reaction \cite{Ohlsen, 1971; Grunder, 1971}. This was achieved by measuring the polarization at the energy used in the experiment, then lowering the incident deuteron energy in 20 keV steps and remeasuring the polarization until neutron production in the target ceased. No depolarization effects were observed. The results of this measurement are shown in Figure 2-9.
Figure 2-9: Polarization of the deuteron beam after degrading. The horizontal axis is the energy of the deuterons before the degrading foil. The circles represent measurements made using the m=1 and m=0 states of the deuteron. The crosses represent measurements made using the m=0 and m=-1 states of the deuteron.
CHAPTER 3

DATA REDUCTION

3.1 Fitting and summing procedures.

a) Background measurement and normalization

This experiment was performed using a tritiated titanium foil, necessitating measurement of the background resulting from the titanium so that it could be subtracted from the data. This was done by inserting a plain titanium foil of similar thickness to the tritiated titanium foil into the deuteron beam and counting with the NaI detectors, usually for 40% of the integrated charge (to obtain adequate statistical accuracy in the minimum time) used with the tritiated titanium foil. Corrections were made for the difference in integrated charge and for the slight difference in titanium foil thickness (note that the beam was stopped in the foil in the experiment at 400 keV, so that the thickness of the foreground and background foils was essentially equal.) The difference in thicknesses was measured by elastically scattering deuterons off of the titanium foils and collecting them in a solid-state silicon detector. The relative count rates, normalized by the total charge delivered to the target gave the ratio of the two titanium target thicknesses.

b) Summing Procedures

The summing of the $\gamma$-rays in the spectra was performed by the program Mulfit [King, 1983], which fits the peak of interest to an empirically determined $\gamma$-ray response [Turner, 1978], determining the centroid and the FWHM width of the peak. The program sums 1.1 widths up from the centroid of the peak and a variable number of widths below
the centroid. In the experiment measuring $\sigma(\theta)$ and $\lambda_y(\theta)$ at 8.6 MeV, the sum was carried out to 2.0 widths below the centroid. In the experiments measuring $T_{20}(\theta)$ at 8.6 MeV, the sum was done down to 1.0 widths below the centroid. For all of the experiments at $E_q = 400$ keV, the summing region was cut off at 0.5 widths below the centroid. The reason for summing less than 2 widths below the centroid in the above was to avoid background that was close to the $\gamma$-ray of interest. In the data at low energy, this was particularly a problem because of the large isotropic neutron flux.

3.2 Scaler Corrections

Several scalers were used for the purpose of correcting the data. The dead time in the ADC was corrected for by counting the number of gates used on the linear $\gamma$-ray signal previous to the ADC in a scaler and comparing this number to the number of events digitized by the ADC and stored in the spectrum. This correction varied from less than 1% to about 3%.

Accidental coincidences between the NaI and its surrounding shield were corrected for by storing two scalers that counted the number of real coincidences and the number of accidental coincidences. These numbers were used to correct the observed data by the factor

$$\frac{\text{COINCIDENCES}}{\text{COINCIDENCES-ACCIDENTALS}}$$

3-1
to get the actual number of counts that would have been seen in the absence of accidental coincidences. This correction dominated the correction factor used by the program Mulfit. This correction ranged between 2% and 15% with a typical value of 6% under normal conditions. An effort was made to hold this correction under 10% at all
times, but, occasionally, this was impossible because of the amount of beam needed to have the capacitive pickoff unit for TOF measurements function properly.

A correction for missed pickoffs in the TOF system was also made by counting the number of pickoffs and the amount of live time in the run with scalers. The number of pickoffs was compared to the frequency of the beam bunching multiplied by the time scaler to get the correction factor. This correction was generally held to 1% or less.

3.3 Corrected Data

The net sums of the γ-ray peak after background subtraction and corrections discussed in this chapter are presented in tables at the end of this section. Along with the corrected sums, the background sum, the correction factors for the foreground and background sums, and the BCI (integrated current) scaler for the foreground and background are presented. In subsequent calculations, the sums at 90 degrees have been corrected for the difference in target thickness caused by rotating the target so that it was not edge-on to the detector.
Table 3-1: Corrected sums from the $\sigma(\theta)$ and $\Lambda_y(\theta)$ measurements at 8.6 MeV. The columns from left to right are: 1) laboratory angles of the right and left detectors; 2) the run number; 3) detector (right or left); 4) spin state (up or down); 5) beam current integrated with target foil in; 6) beam current integrated with background foil in; 7) correction factor used on data sum; 8) correction factor used on background; 9) data sum after corrections and background subtraction; 10) background that was subtracted.
Table 3-2: Corrected sums from the $T_{20}(\theta)$ measurements at 8.6 MeV. The columns from left to right are: 1) laboratory angles of the right and left detectors; 2) the run number; 3) detector (right or left); 4) spin state ($m=1$ or $2$); 5) beam current integrated with target foil in; 6) beam current integrated with background foil in; 7) correction factor used on data sum; 8) correction factor used on background; 9) data sum after corrections and background subtraction; 10) background that was subtracted.
Table 3-3: Corrected sums from the differential cross section measurements at 400 keV. The columns from left to right are: 1) run number; 2) laboratory angles of the right and left detectors; 3) detector (right or left); 4) beam current integrated with target foil in; 5) correction factor used on data sum; 6) correction factor used on background; 7) data sum after corrections and background subtraction; 8) background that was subtracted; 9) the ratio of the target foil BCI to the background foil BCI.
Table 3-4: Corrected sums from the $\lambda_y(\theta)$ and $\lambda_{yy}(\theta)$ measurements at 400 keV. The columns from left to right are: 1) laboratory angles of the right and left detectors; 2) the run number; 3) spin state (state $m=1,2,3$) (up or down); 4) detector (right or left); 5) beam current integrated with target foil in; 6) correction factor used on data sum; 7) correction factor used on background; 8) data sum after corrections and background subtraction; 9) background that was subtracted; 10) ratio of target foil BCI to background foil BCI.
Chapter 4

Experimental Results

4.1 $\sigma(\theta), A_\gamma(\theta)$, and $T_{20}(\theta)$ at 8.6 MeV

The absolute cross section, as a function of angle and energy, is given by

$$\sigma(\theta,E) = \frac{N_\gamma(\theta,E)}{N_d N_t \Omega \varepsilon},$$

4.1

where $N_\gamma$ is the number of counts of the $\gamma$-ray of interest in the detector, $N_d$ is the number of deuterons incident on the target, $N_t$ is the number of tritium nuclei/cm$^2$, $\Omega$ is the solid angle of the detector, and $\varepsilon$ is the detector efficiency.

$N_\gamma$ was determined by methods discussed in the previous chapter. In all of these experiments, $\Omega$ was 0.045 sr for the distance of 41.75 inches between the target and the rear face of the NaI detector. $\varepsilon$ is defined as the ratio of the observed $\gamma$-rays, $N_\gamma$, to the actual number of $\gamma$-rays entering the detector. The method used to determine the efficiency has been previously published [Weller, 1980]. The efficiency of the right NaI in this experiment was 0.21 for a $\gamma$-ray energy of 22 MeV. The left NaI was normalized to the right.

Some systematic errors are involved in the absolute cross section. $N_\gamma$ is estimated to have an uncertainty of 10% due to the choice of summing region. The product $\Omega \varepsilon$ is estimated to have an uncertainty of 10%. Due to non-uniformities in the target, and possible movement of the beam spot on target, $N_t$ is estimated to have an uncertainty
of 10%. Checks on charge integration have indicated that an uncertainty of 1% is involved due to charge that did not enter the Faraday cup and drift in the charge integrator. Propagation of these uncertainties implies that the systematic error in the absolute cross section is on the order of 17%.

For a spin-one incident particle, the differential cross section is given by [Seyler and Weller, 1979]

\[ \sigma(\theta, \phi) = \sigma(\theta)[1 + \frac{3}{2} \, p_y \, A_y(\theta) + t_{2c} \, T_{2c}(\theta) + 2 \Re t_{21} \, T_{21}(\theta) + 2 \Re t_{22} \, T_{22}(\theta)] \]

4-2

Expansion in terms of Legendre and associated Legendre polynomials gives

\[ \sigma(\theta, \phi) = A_0 \sum_{k=0}^{\infty} \left[ a_k P^k_x(\cos \theta) + b_k P^1_x(\cos \theta) + c_k t_{20} P^0_x(\cos \theta) \right. \\
\left. + d_k \Re t_{21} P^1_x(\cos \theta) + e_k \Re t_{22} P^2_x(\cos \theta) \right] \]

4-3

where the Legendre polynomials used are given by (using \( x = \cos(\theta) \))

\[ P_n(x) = \frac{1}{2^n n!} \frac{d^n}{dx^n}(x^2 - 1)^n, \text{where } n = 0, 1, 2, \ldots \]

4-4

and the associated Legendre polynomials are given by

\[ P_n^m(x) = (1 - x^2)^{m/2} \frac{d^m}{dx^m} P_n(x) \]

4-5

The following notation is used to define the coordinate system of this experiment:
4-6 \( \mathbf{k}_{\text{in}} \) = direction of propagation of incoming particle
\( \mathbf{k}_{\text{out}} \) = direction of propagation of outgoing particle
\( \mathbf{y} = \mathbf{k}_{\text{in}} \times \mathbf{k}_{\text{out}} \) (in a right-handed coordinate system)
\( \mathbf{z} = \mathbf{k}_{\text{in}} \)
\( \mathbf{s} = \) polarization axis of the beam
\( \beta = \) angle between \( \mathbf{k}_{\text{in}} \) and \( \mathbf{s} \)
\( \phi = \) angle between the projection of \( \mathbf{s} \) in the \( \mathbf{y}-\mathbf{z} \) plane and the \( \mathbf{y} \) axis (\( \phi > 0 \) towards + \( \mathbf{x} \))

In this notation [Darden, 1970]:

\[ P_y = P_z \sin \beta \cos \phi \]

\[ t_{20} = \frac{P_{zz} \sqrt{3}}{2} \frac{3 \cos^2 \beta - 1}{\sqrt{2}} \]

\[ \text{Ret}_{21} = \frac{P_{zz} \sqrt{3}}{4} \sin 2\beta \sin \phi \]

\[ \text{Ret}_{22} = \frac{-P_{zz} \sqrt{3}}{4} \sin^2 \beta \cos 2\phi \]

for a deuteron beam, where \( P_z \) and \( P_{zz} \) are the vector and tensor polarizations, respectively.

For unpolarized beam, Equation 4-3 reduces to

\[ \frac{\sigma(\theta)}{A_0} = 1 + \sum_{k=l} a_k Q_k P_k \]

4-7

where the factor \( Q_k \) has been introduced as a correction for the finite size of the detector.

In order to obtain the \( b_x \) coefficients of Equation 4-3, the polarized source is run in states where \( P_{zz} = 0, \beta = 90^\circ, \phi = 0^\circ, \) and \( P_z = +1 \) for the state "+"; and \( \phi = 180^\circ, \) and \( P_z = -1 \) for the state "-". Taking Equation 4-3 for these cases and comparing with Equation 4-2, we obtain (noting that \( P_y^+ = -P_y^- = P_y \))
\[
\frac{3}{2} \frac{\sigma(\theta) A_y(\theta)}{A_0} = \sum_{k=1}^{N} b_k Q_k P_k^1 (\cos \theta)
\]

4-8

\[
A_y = \frac{2}{3} \frac{1}{P_y} \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}
\]

The TUNL Lamb-Shift PIS produces a beam polarization of \(P_y = -2Q/3\), where \(Q\) is the percentage beam polarization, when in this purely vector polarized deuteron mode.

Measuring the tensor analyzing power \(T_{20}(\theta)\) allowed us to obtain the \(c_k\) coefficients of Equation 4-3 by running the source in the mode where \(P_z \neq 0\), \(P_{zz} \neq 0\), \(\beta = 0\), and \(\phi\) is undetermined. In this mode \(P_y = \text{Ret}_{21} = \text{Ret}_{22} = 0\) and \(t_{20} = P_{zz}/\sqrt{2}\). We will call the tensor moment of hyperfine state \(m=1\) \(t_1\) and that of state \(m=0\) \(t_2\). Taking Equation 4-3 for the source in this mode and in these two states, and comparing to Equation 4-2, we obtain:

\[
\frac{T_{20}(\theta) \sigma(\theta)}{A_0} = \sum_{k=0}^{N} c_k Q_k P_k^1 (\cos \theta),
\]

4-9

\[
T_{20}(\theta) = \frac{\sigma_1 - \sigma_2}{\sigma_1 t_1 - \sigma_2 t_2}
\]

and

If we note that the polarizations of \(t_1\) \((P_{zz} = 1)\) and \(t_2\) \((P_{zz} = -2)\) make it convenient to express them as \(t_{20} = -2t_1 = t_2\) and that \(t_{20} = -Q/2\), where \(Q\) is the percentage polarization of the beam, we can express \(T_{20}(\theta)\) as

\[
T_{20}(\theta) = \frac{\sqrt{2}}{Q} \frac{\sigma_1 - \sigma_2}{2\sigma_1 + \sigma_2}
\]

4-10

Unpolarized differential cross section, vector analyzing power, and tensor analyzing power angular distributions were measured at seven angles at \(E_d = 8.6\) MeV and are shown in Figures 4-1, 4-2, and 4-3 respectively and given in Table 4-1. The polynomial fits described in
Equations 4-7, 4-8, and 4-9 are shown in Figures 4-4, 4-5, 4-6 respectively, and the coefficients derived are given in Table 4-2.
Figure 4-1: Absolute cross section at 8.6 MeV. \( \sigma(\theta) \) is given in \( \mu b/sr \). The error bars represent statistical uncertainties associated with the data points. The absolute cross section has an additional systematic error on the order of 17% (see text).
Figure 4-2: Vector analyzing power $A_y(\theta)$ at 8.6 MeV. The error bars represent statistical uncertainties associated with the data points.
Figure 4-3: Tensor analyzing power $T_{20}(\theta)$ at 8.6 MeV. The error bars represent statistical uncertainties associated with the data points.
<table>
<thead>
<tr>
<th>$\theta_{\text{cm}}$</th>
<th>ERROR $\Delta \chi^2(\theta)$</th>
<th>$\Delta \chi^2(\theta)$</th>
<th>ERROR $\Delta \chi^2(\theta)$</th>
<th>$\Delta \chi^2(\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>0.0082</td>
<td>0.47</td>
<td>0.112</td>
<td>0.02186</td>
</tr>
<tr>
<td>0.020</td>
<td>0.0088</td>
<td>0.45</td>
<td>0.119</td>
<td>0.02179</td>
</tr>
<tr>
<td>0.025</td>
<td>0.0070</td>
<td>0.44</td>
<td>0.118</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.030</td>
<td>0.0060</td>
<td>0.43</td>
<td>0.118</td>
<td>0.02161</td>
</tr>
<tr>
<td>0.035</td>
<td>0.0057</td>
<td>0.42</td>
<td>0.119</td>
<td>0.02172</td>
</tr>
<tr>
<td>0.040</td>
<td>0.0056</td>
<td>0.43</td>
<td>0.118</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.045</td>
<td>0.0051</td>
<td>0.42</td>
<td>0.118</td>
<td>0.02169</td>
</tr>
<tr>
<td>0.050</td>
<td>0.0049</td>
<td>0.42</td>
<td>0.118</td>
<td>0.02168</td>
</tr>
<tr>
<td>0.055</td>
<td>0.0046</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02171</td>
</tr>
<tr>
<td>0.060</td>
<td>0.0043</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.065</td>
<td>0.0040</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.070</td>
<td>0.0037</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.075</td>
<td>0.0034</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.080</td>
<td>0.0031</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.085</td>
<td>0.0028</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.090</td>
<td>0.0025</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.095</td>
<td>0.0022</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
<tr>
<td>0.100</td>
<td>0.0019</td>
<td>0.41</td>
<td>0.119</td>
<td>0.02170</td>
</tr>
</tbody>
</table>

Table 4-1: $\sigma(\theta)$, $\Delta \chi^2(\theta)$, $T_{20}(\theta)$ at $8.6 \text{ NeV}$. 
Figure 4-4: Legendre polynomial fit obtained using Equation 4-7 for $^3$H(d,γ)$^6$He at 8.6 MeV. The error bars represent statistical uncertainties associated with the data points. The solid line is the fit to the data.
Figure 4-5: Legendre polynomial fit obtained using Equation 4-8 for $^3\text{H}(d,\gamma)^5\text{He}$ at 8.6 MeV. The error bars represent statistical uncertainties associated with the data points. The solid line is the fit to the data.
Figure 4-6: Legendre polynomial fit obtained using Equation 4-9 for $^3\text{H}(d,\gamma)^5\text{He}$ at 8.6 MeV. The error bars represent statistical uncertainties associated with the data points. The solid line is the fit to the data.
Table 4-2: Coefficients from Legendre polynomial expansions at 8.6 MeV.

| \( n_1 = 0.112 \pm 0.014 \) | \( h_1 = -0.009 \pm 0.021 \) | \( c_0 = -0.0353 \pm 0.0090 \) |
| \( n_2 = -0.206 \pm 0.025 \) | \( h_2 = -0.053 \pm 0.014 \) | \( c_1 = -0.0371 \pm 0.0165 \) |
| \( \) | \( \) | \( c_2 = -0.0252 \pm 0.0306 \) |
4.2 $\sigma(\theta)$, $A_y(\theta)$, and $A_{yy}(\theta)$ at $E_d=400$keV

In the experiments at low energy, we measured an unnormalized differential cross section $\sigma(\theta)$ at nine angles and $A_y(\theta)$ and $A_{yy}(\theta)$ at seven angles. It should be noted that a deuteron beam with mixed vector and tensor polarizations was used and the tensor analyzing power $A_{yy}(\theta)$ was measured simultaneously with $A_y(\theta)$. With this type of beam, $P_y$ is $Q$, the percentage polarization of the beam and all three hyperfine states are used to measure $A_y(\theta)$ so that the second part of Equation 4-8 becomes

$$A_y = \frac{1}{P_y} \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_2 + \sigma_3}$$

4-11

The cartesian analyzing power $A_{yy}(\theta)$ is related to the spherical tensors by

$$A_{yy}(\theta) = \frac{-1}{\sqrt{2}} \ T_{20}(\theta) - \sqrt{3} \ T_{22}(\theta)$$

4-12

Measurement of $A_{yy}(\theta)$ allows us to obtain information about the $c_k$ and $e_k$ coefficients of Equation 4-3 by running the source in the mode where $P_z \neq 0$, $P_{zz} \neq 0$, $\beta=90$, $\phi=0$. With this precession of the beam, $P_y=P_z$, $t_{20}=-P_{zz}/2\sqrt{2}$, $t_{21}=0$, $t_{22}=-\sqrt{3}P_{zz}/4$. Taking Equation 4-3 for states 1, 2, and 3 (hyperfine states $m=1$, 0, -1, respectively), and comparing Equation 4-3 with 4-2, we can write from Equation 4-11

$$\frac{\sigma(\theta)A_{yy}(\theta)}{A_0} = \frac{-1}{\sqrt{2}} \sum_{k=0} c_k Q_k P_k(\cos\theta) - \frac{\sqrt{3}}{2} \sum_{k=2} e_k Q_k P_k^2(\cos\theta),$$

and

$$A_{yy}(\theta) = \frac{1}{P} \frac{\sigma_1 + \sigma_3 - 2\sigma_2}{\sigma_1 + \sigma_2 + \sigma_3}$$

4-13

65
It must be noted here that it was not possible to extract the $c_k$ and $e_2$ from the data due to the fact that $P^2_2$ is not orthogonal to the $P_k$. Since the $c_k$ dominate, the fit given by equation 4-13 was performed without the $e_k$. However, it was possible to find the $e_k$ by writing the coefficients in terms of amplitudes and phases of the transition matrix elements; this analysis will be presented in Chapter 5.

The differential cross section, $A_y(\theta)$, and $A_yy(\theta)$ are shown in Figures 4-7, 4-8, 4-9, respectively and $A_y(\theta)$, and $A_yy(\theta)$ are given in Table 4-3. The fits described by the polynomial expressions in equations 4-7, 4-8, and 4-13 are shown in Figures 4-10, 4-11, 4-12, respectively and the coefficients derived are given in Table 4-4.
Figure 4-7: Unnormalized yield $\sigma(0)/A_0$ at 400 keV. The error bars represent statistical uncertainties associated with the data points.
YIELD (θ) (unnormalized)
Figure 4-8: Vector analyzing power \( A_y(\theta) \) at 400 keV. The error bars represent statistical uncertainties associated with the data points.
Figure 4-9: Tensor analyzing power $A_{yy}(\theta)$ at 400 keV. The error bars represent statistical uncertainties associated with the data points.
<table>
<thead>
<tr>
<th>$\theta_{\text{FM}}$</th>
<th>$\Delta \gamma(\theta)$</th>
<th>Error $\Delta \gamma(\theta)$</th>
<th>$\Delta \gamma_y(\theta)$</th>
<th>Error $\Delta \gamma_y(\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.821</td>
<td>0.047</td>
<td>0.024</td>
<td>0.218</td>
<td>0.032</td>
</tr>
<tr>
<td>50.364</td>
<td>-0.014</td>
<td>0.016</td>
<td>0.158</td>
<td>0.022</td>
</tr>
<tr>
<td>70.446</td>
<td>0.029</td>
<td>0.012</td>
<td>0.120</td>
<td>0.100</td>
</tr>
<tr>
<td>90.474</td>
<td>0.0095</td>
<td>0.037</td>
<td>0.164</td>
<td>0.120</td>
</tr>
<tr>
<td>110.445</td>
<td>0.0095</td>
<td>0.016</td>
<td>0.148</td>
<td>0.022</td>
</tr>
<tr>
<td>130.362</td>
<td>0.011</td>
<td>0.016</td>
<td>0.079</td>
<td>0.022</td>
</tr>
<tr>
<td>137.819</td>
<td>-0.044</td>
<td>0.027</td>
<td>0.099</td>
<td>0.037</td>
</tr>
</tbody>
</table>
Figure 4-10: Legendre polynomial fit obtained using Equation 4-7 for $^3\text{H}(d,\gamma)^5\text{He}$ at 400 keV. The error bars represent statistical uncertainties associated with the data points. The solid line is the fit to the data.
Figure 4-11: Legendre polynomial fit obtained using Equation 4-8 for $^3$H(d,$\gamma)^5$He at 400 keV. The error bars represent statistical uncertainties associated with the data points. The solid line is the fit to the data.
Figure 4-12: Legendre polynomial fit obtained using Equation 4-13 for \(^3\text{H}(d,\gamma)^5\text{He}\) at 400 keV. The error bars represent statistical uncertainties associated with the data points. The solid line is the fit to the data.
TABLE 4-4

Coefficients from Legendre polynomial expansions at 400 keV

\[
\begin{align*}
a_1 &= 0.002 \pm 0.011 \\
a_2 &= 0.018 \pm 0.017 \\
b_1 &= -0.024 \pm 0.012 \\
b_2 &= -0.005 \pm 0.008 \\
c_0 &= -0.203 \pm 0.016 \\
c_1 &= -0.091 \pm 0.028 \\
c_2 &= 0.058 \pm 0.070 \\
\end{align*}
\]
Chapter 5

TRANSITION MATRIX ELEMENT ANALYSIS OF DATA AT $E_d = 400$ keV

In chapter 4, the data for cross-section and analyzing powers were fit to Legendre and associated Legendre coefficients. Further analysis of the data is possible by performing a transition matrix element analysis. In this analysis, all of the differential cross section, $A_y(\theta)$, and $A_{yy}(\theta)$ data were simultaneously fit in terms of the amplitudes and phases of the appropriate transition matrix elements. Some simplifying assumptions consistent with angular momentum conservation were made in order to reduce the number of degrees of freedom in the fit due to the large number of amplitudes and phases which could be present.

This simplification was to collapse the $j$-index of the amplitudes, and search on the percentages of the resulting amplitudes defined by their channel spin $\vec{S}$ and orbital angular momentum $\vec{l}$. This simplification is supported by the findings in elastic scattering phase shift analyses and capture reactions in other light nuclei at low energies which indicate there is little or no $\vec{J}$ dependence in the transition matrix elements of like $\vec{S}$ and $\vec{l}$ [Jenny, 1980, Skopik, 1979]. If the angular momenta of the $^3\text{He}(d,\gamma)^6\text{He}$ reaction are written as $\vec{a}(\vec{x}, \vec{l}) \vec{c}$ where $\vec{a}$ is the spin of the target, $\vec{x}$ is the spin of the projectile, $\vec{l}$ is the multipolarity of the emitted $\gamma$-ray, $\vec{c}$ is the spin of the residual nucleus, and $\vec{l}$ is the orbital angular momentum of the deuteron, then
\[ \mathcal{X} + \mathcal{Z} = \mathcal{S} \]

5-1

\[ \mathcal{I} + \mathcal{S} = \mathcal{J} \]

\[ \mathcal{L} + \mathcal{C} = \mathcal{J} \]

From the above, the incident deuteron must have \( \mathcal{I} = 0, 1, 2, 3, \) or 4. In an E1 transition, conservation of parity allows only \( \mathcal{I} = 0, 2, \) or 4 for the incident deuteron. Likewise, in an M1 transition only \( \mathcal{I} = 1 \) or 3 is allowed.

The LS coupling configurations in terms of the above intermediate states and Equations 5-1 are shown for the E1 and M1 transitions in Figure 5-1. For this transition matrix analysis, \( \mathcal{I} > 1 \) are not included because of the low energy nature of the experiment. The penetrability was calculated for the d-\(^{3}\)H system and was found to be 0.2479 for \( \mathcal{T} = 0 \), 3.097x10\(^{-2} \) for \( \mathcal{T} = 1 \), 6.728x10\(^{-4} \) for \( \mathcal{T} = 2 \), and 5.288x10\(^{-6} \) for \( \mathcal{T} = 3 \). This rapid decrease in the penetrability by 3 orders of magnitude by \( \mathcal{T} = 2 \) indicates that it should be justifiable to not include \( \mathcal{T} > 1 \) in the calculation. The notation used for the entrance channel is \(^{25+1}1\mathcal{J} \) (where \( \mathcal{I} = 0, 1, 2 \) are given by S, P, D respectively.) The different values of \( \mathcal{J} \) are combined to form \(^{2}S \) (E1), \(^{4}S \) (E1), \(^{4}P \) (M1), \(^{2}P \) (M1) entrance channels so that this analysis could reveal the presence of any M1 radiation and also the predominance of the \( S = 3/2 \) entrance channel. (This predominance is expected because of the presence of the \( 3/2^+ \) "fusion" resonance at \( E_d = 107 \) keV, which is presumably populated with \( \mathcal{T} = 0 \) and \( \mathcal{S} = 3/2 \) incoming waves.) The \(^{25+1}1\mathcal{J} \) symbols denote the amplitude of the reduced transition matrix element (T-matrix)

5-2

\[ T = \langle \rho L(C) \mathcal{J}\mathcal{M} | | T | l(s_d s_t)S\mathcal{J}\pi \rangle \]

82
Figure 5-1: LS coupling configurations in terms of the intermediate states given in the text and Equation 5-1 for both E1 and M1 transitions.
where \( C \) is the spin of the ground state of \( ^5\)He, \( \pi \) is the parity of the intermediate state, \( s_d \) is the spin of the deuteron, \( s_t \) is the spin of the triton, and the operator \( T \) is the interaction multipole operator. Since this matrix element is a complex number, each amplitude has a corresponding phase. The coefficients of the Legendre and associated Legendre expansions of the cross section and analyzing powers (Equations 4-7, 4-8, 4-13) can be expressed in terms of the \( T \)-matrix amplitudes and phases [Seyler and Weller, 1979]. These equations are listed in the appendix. The resulting expressions for \( \sigma(\theta)/A_0 \), \( A_\gamma(\theta) \), and \( A_\gamma(\theta) \) were then used to fit the measured values in terms of \( ^2S \), \( ^4S \), \( ^2P \), and \( ^4P \) amplitudes and their relative phases by the non-linear regression routine NREG. The results of this fit are shown in Table 5-1 and Figure 5-2. The \( ^4S \) (El) amplitude predominates with 95\% of the strength, with 2.5\% in the \( ^2S \) (El) and 2.5\% M1 strength. The Legendre polynomial coefficients resulting from this fit are compared with those presented in Chapter 4 in Table 5-2. A list of the Legendre coefficients in terms of these j-independent transition matrix elements is given in the Appendix. A fit with similar \( \chi^2 \) but different phases for the \( ^2P \) and \( ^4P \), -72.68 and 51.85 degrees respectively, allows 7.66\% M1 radiation and 2.93\% \( ^2S \) (El) radiation. This is in contrast to the previous analysis of the \( ^3H(d,n)^4He \) cross section data [Jarmie, 1984] which indicates that essentially no \( S=1/2 \) background was present in the energy region below 250 keV in the neutron channel. The present results indicate the power of the tensor polarized deuteron capture technique as a tool for sensing small portions of the ground state wavefunction.
Table 5-1: Amplitudes and phases found by transition matrix analysis of $\sigma(\theta)/A_0$, $A_y(\theta)$, and $A_{yy}(\theta)$ for $^3H(d,\gamma)^5He$ at 400 keV.
<table>
<thead>
<tr>
<th>MATRIX ELEMENT</th>
<th>RELATIVE INTENSITY</th>
<th>PHASE ANGLE (DEG.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2S</td>
<td>0.026 ± 0.005</td>
<td>174.34 ± 0.49</td>
</tr>
<tr>
<td>4S</td>
<td>0.949 ± 0.067</td>
<td>0.00 ± 0.0</td>
</tr>
<tr>
<td>2p</td>
<td>0.005 ± 0.003</td>
<td>4.15 ± 0.22</td>
</tr>
<tr>
<td>4p</td>
<td>0.020 ± 0.005</td>
<td>-0.14 ± 0.86</td>
</tr>
</tbody>
</table>
Figure 5-2 (three pages): Fits to $\sigma(\theta)/A_0$, $A_y(\theta)$, and $A_{yy}(\theta)$ by transition matrix analysis at 400 keV. The solid line represents the fit. All error bars are purely statistical.
YIELD(θ)

θ cm

0 30 60 90 120 150 180

2000 4000 6000
Table 5-2: Comparison of Legendre polynomials coefficients obtained in Chapter 4 and those obtained by the transition matrix element analysis.
<table>
<thead>
<tr>
<th>FROM LEGENDRE POLYNOMIAL FITS</th>
<th>TRANSITION MATRIX ELEMENTS ANALYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1 = 0.002 \pm 0.011$</td>
<td>$a_1 = 0.026 \pm 0.008$</td>
</tr>
<tr>
<td>$a_2 = 0.018 \pm 0.017$</td>
<td>$a_2 = 0.018 \pm 0.005$</td>
</tr>
<tr>
<td>$b_1 = -0.024 \pm 0.012$</td>
<td>$b_1 = 0.007 \pm 0.004$</td>
</tr>
<tr>
<td>$b_2 = -0.005 \pm 0.008$</td>
<td>$b_2 = 0.007 \pm 0.002$</td>
</tr>
<tr>
<td>$c_0 = -0.203 \pm 0.016$</td>
<td>$c_0 = 0.002 \pm 0.001$</td>
</tr>
<tr>
<td>$c_1 = -0.091 \pm 0.028$</td>
<td>$c_1 = -0.046 \pm 0.013$</td>
</tr>
<tr>
<td>$c_2 = 0.058 \pm 0.070$</td>
<td>$c_2 = -0.219 \pm 0.018$</td>
</tr>
</tbody>
</table>

$e_2 = -0.089 \pm 0.007$
Chapter 6

DIRECT CAPTURE CALCULATIONS AT 8.6 MeV

A direct-capture calculation was carried out for the $^3\text{H}(d,\gamma)^5\text{He}$ reaction at 8.6 MeV using a d-$^3\text{H}$ cluster model. This model is expected to be valid at this energy since no resonance-like behavior has been reported here, in contrast to the situation at $E_d=400\text{keV}$. In this manner we may calculate the relative strengths of the T-matrix elements and thus the reaction observables. The $a_k$, $b_k$, $c_k$, and $e_k$ coefficients were generated also to compare with the experimental results.

Capture reactions are transitions from an initial continuum scattering state to the ground state of the compound nucleus by interaction with the electromagnetic field. The theory of direct capture reactions has been described in detail by [Brown, 1964; Rolfs, 1973; Dietrich, 1977] and only a brief discussion will be presented here.

In this theory, the initial continuum state may be described by a distorted wave with the interaction Hamiltonian represented by the electromagnetic operator, and the final state described as a standing wave of specific orbital angular momentum. The radial part of the transition matrix elements is given [Weller, 1980] by

$$6-1 \quad R = <u_b|r^L|X^+>$$

Where $r^L$ is the radial part of the electromagnetic operator of multipolarity $L$ in the long wavelength approximation. For E1 transitions, this is just $r$. $X^+$ is
the continuum state distorted by the optical potential, and $u_b$ is the radial part of the bound state. Calculation of the radial matrix elements was performed by the code RADCAP.

The initial-state wave functions are obtained using an optical model potential with radial form

$$V(r) = V_c(r) + V_n(r) + W_n(r) + V_{so}(r) \tilde{r} \cdot \tilde{S}$$

where $V_c(r)$ is the coulomb potential between the deuteron and the triton, which were treated as a uniformly charged spheres, $V_n(r)$ is the real central potential which has a Woods-Saxon shape, $W_n(r)$ is the imaginary central potential which has a surface-derivative Woods-Saxon form, and $V_{so}(r)$ is the spin-orbit potential, which, because of calculational considerations, was added into the central potential for different values of $\tilde{r} \cdot \tilde{S}$ instead of the usual method of treating it as a surface derivative term. This procedure has previously been used in describing the $^4\text{He}(d,\gamma)^6\text{Li}$ reaction [McIntyre and Haeberli]. The Woods-Saxon form factor is given by

$$f(r,r_0,a_0) = \frac{1}{1 + \exp[(r-r_0)/a_0]}$$

6-3

Because of the lack of optical model parameters for this reaction at this energy, the parameters used for the continuum state were the same as for the bound state, with a spin-orbit potential taken from [Perey and Perey, 1976]. The bound state wave function used in RADCAP was calculated by adjusting the well depth of the Woods-Saxon in the real part of the optical model potential to obtain the correct binding energy for $^5\text{He}$. In the present case, the ground state is actually unbound with respect to neutron emission. However, it is bound in the $d+^3\text{H}$
channel and was treated as a bound state (no width) in the present calculation.

The transition matrix elements in the jj coupling scheme may be obtained from the radial matrix elements $R$ given in Equation 6-1 by [Weller, 1980]

$$T_{j,j_a}^{L,1} = i^{L-1} C(j L j_a, 1/2, 0, 1/2) \frac{1}{\sqrt{C^2 S_{ij}}} R_{j a}^{L,1}$$

6-4

where $l_a$ and $j_a$ are the orbital and total angular momenta of the incident particle, $l$ and $j$ are the orbital and total angular momenta of the final bound state with spectroscopic factor $C^2 S_{ij}$ (C being the isospin Clebsh-Gordon coefficient), and $L$ is the multipolarity of the $\gamma$-ray. $j$ is given by

$$j = (2j+1)^{1/2}$$

6-5

The resulting transition matrix element is a complex number represented by a real amplitude and a phase angle. These matrix elements were then transformed from the jj coupling scheme to the LS coupling scheme using the prescription of [Seyler and Weller, 1979].

This calculation included only $\text{E}1$ radiation. Referring to Fig. 5-1, which shows the allowed angular momentum combinations allowed for this reaction, we can see that there are two channel-spins available in this reaction: $\vec{S} = 1/2$ and $\vec{S} = 3/2$. The transition matrix elements were arranged into $\vec{S} = 1/2$ and $\vec{S} = 3/2$ and admixed by

$$\rho |\vec{S} = 1/2\rangle + \sqrt{(1-\rho^2)} |\vec{S} = 3/2\rangle = \psi_{\text{gs.}}$$

6-6
The Legendre coefficients $a_1$, $a_2$, $b_1$, $b_2$, $c_0$, $c_1$, $c_2$, from equation 4-7, 4-8 and 4-9 were then generated from the transition matrix elements [Seyler and Weller, 1979] with $\rho$ varied from 0 to 1.0 to judge what percent admixture of $\tilde{S}=3/2$ was necessary for the experimentally derived coefficients. The results of a calculation with no spin-orbit interaction are shown in Figure 6-1. This comparison suggests an admixture of between 35% and 75% $\tilde{S}=3/2$ from the $b_2$, $c_0$, and $c_2$ coefficients, whereas for $b_1$ the experimental value is consistent with zero and the theoretical calculation is zero for all admixtures. The $a_1$, $a_2$, and $c_1$ coefficients do not compare as well to the experimentally derived values. $a_1$ and $c_1$ calculations are zero for all admixtures in contrast to the non-zero experimental values, whereas the calculated value for $a_2$ is approximately twice the magnitude of $a_2$. Most likely, the reason for these disparities is the lack of non-E1 radiation in the calculation. Optical model parameters used in this calculation are given in Table 6-1.

### Table 6-1

<table>
<thead>
<tr>
<th>Parameters Used in the Optical Model for the Bound State</th>
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<tbody>
<tr>
<td>$V_n=-93.16$</td>
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<table>
<thead>
<tr>
<th>Parameters Used in the Optical Model for the Continuum State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_n=-93.16$</td>
</tr>
</tbody>
</table>
Figure 6-1 (two pages): Comparison of Legendre polynomial coefficients obtained in Chapter 4 for $^3\text{H}(d,\gamma)^5\text{He}$ at 8.6 MeV and those generated by the direct-capture calculation described in the text. The shaded areas represent the experimentally determined coefficients and their statistical errors. The solid lines represent the calculated values with no spin-orbit interaction.
In an effort to better determine the amount of $S=3/2$ necessary to get the best agreement with the data, a spin-orbit potential was added to the optical model potential used previously. It was thought that perhaps the vector analyzing power could be more effectively represented by a spin-orbit interaction. The results are shown in Fig 6-2. The calculated values for $a_1$, and $c_1$ remained zero, which they must for a pure El calculation. The calculated value of $a_2$ was brought nearer to the experimental value and the amount of $S=3/2$ necessary for agreement with $b_2$, $c_0$, and $c_2$ was raised to a range of 88% to almost 100%, with $b_1$ still zero in agreement with the experimental value for any admixture. Optical model parameters used in this calculation with a spin-orbit interaction are given in Table 6-2.

**Table 6-2**

**Parameters Used in the Optical Model for the Bound State**

$V_n=-93.16 \quad W_n=0 \quad r_0=1.25 \quad a=.65$

**Parameters Used in the Optical Model for the Continuum State**

$V_n=-93.16 \quad W_n=0 \quad r_0=1.25 \quad a=.65 \quad V_{SO}=5$ MeV.

These data are therefore consistent with a El strength which is 88-100% $S=3/2$ when a spin-orbit interaction is introduced. The ground state is found to be 88-100% $S=3/2$ in this model calculation. This result
is consistent with the result obtained at low energies in Chapter 5 (95% $S=3/2$ E1).
Figure 6-2 (two pages): Comparison of Legendre polynomial coefficients obtained in Chapter 4 for $^3\text{H}(d,\gamma)^5\text{He}$ at 8.6 MeV and those generated by the direct-capture calculation described in the text. The shaded areas represent the experimentally determined coefficients and their statistical errors. The solid lines represent the calculated values with a spin-orbit interaction.
Chapter 7

Conclusions

Through the measurement of cross section and analyzing powers of the $^3$H(d,γ)$^5$He reaction, it has been possible to draw some conclusions about the reaction.

The transition matrix element analysis of the data obtained at $E_d = 400$ keV indicates that the reaction proceeds primarily by the $S=3/2$ channel via E1 radiation with 95% strength in the $^4S$ amplitude, with 2.5% strength in the $^2S$ (E1) amplitude and 2.5% strength in the $^4P$ and $^2P$ (M1) amplitudes. This indicates the usefulness of tensor polarized deuteron capture in determining the presence of small transition amplitudes which contribute to the reaction.

An E1 direct capture d-$^3$H cluster model calculation was performed at 8.6 MeV to calculate the relative strength of the T-matrix elements and thus the reaction observables. It was found that if a spin-orbit interaction was included in calculating the continuum wavefunction, then the data were consistent with a 88-100% $S = 3/2$ component in the ground state of $^5$He. This result is also consistent with the 95% $S = 3/2$ E1 strength found through a transition matrix element analysis for the data at $E_d = 400$ keV since this E1 strength is predominantly $S\Delta S$ strength. Unfortunately, this direct capture calculation cannot be performed at 400 keV because of the presence of resonant behavior in this energy region.

106
APPENDIX

Legendre polynomial coefficients in terms of the transition matrix amplitudes and phases

\[ A_0 = 2|2S|^2 + 4|4S|^2 + 6|2P|^2 + 12|4P|^2 \]

\[ a_1 = 8.325 \, 2S \, 2P \cos(T_{2P} - T_{2S}) \]

\[ a_2 = 2.865 \, |2P|^2 - 12|2P|^2 \]

\[ b_1 = -1.162 \, 2S \, 2P \sin(T_{2P} - T_{2S}) - 4.243 \, 2S \, 4P \sin(T_{4P} - T_{2S}) \]
\[ + 3.581 \, 4S \, 2P \sin(T_{2P} - T_{4S}) - 13.416 \, 4S \, 4P \sin(T_{4P} - T_{4S}) \]

\[ b_2 = -0.632 \, |2P|^2 - 2.943 \, 2P \, 4P \sin(T_{4P} - T_{2P}) + 4.6 \, |4P|^2 \]

\[ c_0 = 1.47 \, 2P \, 4P \cos(T_{4P} - T_{2P}) \]

\[ c_1 = -3.341 \, 4S \, 2P \cos(T_{2P} - T_{4S}) \]

\[ c_2 = -0.894 \, 2S \, 4S \cos(T_{4S} - T_{2S}) - 1.131 \, |4S|^2 - 1.47 \, 2P \, 4P \cos(T_{4P} - T_{2P}) \]

\[ e_2 = -0.365 \, 2S \, 4S \cos(T_{4S} - T_{2S}) - 0.462 \, |4S|^2 \]

Note: In the transition matrix element calculation, T_{4S} is arbitrarily set equal to zero. The notation T_{(2S+1)L} represents the phase of the transition matrix element whose amplitude is denoted by \( ^{2S+1}L \). L=0 (S-wave) amplitudes correspond to E1 transitions, while L=1 (P-wave) amplitudes are M1 transitions.
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