3 Dynamics of Very Light Nuclei

3.1 Four and Five-Nucleon Reactions

3.1.1 Measurement of Longitudinal and Transverse Polarization Transfer in the T(\bar{p},\bar{n}) Reaction at Low Energies


A series of measurements was performed at TUNL of the longitudinal (K_{z}^{l}) and transverse (K_{y}^{t}) polarization-transfer coefficients at zero degrees for the T(\bar{p},\bar{n}) neutron production reaction at low energies. The results verify a striking resonance behavior in K_{z}^{l} that is predicted from R-matrix calculations for the mass-four system. The resonance occurs at about 800 keV neutron energy and is a clear manifestation of the 0^{-} level in ^{4}He [Til92]. Data previously available for K_{y}^{t} extended no lower than 4 MeV proton energy [Jar74].

Eight measurements of K_{z}^{l} were made using a polarized proton beam incident on a tritium target [Wal96]. Proton energies ranged from 1.3 to 2.8 MeV; the proton beam polarization was determined by p-^4He elastic scattering measurements. The neutron polarization was determined by measuring the transmission asymmetry through a dynamically polarized proton target [See95].

Due to systematic uncertainties in the determination of the target polarization times thickness by NMR and weight measurements, an overall calibration of the transmission data was required. To confirm the absolute value of K_{z}^{l} at a proton energy of 1.62 MeV, we carried out a separate measurement using a high-pressure ^4He scattering polarimeter of known analyzing power. A schematic of the experiment is shown in Figure 3.1–1. For this purpose the polarization of the neutron beam was precessed from the longitudinal to the transverse direction in a magnetic field located after the neutron production cell. This absolute measurement was then used to calibrate the eight transmission measurements. Calibrated results are given in Figure 3.1–2. A measurement of K_{y}^{t} at zero degrees was also performed at 1.62 MeV.

The results are consistent with a longitudinal polarization transfer approaching 96% at a neutron energy of 750 keV. At the same energy the transverse polarization transfer was measured to be 9%. Without changing any of the resonance parameters the R-matrix parameters of Hale [Til92] provide quite a good fit to the longitudinal K_{z}^{l} data. The

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3Los Alamos National Laboratory, Los Alamos, NM.
low value of $K^{1/2}$ is also predicted from the resonance parameters. The $T(p,\bar{n})$ reaction is a copious source of longitudinally polarized neutrons and the data for $K^{2/2}$ show clear evidence for the presence of the 0$^-$ level in $^4$He.

Figure 3.1–1: Experimental layout for absolute neutron polarization measurements. (1) Longitudinally polarized proton beam incident on the tritiated titanium neutron production target produced a beam of longitudinally polarized neutrons. The neutron beam traveled through a (2) superconducting magnet used to precess the neutron spin to transverse. (3) A collimator defined the beam incident on the (4) high-pressure $^4$He scintillator. Neutron detectors (5) located at 59° detect scattered neutrons.

Figure 3.1–2: Comparison of experimental data (TUNL) for $K^{2/2}(0^+)$ with previous data (Jarmer 74) and an R-matrix calculation.


3.1.2 The $^4\text{He}(\gamma,d)^2\text{H}$ Reaction at $E_\gamma = 150 - 250 \text{ MeV}$.


The four-nucleon system is becoming a critical testing ground for many current theoretical calculations of few-body systems at low energies. Recent advances in calculational techniques, which require accurate data at higher energies, have illuminated the lack of consistent and precise data sets in certain systems at or above pion threshold. The $^4\text{He}(\gamma,d)^2\text{H}$ reaction with $E_\gamma = 150 - 250 \text{ MeV}$ exemplifies this lack of high-quality data. In the past thirty years, five separate measurements have yielded an uncertainty of a factor of 100 in the $(\gamma,dd)$ cross section [Sil84, O'R95] in this energy region.

We have performed a measurement of this cross section at the Saskatchewan Accelerator Laboratory (SAL) with the goal of obtaining a high-precision result. The experiment was performed using bremsstrahlung $\gamma$ rays produced by a 275 MeV electron beam. The target was liquid helium contained in a simple cryostat with mylar entrance and exit windows for the beam and reaction particles, respectively. The beam energy and target geometry combined to limit the range of energies for which the cross section could be measured to $E_\gamma = 150 - 250 \text{ MeV}$. An array of six plastic scintillator telescopes was constructed and utilized to create one detector “arm”. Fourteen more plastic scintillator paddles were made and used in combination with a long bar of plastic scintillator to constitute the other “arm.”

The smallness of the cross section (less than 1 nb/sr) and the presence of many competing channels with much higher cross sections made the choice between running with untagged or tagged $\gamma$ rays a difficult one. As a compromise we ran in both modes, allotting the bulk of the beam time to untagged operation with its high count rate. The tagged data, with its lower count rate but additional kinematics information, was taken to provide background estimates for the competing channels. The tagged data also provided a reliable means of determining the absolute cross section.

Preliminary results from the production run, which ended in December 1996, indicate tolerable backgrounds as well as reasonably good particle identification. A very preliminary relative angular distribution, representing partial analysis of 80% of the data, is shown in Figure 3.1–3. These preliminary data resemble a $\sin^2 2\theta + \text{constant}$ angular distribution of the cross section. This is as expected for an $E2$ process involving $s$, $d$, and $g$ waves in the outgoing channel and contradicts the suggestion that the reaction might be dominated by $E1$ radiation. A least-squares fit to an expansion in terms of even Legendre polynomials ($P_0$, $P_2$, and $P_4$) was performed, and the coefficients are presented in Figure 3.1–3. First efforts at determining the absolute cross section are also indicated in the figure by the scale and by the display of data from two of the more recent attempts to measure this cross

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$^1$George Washington University, Washington, DC.
$^2$Saskatchewan Accelerator Laboratory, Saskatoon, SK, Canada.
Cross Section Data for $^4$He($\gamma$,$d\,d$)

Figure 3.1–3: Preliminary relative cross-section data for $^4$He($\gamma$, $d\,d$) at $E_{\gamma} = 155 - 190$ for $\theta = 45^\circ$, $62^\circ$, $90^\circ$, $107^\circ$, $124^\circ$, and $140^\circ$. The errors given are purely statistical. The shape of the angular distribution is suggestive of a $\sin^2 \theta + \text{constant}$ distribution, which is expected for an $E2$-dominated process.

As the figure shows, our preliminary assessment of the absolute cross section is in reasonable agreement with the Silverman data. The uncertainties in the displayed data are solely statistical in nature. A determination of the systematic uncertainties is planned during the remaining analysis of the data.

Analysis of all the data, including data from the ($\gamma$, $p\,l$) and ($\gamma$, $n\,p\,d$) channels, continues. These data will be combined with additional polarized $\gamma$-ray data from an experiment conducted at LEGS. A transition-matrix element analysis will be performed on the total data set to extract the amplitudes of the contributing transition-matrix elements. The implications of these results for current few-body theory will be vigorously investigated.


3.1.3 Measurements of the $^3\text{He}(d,p)^4\text{He}$ Reaction at Low Energies

C. R. Brune, W. H. Geist, H. J. Karwowski, and E. J. Ludwig

The $^3\text{He}(d,p)^4\text{He}$ reaction proceeds primarily through a broad $3/2^+$ $s$-wave resonance at a deuteron energy of 430 keV. For a $3/2^+$ $s$-wave reaction amplitude the cross section is isotropic, while the analyzing powers follow certain relationships [Sei74], namely the tensor analyzing powers $A_{yy} = 1/2$, $A_{zz} = (1 - 3 \cos^2 \theta)/2$, and $A_{xz} = -3/2 \cos \theta \sin \theta$, and the vector analyzing power $A_y$ is zero. Measurements of these analyzing powers around the resonance will enable us to understand the reaction mechanism and determine if other reaction amplitudes, including a direct contribution, are important in the low-energy regime. Such an analysis, for example, will be useful for determining the bare nuclear cross section at very low energies where an improvement in the accuracy is needed to better understand electron screening effects [Lan96].

![Figure 3.1-4](image_url)

Figure 3.1-4: The $^3\text{He}(d,p)^4\text{He}$ cross-section angular distribution measured at $E_d = 430$ keV. The solid squares are the absolute calibration points obtained from the D($^3\text{He},p)^4\text{He}$ reaction and the open circles are the relative angular distribution points normalized to the absolute cross-section measurement.

We have confirmed our ongoing measurements of analyzing powers and differential cross sections for the $^3\text{He}(d,p)^4\text{He}$ reaction. We now have measured full angular distributions of $\sigma, A_y, A_{yy}, A_{xz},$ and $A_{zz}$ at $E_d = 72, 110, 210, 430$ and 650 keV. These are the first analyzing power measurements made below 300 keV for this reaction. These measurements were performed by accelerating a polarized deuteron beam through the low-energy beam facility [Bla93] and into a $^3\text{He}$ ion-implanted target [Gei96]. Three pairs of silicon detectors were symmetrically placed on rotating plates inside the high-voltage chamber [Lud97].
excitation function of the relative cross section from 80 to 680 keV and an absolute determination of the cross section was also measured. The measurement of the absolute cross section was done at the resonance energy using the D(3He,p)4He reaction, Figure 3.1–4. A deuterated carbon foil was used and the target thickness was measured with the D(d,p)T reaction where the cross section is known [Bro90] to better than 3%.

![Graph showing excitation function for different energies](image)

Figure 3.1–5: $\sigma A_{yy}$ at $E_d = 110, 210, 430$ and 650 keV along with Legendre polynomial fits up to $L = 4$. The dashed curves show the best fit for even $L$ only and the solid curves correspond to both even and odd $L$.

The data indicate the presence of a direct process contributing to the reaction. First of all, this can be inferred by the non-zero values of $A_y$ which should be identically zero for an s-wave resonance. Secondly, the need for both odd and even order Legendre polynomials to reproduce the $\sigma A_{yy}$ data, as seen in Figure 3.1–5, reveals the presence of p waves contributing to the reaction. The p-wave contribution is most likely a result from a direct part to the reaction because there are no experimentally known p-wave resonances in this energy region. Calculations are underway which will further evaluate the role of direct processes in this reaction.

3.2 Measurements of D States of Very Light Nuclei Using Transfer Reactions

3.2.1 Analyzing Powers of \((^6\text{Li},d)\) Reactions and the D State of \(^{6}\text{Li}\)

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There is considerable theoretical and experimental interest in investigating the structure of the \(^{6}\text{Li}\) nucleus. A recent article [Eir95] summarizes existing information about the D-state component to the \(^{6}\text{Li}\) ground-state wave function for the \((d\alpha)^6\text{Li})\) bound-state overlap in terms of the parameter \(\eta(^6\text{Li})\), defined as the ratio of the D- and S-state asymptotic normalization constants. Current estimates of the D-state amplitude are so widely varying that even the sign of \(\eta(^6\text{Li})\) is unknown. To understand more about the \(d\) cluster structure of the \(^{6}\text{Li}\) nucleus, we have chosen to examine transfer reactions that are sensitive to this structure.

Last year [Vea96], we reported measurements of the analyzing powers \(A_y\) and \(A_{zz}\) of the \(^{58}\text{Ni}(^6\text{Li},d)^{62}\text{Zn}\) reaction leading to the \(0^+\) ground state in \(^{62}\text{Zn}\). In addition to this we have also extracted the analyzing powers for the transfer to the lowest \(2^+\) state in \(^{62}\text{Zn}\). We have completed our measurements of the \(^{58}\text{Ni}(^6\text{Li},d)^{62}\text{Zn}\) reaction by measuring the analyzing power \(A_{xz}\) for these two transitions. We have also measured the analyzing powers \(A_y, A_{zz},\) and \(A_{xz}\) of the \(^{40}\text{Ca}(^6\text{Li},d)^{44}\text{Ti}\) reaction for transfers leading to the \(0^+\) ground state and the lowest \(2^+\) state at \(E_x = 1.08\) MeV in \(^{44}\text{Ti}\). These data, along with calculations described below, are shown in Figure 3.2-1.

The experiments were performed using the optically-pumped polarized lithium ion source at Florida State University. The \(^{58}\text{Ni}\) target for the \(A_{xz}\) measurements was a 2.0 mg/cm\(^2\) self-supported, isotopically-enriched rolled foil. The \(^{40}\text{Ca}\) targets used were 0.9 mg/cm\(^2\) of nat Ca sandwiched between 0.3-mg/cm\(^2\) layers of Au. The detectors used were \(\Delta E - E\) telescopes with a total thickness of 6 mm of Si, where the \(E\) detectors were 5-mm Si(Li) detectors. The polarization of the beam was monitored via the \(^4\text{He}(^6\text{Li},^4\text{He})^6\text{Li}\) reaction. Typical beam polarizations were \(p_x, p_z \approx -0.65, -1.15\).

We are analyzing these reactions assuming a direct \(\alpha\)-transfer process. The optical model parameters used to describe the reaction came from global parameterizations of \(^6\text{Li}\) and deuteron elastic scattering. To describe the \((d\alpha)^6\text{Li})\) bound-state overlap, we are using

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2 University of Lisbon, Lisbon, Portugal.
3 University of Silesia, Katowice, Poland.
4 University of Munich, Garching, Germany.
5 University of Surrey, Guildford, UK.
Figure 3.2-1: Vector and tensor analyzing powers $A_y$, $A_{zz}$, and $A_{xz}$ for the $^{40}$Ca($^6$Li,$d$)$^{44}$Ti reaction leading to the $0^+$ ground state and the $2^+$ state at $E_x = 1.08$ MeV. The solid curve represents the best fit to that tensor analyzing power corresponding to a particular value of $\eta(^6\text{Li})$. The dotted curve corresponds to a calculation with $\eta(^6\text{Li}) = +0.0112$ while the dashed curve corresponds to $\eta(^6\text{Li}) = -0.0112$. This magnitude of $\eta(^6\text{Li})$ corresponds to a D-state spectroscopic amplitude of $|b_D| = 0.08$. 

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Figure 3... Determinations of $^6\text{Li}$ from the eight tensor analyzing power measurements. The dashed lines correspond to the approximate expected magnitude for previous determinations. A Woods-Saxon prescription with geometric $W = 1.90$ fm and $a = 0.065$ fm has been chosen to reproduce the separation energy between the $\alpha$ and deuteron.

We have obtained good agreement with our $^\alpha$Sn and $^9$C data assuming a direct one-Woods-Saxon prescription, with geometric $W = 1.90$ fm and $a = 0.065$ fm. The depth is chosen to reproduce the separation energy between the $\alpha$ and deuteron.

The individual uncertainties on each determination, $\sigma_{^6\text{Li}}$, are the difference between the calculated value of $^6\text{Li}$ at $\Theta_{\text{min}}$ and the value of $^6\text{Li}$ at $\Theta_{\text{min}} + 1$. Our results show statistically valid data for all cases.

The individual uncertainties on each determination are shown in Figure 3-7. The uncertainties displayed are the standard deviation of the measurements from the Woods-Saxon model. The errors are due to the uncertainties in the optical model parameters, which are not fully accounted for in the previous determination.
3.2.2 Cross-Section Measurements of the $^{28}$Si($^6$Li,$\alpha$)$^{30}$P Reaction

C. R. Brune, H. J. Karowski, K. W. Kemper$^1$, E. J. Ludwig, and K. D. Veal

As described in a previous report [Vea95], the goal of the $^6$Li D-state study is to extract $\eta(^6\text{Li})$, the ratio of the D- and S-state asymptotic normalization constants, from an analysis of the tensor analyzing powers from ($^6\text{Li},d$) and ($^6\text{Li},\alpha$) reactions. It has been shown [Eir95] that the tensor analyzing powers from these transfer reactions are sensitive to the magnitude and sign of $\eta(^6\text{Li})$. To date, we have made measurements of several tensor analyzing powers for ($^6\text{Li},d$) reactions (see Section 3.2.1).

However, there is strong interest in continuing this study by measuring the tensor analyzing powers of ($^6\text{Li},\alpha$) reactions. To reduce theoretical complications by singling out pure $L$ transfer reactions, it would be advantageous to measure reactions where the target has $J^\pi = 0^+$ and the state populated by the transfer reaction has $J^\pi = 2^+$. Since a reaction of this form is a natural-parity transfer reaction, it can only be populated by an $L = 2$ angular-momentum transfer. An added advantage to ($^6\text{Li},\alpha$) reactions is that there are no spin-dependent optical potentials in the exit channel. Unfortunately, there is a limited number of candidate targets for which a well-separated ($i.e.$ by $\sim 0.5$ MeV) $2^+$ state in the residual nucleus exists.

We have chosen to investigate the $^{28}\text{Si}(^6\text{Li},\alpha)^{30}\text{P}$ ($2^+, E_x = 1.454$ MeV) reaction. There were several factors that needed to be explored before a measurement of the analyzing powers could take place. It was thought that with the large $Q$-value of ($^6\text{Li},\alpha$) reactions we might be able to detect the outgoing alpha particles without a detector telescope. Also, there are no published cross-section data for the $^{28}\text{Si}(^6\text{Li},\alpha)^{30}\text{P}$ reaction, so we were unable to make a count-rate estimate. Therefore, a test run was performed at Florida State University using an unpolarized $^6\text{Li}$ beam from the SNICS source accelerated to 34 MeV. The target used was a self-supporting nat SiO$_2$ target prepared by electron-gun evaporation with an approximate thickness of 0.1 mg/cm$^2$.

Several detector configurations were explored including single detectors and $\Delta E - E$ telescopes, both with and without tantalum foils to stop the elastically scattered $^6\text{Li}$ ions. From the observed spectra, we found that the best configuration to detect the outgoing alpha particles was a $\Delta E - E$ telescope without a stopping foil but with a $\Delta E$ detector that was thick enough to stop the elastic $^6\text{Li}$ ions. A typical spectrum for this detector configuration is shown in Figure 3.2–3(a).

To determine the relative cross section of these reactions, we placed a small fixed-angle detector at 135$^\circ$ with respect to the beam to monitor the target. We were then able to extract cross-section yields from the chamber detectors by taking the ratio of the counts in each detector to those in the monitor detector. However, since the elastically scattered

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The extracted cross section for the state of interest ($J^π = 2^+$, $E_x = 1.454$ MeV) for possible analyzing power measurements.

$^6$Li ions did not register a coincidence in our telescopes, we normalized our data to the $^{16}\text{O}(^6\text{Li},\alpha)^{18}\text{F}$ ($1^+, \text{gs}$) reaction where the cross section is known to 8% [Kem77].

The extracted cross section for the $^{28}\text{Si}(^6\text{Li},\alpha)^{30}\text{P}$ ($2^+$, 1.454 MeV) reaction with errors reflecting our counting statistics is shown in Figure 3.2--3(b). The cross section is $\approx 1 \mu\text{b/sr}$ over the angular range measured. This is smaller by an order of magnitude than the ($^6\text{Li},d$) reaction cross sections we have measured. With limited polarized beam current available and the requirements to resolve this peak, we conclude that it would be very difficult to measure the analyzing powers for this reaction. Therefore, we have chosen to delay the analyzing power measurements for the present time.

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3.3 Radiative-Capture Reactions and Few-Nucleon Systems

3.3.1 Measurement of $iT_{11}$ for the Reaction $p(d,\gamma)^3$He at $E_d = 80 - 0$ keV

R. S. Canon, M. A. Godwin, J. Kelley, R. M. Prior$^1$, B. J. Rice, M. Spraker, D. R. Tilley, H. R. Weller, and E. A. Wulf

Recent theoretical studies [Fri91, Viv96] of the $p$-$d$ system have highlighted the importance of meson-exchange currents (MECs) at low center-of-mass energies in the $p(d,\gamma)^3$He and $d(p,\gamma)^3$He reactions. The Radiative-Capture Group at TUNL has studied these systems for the past several years. These studies have shown that the low energy vector and tensor analyzing powers for these reactions are particularly sensitive to the detailed treatment of the MECs. This report describes results of a new measurement of the vector analyzing power $iT_{11}$ for the reaction $p(d,\gamma)^3$He at $E_d = 80 - 0$ keV.

The present work was performed at TUNL on the Low-Energy CAPture beam line (LECAP). A purely vector polarized deuteron beam was prepared using the Atomic Beam Polarized Ion Source (ABPIS). The beam was fast spin-flipped between two polarization states with theoretical maximum polarizations of $p^+ = 2/3$ and $p^- = -2/3$. Relative polarizations were obtained using the Spin-Filter Polarimeter (SFP) and were measured to be $p^+ = 0.44 \pm 0.05$ and $p^- = -0.61 \pm 0.05$. The beam was directed toward an H$_2$O ice target. The outgoing $\gamma$ rays were detected using High Purity Germanium (HPGe) detectors with 4.4 keV resolution at 5.5 MeV. The $iT_{11}$ vector analyzing power was measured at seven angles between $15^\circ$ and $149^\circ$. The data are shown in Figure 3.3-1.

The results of the three-body calculation of Viviani et al. [Viv96] for $E_d = 70$ keV are also shown in Figure 3.3-1. These curves were generated using the same calculation shown in Ref. [Sch96] for $\sigma(\theta)$, $A_y(\theta)$, $T_{20}(\theta)$, and $P_{1}(\theta)$. In that paper it was pointed out that $A_y$ is especially sensitive to MEC effects, changing by a factor of three when the calculation is performed with (Full) and without (IA) two-body currents (MECs). Figure 3.3-1 indicates that $iT_{11}$ is even more sensitive to MEC effects, changing by a factor of twenty at $90^\circ$ for example, when MECs are and are not included.

A transition-matrix element (TME) analysis of the data was performed in order to extract information about the contributing multipoles. In addition to $iT_{11}$, the data set used in this analysis included data published by Schmid et al. [Sch96] which consisted of $\sigma(\theta)$, $A_y(\theta)$, $T_{20}(\theta)$, and $P_{1}(\theta)$. Only those data in the energy range $E_{c.m.} = 27 - 0$ keV, corresponding to $E_d = 8 - 0$ keV, were included in this analysis, with the exception of the $P_3$ data which were in the range $E_{c.m.} = 34 - 0$ keV. It was found that good fits to the data could be obtained using the $E1 (\ell=1)$ and $M1 (\ell=0)$ TMEs (see Table 3.3-1).

The results of two TME fits are presented in Table 3.3-1. The first was performed without the $iT_{11}$ data. In order to obtain a physically reasonable fit to the data two

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restrictions were placed upon the matrix elements: the amplitudes and phases of the $^2p_2$ and $^2p_4$ TMEs were constrained to be equal. This constraint is equivalent to assuming a pure $\sin^2\theta$ shape to the cross-section angular distribution for the $E1$ $s = 1/2$ transitions, as is the case when spin-orbit coupling is negligible. With the addition of the $\iT_{11}$ data these restrictions could be removed. However, inspection of the results showed an unexpected phase difference between the $M1$ $s$-wave TMEs. Since it is difficult to motivate a mechanism for such a phase difference and since the work by Viviani et al. predicts a phase difference of only $0.15^\circ$, the constraint that these phases be equal was placed on the fit which included the $\iT_{11}$ data.

The key result of this analysis is the emergence of a precise determination of the distribution of $M1$ strength between the $s = 1/2$ and $s = 3/2$ terms. This distribution is characterized by the ratio of the cross-section fraction of the $s = 3/2$ term to the $s = 1/2$ term. The ratios obtained from the TME fits are listed in Table 3.3–2. Also listed in Table 3.3–2 are the ratios predicted by Friar et al. [Fri91] and Viviani et al. [Viv96]. The Viviani IA ratio is from an impulse approximation calculation where the MECs have not been included. The Viviani Full ratio is from a calculation which includes MECs. The result of the TME fit including the $\iT_{11}$ data, $0.49 \pm 0.12$, agrees well with the prediction by Viviani of 0.47 and is consistent within uncertainties with the Friar prediction at zero-energy [Fri91] of 0.58.
Table 3.3-1: Results of TME fits with and without the $iT_{11}$ data.

<table>
<thead>
<tr>
<th>TME $(2^{s+1}l_{2j+1})$</th>
<th>Without $iT_{11}$</th>
<th>With $iT_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$ Fraction</td>
<td>Phase (deg)</td>
</tr>
<tr>
<td>$^2p_2$</td>
<td>0.216 ± 0.007</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>$^2p_4$</td>
<td>0.432 ± 0.014</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>$^4p_2$</td>
<td>0.035 ± 0.019</td>
<td>79.12 ± 6.11</td>
</tr>
<tr>
<td>$^4p_4$</td>
<td>0.014 ± 0.010</td>
<td>91.98 ± 6.35</td>
</tr>
<tr>
<td>$^2s_2$</td>
<td>0.129 ± 0.053</td>
<td>-48.22 ± 8.90</td>
</tr>
<tr>
<td>$^4s_4$</td>
<td>0.174 ± 0.054</td>
<td>-8.96 ± 4.58</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>1.57</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 3.3-2: Table of $M1$-fraction ratios.

<table>
<thead>
<tr>
<th>TME fit to Experiment</th>
<th>$^{3/2}_{-1/2}$</th>
<th>Theoretical Calculation</th>
<th>$^{3/2}_{-1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without $iT_{11}$</td>
<td>1.35 ± 0.69</td>
<td>Friar ($E_d = 0$ keV)</td>
<td>0.58</td>
</tr>
<tr>
<td>With $iT_{11}$</td>
<td>0.49 ± 0.12</td>
<td>Viviani IA ($E_d = 70$ keV)</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Viviani Full ($E_d = 70$ keV)</td>
<td>0.47</td>
</tr>
</tbody>
</table>


3.3.2 Measuring the $\gamma$-Ray Analyzing Power for $^2$H($p\gamma$)$^3$He

R. S. Canon, M. A. Godwin, J. H. Kelley, R. M. Prior1, B. J. Rice, M. Spraker, D. R. Tilley, H. R. Wellen, and E. A. Wulf

In an effort to check theoretical predictions on the effect of Meson-Exchange Currents (MEC) in the few-body $^3$He system [Viv96], five observables have been measured at $E_p = 80$ keV and $E_d = 80$ keV: cross section, vector analyzing power $A_y$, $T_{20}$, $\gamma$-ray polarization ($P_\gamma^0$) [Sch96], and $iT_{11}$. These measurements have constrained the Transition-Matrix Elements (TME) that contain the MEC strength, but a new observable that is sensitive to MEC effects would improve these constraints. One such observable is the $\gamma$-ray analyzing power, defined as $A_y = P_\gamma^1 - P_\gamma^1$, where $P_\gamma^1$ and $P_\gamma^1$ are the observed $\gamma$-ray polarizations with the spin

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Figure 3.3-2: The theoretical predictions for the IA and MEC with the current data points for (a) $A_\gamma$ and (b) $P_\gamma^0$. 
of the incident protons up and down, respectively. The theory makes predictions for the Impulse Approximation (IA), which corresponds to the “nucleons only” approximation, and for the full calculation, which includes two-body meson-exchange and delta-isobar currents. $P_\gamma^0$ is not sensitive to MECs because the TMEs sensitive to MEC effects are squared as opposed to $P_\gamma^p$ and $P_\gamma^d$ which have cross terms. This means that for $A_\gamma$ there is nearly a factor of two difference between the IA and the MEC theoretical predictions while the difference is small for $P_\gamma^D$ (see Figure 3.3-2).

Polarized protons from the polarized ion source having an energy of 80 keV were stopped in a thick heavy water ice target. The $P_\gamma$ measurements were done using the Compton polarimeter without collimation (see Section 7.5.4). The data point at 90° is from a week of data. Another week of data will reduce the error bar enough to differentiate between the two theoretical predictions. In the $iT_{11}$ and $A_\gamma$ data there is a fore-aft asymmetry that may show up in the $A_\gamma$ data. Therefore, we will also measure a forward and backward angle in future runs.


3.3.3 Formalism for $\gamma$-Ray Polarizations in Radiative-Capture Reactions Induced by Polarized Beams

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As mentioned in [Gui96], we have been examining the sensitivity of the $\gamma$-ray polarization to the polarization of the proton beam used in d radiative-capture reaction studies. In order to illustrate this sensitivity we consider the special case of the $D(\bar{p}\gamma)^3$He reaction at very low energies, where $s$- and $p$-wave capture dominate. If we neglect the $S = 3/2$ $E1$ capture and set the two remaining $p$-wave $E1$ amplitudes equal (i.e., no $j$-dependence), and set the two $s$-wave capture $M1$ amplitudes equal, we have just a single $s$-wave and a single $p$-wave capture amplitude. In this case the $\gamma$-ray polarization for proton spin-up ($\uparrow$) or spin-down ($\downarrow$) is given by

$$P_\gamma^\pm = \frac{3}{2} |p|^2 (1 - \cos^2 \theta) + \frac{5}{3} f^\pm |s| |p| \sin \theta \cos \Delta$$

where $f^\uparrow$ is the beam polarization for the two cases. Clearly the $s$, $p$ interference term is only present in the case of polarized beams. This is the key to the sensitivity of the observables $P_\gamma^s$ and $P_\gamma^p$. By taking their difference ($A_\gamma \equiv P_\gamma^s - P_\gamma^p$) we obtain a quantity which is quite sensitive - in the case of $D(\bar{p}\gamma)^3$He - to the effects of meson-exchange currents.
In the course of studying this formalism we have derived a relationship between the \( \gamma \)-ray polarization obtained with unpolarized beam \( P_0^\gamma \) and that for polarized beam \( (P_2^\gamma) \):

\[
P_0^\gamma = \frac{P_2^\gamma (1 + A_y) + P_1^\gamma (1 - A_y)}{2}
\]

for \( A_y = 0 \), \( P_0^\gamma = \frac{P_2^\gamma + P_1^\gamma}{2} \).

This expression has been useful in checking the consistency of both the formalism and the experimental data.