3 Dynamics of Very Light Nuclei

3.1 Polarized-Beam and Polarized-Target Reactions

3.1.1 A Polarized Solid $^3$He Target for Neutron-Transmission Experiments


In the past year we have completed measurements of polarized neutron–polarized $^3$He scattering in the few MeV region. Measurements of the total cross-section differences $\Delta \sigma_T$ and $\Delta \sigma_L$ have been obtained for neutrons with incident energies 1-10 MeV. The results are sensitive to the excited state structure of the alpha particle and may be compared to phase-shift predictions based on a number of analyses of the n-$^3$He system. The $\Delta \sigma_T$ results are in agreement with a recent R-matrix analysis of $A = 4$ scattering and reaction data, and lend support to the $^4$He level scheme derived from that analysis. The $\Delta \sigma_L$ data is currently being analyzed.

The experiments were performed with the largest polarized solid $^3$He target ever used in a nuclear physics experiment [Kei95]. The target, which contains 0.4 moles of $^3$He, is polarized to 38% in the TUNL spin-spin polarized target cryostat by cooling the sample to 12 mK in a 7 Tesla magnetic field. Such a target is suitable for nuclear physics measurements which produce beam heating of a few microwatts and are insensitive to the large magnetic field.

The density of the condensed phases of $^3$He corresponds to approximately 100 MPa of room temperature gas. In a neutron transmission experiment, the effectiveness of the target can be described by a figure of merit $(P_t x_3)^2$ where $P_t$ is the target polarization and $x_3$ the target thickness in atoms/cm$^2$. The number of transmitted neutrons that must be counted to achieve a given precision is inversely proportional to $(P_t x_3)^2$. If we compare the TUNL condensed $^3$He target ($P_t = 38\%$, $x_3 = 4.3 \times 10^{22}$ atoms/cm$^2$) with a state of the art $^3$He gas target ($P_t = 55\%$, $x_3 = 1.9 \times 10^{21}$ atoms/cm$^2$), the figure of merit of the solid target is larger by a factor of 250. For example, our neutron transmission measurement would have required over 150 days to complete with a gas target.

The solid $^3$He samples were grown directly from liquid $^3$He at 1.1 K. The target cell is constructed of beryllium copper alloy for strength and high thermal conductivity. To improve the thermal linkage to the solid $^3$He, the sample space is filled with 3 mm silver powder packed to 19% of the density of solid silver. The target cell is shown in Figure 3.1–1. The density of the solid in the target was determined by the melting and freezing
Figure 3.1–1: The polarized solid $^3$He target cell. The sample space is indicated by the gray shaded portion. The interior dimensions of the target are shown to the right.
temperature during sample growth. The polarization of the target was determined from the temperature of the target as measured with $^{60}$CoCo nuclear orientation thermometry and $^3$He melting curve thermometry. A cooling curve for the target is shown in Figure 3.1–2.

There are applications of a solid polarized target for photon scattering experiments [FEL94]. It is also possible to directly exploit the $^3$He as a neutron scintillation detector [van76]. We are presently studying the possibility of reconfiguring the TUNL solid $^3$He target for this purpose.

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3.1.2 New Impulse Approximation Calculation for the $\bar{d} + d \to d + p + n$ Breakup Reaction

A.C. Fonseca$^1$, C.R. Howell, A. Soldi$^2$ and B. Vlahovic$^2$

Since $\bar{d} + d \to d + p + n$ cross-section data suggest that quasifree nucleon-deuteron processes are the dominant feature, we develop, in the spirit of the impulse approximation, a model which is the coherent sum of four terms: neutron-deuteron and proton-deuteron quasifree scattering while the other nucleon in either the target or the projectile behaves as a spectator. It can be shown that these four terms correspond to the lowest order diagrams in the Born series expansion of the t-matrix for $\bar{d} + d \to n + p + d$. In the framework of the AGS equations [Alt70], the breakup amplitude may be written as the sum of two terms involving both the $2 + 2 \to 2 + 2$ and $2 + 2 \to 1 + 3$ half-shell amplitudes which may be obtained from the solution of the set of coupled integral equations. If only the lowest order diagrams are considered (the amplitudes are zero for the $2 + 2 \to 2 + 2$ term and the one-nucleon exchange Born term for $2 + 2 \to 1 + 3$), the breakup amplitude at a c.m. energy $E$ can be written in terms of three-nucleon t-matrices for $1 + 2 \to 1 + 2$ embedded in four-particle space through an energy shift that equals the kinetic energy of the spectator nucleon relative to the center of mass of the underlying three-nucleon subsystem. The four terms (two in $T_2$ and two in $T_1$) in Equation 3.1 are needed order to account for the identity of deuterons in the initial state and nucleons in the final state.

\[
T = T_2 + T_1 = \left\langle 1\delta' k'_d; \frac{1}{2} u'_1 k'_1; \frac{1}{2} u'_2 k'_2 \right| T(E) \left| 1\delta_k; 1\delta_2 - k \right\rangle \delta(k'_1 + k'_2 + k'_d)
\] (3.1)

\[
T_2 = \frac{1}{\sqrt{2}} \left\{ \left\langle 1\delta' \frac{1}{2} u'_1; Q'_2 | Z(\varepsilon_2) | Q'_2^+; 1\delta_2 \frac{1}{2} u \right| \chi_d \left[ q'_2^+; \left( \begin{array}{c} \frac{1}{2} \\ u \\ u' \end{array} \right) \left( \begin{array}{cc} s & l \\ s_z & m \end{array} \right) \right] \right\}
\]

\[
+ \left\langle 1\delta' \frac{1}{2} u'_1; Q'_2 | Z(\varepsilon_2) | Q_2^-; 1\delta_2 \frac{1}{2} u \right| \chi_d \left[ q_2^-; \left( \begin{array}{c} \frac{1}{2} \\ u \\ u' \end{array} \right) \left( \begin{array}{cc} s & l \\ s_z & m \end{array} \right) \right] \}
\] (3.2)

\[
T_1 = \frac{1}{\sqrt{2}} \left\{ \left\langle 1\delta' \frac{1}{2} u'_2; Q'_1 | Z(\varepsilon_1) | Q'_1^+; 1\delta_1 \frac{1}{2} u \right| \chi_d \left[ q'_1^+; \left( \begin{array}{c} \frac{1}{2} \\ u \\ u' \end{array} \right) \left( \begin{array}{cc} s & l \\ s_z & m \end{array} \right) \right] \right\}
\]

\[
+ \left\langle 1\delta' \frac{1}{2} u'_2; Q'_1 | Z(\varepsilon_1) | Q_1^-; 1\delta_1 \frac{1}{2} u \right| \chi_d \left[ q_1^-; \left( \begin{array}{c} \frac{1}{2} \\ u \\ u' \end{array} \right) \left( \begin{array}{cc} s & l \\ s_z & m \end{array} \right) \right] \}
\] (3.3)

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where \( Z \) is the three-nucleon t-matrix, \( \chi_d \) is the deuteron wave function, and

\[
Q_i^\pm = -\frac{2}{3} k_i' - k_d', Q_i^\mp = -\frac{2}{3} k_i' \mp k,
\]

(3.4)

\[
q_i^\pm = k_i' \pm \frac{1}{3} k, \quad \varepsilon_i = E - \frac{4}{3} k_i'^2,
\]

(3.5)

\[
E + 2 \epsilon_d - k^2 = 0,
\]

(3.6)

and

\[
E + \epsilon_d - k_1'^2 - k_2'^2 - \frac{k_d'^2}{2} = 0.
\]

(3.7)

All momenta \( \vec{k} \) are in the four nucleon c.m. system. The momenta \( \vec{k}, \vec{k}_d', \) and \( \vec{k}_i \) are of the incident deuteron, the outgoing deuteron and the outgoing nucleons \((i = 1, 2)\), respectively. The \( \delta_i' \) and \( u (\delta_i' \) and \( u_i') \) represent the spin projections of the initial (final) deuteron(s) and nucleon(s).

Assuming that deuteron “one” is polarized, than \( T_2 \) and \( T_1 \) in Equation 3.1 correspond to target breakup and projectile breakup, respectively. Given the on-shell relation of Equation 3.6, the three-body t-matrix \( Z \) is on-shell on the left side \((\varepsilon_i = E - \frac{4}{3} k_i'^2 = -\epsilon_d + \frac{3}{2} Q_i'^2)\) and off-shell on the right side \((\varepsilon_i \neq -\epsilon_d + \frac{3}{2} (Q_i')^2)\). Before realistic 3N calculations were available, one used measured elastic nucleon-deuteron cross sections to predict the \( d + d \rightarrow d + p + n \) breakup cross section. That approach had two shortcomings. First it ignored the fact that nucleon-deuteron quasifree amplitudes are off-the-energy-shell in deuteron-induced deuteron three-body breakup. It has been shown [McI72] that using off-shell amplitudes can change the calculated cross section significantly. Second and more importantly, using only free nucleon-deuteron elastic scattering cross sections, does not take into account the correct interference effect between different poles.

The tensor observables \( T_{kq} \) are compute from Equation 3.1 as

\[
T_{kq} \text{Tr}\{T^\dagger T\} = \text{Tr}\{T^\dagger T \tau_{kq}\} = \sum_{\delta_1 \delta_2 \delta_1' \delta_2'} \langle 1\delta_1 1\delta_2 | T^\dagger T | 1\delta_1' 1\delta_2' \rangle \langle 1\delta_1' 1\delta_2' | \tau_{kq} | 1\delta_1 1\delta_2 \rangle
\]

\[
= \sum_{\delta_1 \delta_2 \delta_1' \delta_2'} \sum_{u_1' u_2' \delta'} \langle 1\delta_1 1\delta_2 | T^\dagger | \frac{1}{2} u_1' u_2' 1\delta' \rangle \langle \frac{1}{2} u_1' u_2' 1\delta' | T | 1\delta_1' 1\delta_2' \rangle \hat{k} C_{\delta_1 u_1}^{\delta_1'}.
\]

In all our calculations we take the Hulthen wave function for the deuteron and calculate for each \( \varepsilon_i \) the half-shell \( n + d \rightarrow n + d \) t-matrix using for the N-N interaction a rank one Yamaguchi separable potential for the channels: \(^1\text{S}_0, ^3\text{S}_1-^3\text{D}_1, ^1\text{P}_1, ^3\text{P}_0, ^3\text{P}_1\) and \(^3\text{P}_2\). In each partial wave the parameters are fitted to the low energy properties of the N-N force such as the scattering length, the effective range, the deuteron binding energy and the deuteron
The quadruple moment [Fon95]. The parametrization of the $^3S_1$-$^3D_1$ force corresponded to a 5.5% D-state in the deuteron. Although the deuteron wave function we used is not fully consistent with the $^3S_1$-$^3D_1$ interaction used to generate Z, one expects the contribution to the cross section and analyzing powers from the D-state of the deuteron to be small in the quasifree region.

Predictions of our model are shown in Figures 3.1–3 and 3.1–4 in comparison to TUNL data [How93] for the $\vec{d} + d \rightarrow d + p + n$ reaction at an incident deuteron energy of 12 MeV. In these measurements the deuteron and proton were detected at 17° on opposite sides of the incident beam axis. The data and calculations are shown as a function of S, the distance along the kinematic locus in the $E_d - E_p$ plane. The calculations were normalized to fit the peak value of the yields spectrum in Figure 3.1–3. Our calculations give a very good description of the shape of the quasi-free enhancement. This is a big improvement over previous impulse-approximation calculations [Val72]. In Figures 3.1–3 and 3.1–4 the solid curves are full calculations with both $T_2$ and $T_1$ in Equation 3.1, the dotted curves are calculations with only $T_2$, and the dashed curves are calculations that include $T_2$ and $T_1$ but not their interference. One immediately sees from Figure 3.1–3 that about 40% of the cross section for the 17° angle pair is due to the interference of the two terms and that the interference is needed to give the correct shape of the spectrum. All analyzing powers in Figure 3.1–4 are well described by the calculation. It is clear from these comparisons that the interference between terms is needed to describe the spin observables. Our calculations
Figure 3.1–4: Analyzing powers for the $\bar{d} + d \rightarrow d + d + n$ reaction as a function of $S$ for the angles $\theta_d = +17^\circ$ and $\theta_p = -17^\circ$. Data and curves are described in the text.
were compared to the data of Howell et al. [How93] at several angles, and the results were similar to those obtained at 17°.


3.1.3 Analyzing Power Measurements of D(d, d)D at $E_d = 3$ MeV and 4.75 MeV


Discrepancies between resonating group model (RGM) calculations of some tensor analyzing powers and previous experimental data at $E_d = 6–10$ MeV [Grü72] for the $A = 4$ system has led us to extend our previous measurements of this system [Fle94]. We are now beginning an investigation of D(d, d)D at energies below the deuteron-breakup threshold in order to test predictions of both RGM and R-matrix theories. Especially interesting here is the importance of certain spin-flip matrix elements which have been set to values which exceed expectations in RGM calculations [Hof93] adjusted to fit the existing data.

We have recently measured the tensor analyzing powers $A_{zz}$ and $A_{yy}$ for D(d, d)D elastic scattering at incident deuteron energies of 3 and 4.75 MeV. At each energy the data were collected over an angular range in the lab of 20–60 degrees using the TUNL FN tandem accelerator. Thin, durable deuterated-carbon targets were bombarded by polarized deuteron beams produced by the TUNL polarized-ion source. Particles exiting the reaction were viewed by two pairs of symmetrically-placed detector telescopes containing $\Delta E$ detectors with thicknesses between 6 and 16 $\mu$m.

Our results for $A_{zz}$ at 4.75 MeV are shown in Figure 3.1–5 along with a prediction of $A_{zz}$ from an R-Matrix parameterization [Hal95]. The reasonable agreement between theory and experiment obtained for $A_{zz}$ does not appear to hold for the case of the $A_{yy}$ data obtained at this energy. Theoretical calculations at 3 MeV are underway.


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Figure 3.1–5: Comparison of $A_{zz}(\theta)$ data for D(d, d)D scattering with a theoretical prediction from an R-matrix parameterization (solid curve) at 4.75 MeV.
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3.2 Measurements of D-States of Very Light Nuclei by Transfer Reactions

A direct result of the nucleon-nucleon (N-N) tensor force in few-body systems is the presence of non-spherical components in the nuclear wave functions, or D-states [Eri85,Leh90]. The tensor force is a crucial component of the nuclear force, responsible for most of the binding for the 3- and 4-nucleon systems [Eri85]. Models based only on pairwise N-N forces, however, fail to account for the triton binding energy and this has led to the introduction into some models of a phenomenological 3-nucleon force, adjusted to yield the correct trinucleon binding energy but also affecting other physical observables. The measurement of D-state observables, affected by the tensor force in the N-N interaction and the inclusion of 3-body forces, can provide a sensitive tests of these models. One such observable which can be compared directly to the results of exact calculations of the ground states of few-body systems is $\eta$, the asymptotic D- to S-state ratio. Our program in recent years has been to determine $\eta$ for nuclei with $A < 7$ from comparisons of DWBA calculations and experiment for tensor analyzing power (TAP) angular distributions for a variety of nuclei. Cases chosen for study have minimum theoretical uncertainty in their interpretation.

3.2.1 The D-State of $^3$H using Sub-Coulomb (d, t) Reactions

B. Kozlowska, Z. Ayer, H. J. Karwowski and E. J. Ludwig

We have now completed out measurements and analysis of TAPs in sub-Coulomb (d, t) reactions. A value of $\eta$ for the triton ($\eta_t$) has been extracted by comparing the TAP data with distorted-wave Born approximation (DWBA) calculations. These reactions were studied at sub-Coulomb energies in order to maximize the reliability of the DWBA calculations. A paper has been published in Physical Review C containing our $\eta_t$ value which is slightly smaller in magnitude than that predicted using several different methods of solving Faddeev calculations [Fri88, Ish88].


3.2.2 The D-State of \( ^3\text{He} \) from \( (d, ^3\text{He}) \) Reactions

Z. Ayer, H. J. Karwowski, B. Kozlowska and E. J. Ludwig

Similar to the \( (d, t) \) analysis described in the previous sub-section, we have extracted four independent values of \( \eta \) for \( ^3\text{He} \) from theoretical comparisons with TAPs measured in \( ^{93}\text{Nb}(d, ^3\text{He})^{92}\text{Zr} \), \( ^{63}\text{Cu}(d, ^3\text{He})^{62}\text{Ni} \), and \( ^{89}\text{Y}(d, ^3\text{He})^{88}\text{Sr} \) reactions. These values were found to be consistent with each other and were combined to yield a final \( \eta \) value of \(-0.0380 \pm 0.0026 \pm 0.0011\). The error in \( \eta \) includes the statistical error in the measurement, effects of using different sets of optical potentials in the analysis and uncertainties in the beam polarization. It does not include uncertainties arising from the absence of tensor potentials which have been used to help describe deuteron elastic scattering TAP angular distributions. The inclusion of these same potentials in calculations of \( (d, ^3\text{He}) \) TAP observables seriously degrades the quality of comparisons with the present experimental data. The present statistical uncertainty obtained for \( \eta \) is smaller than obtained previously. This work has been submitted for publication in Physical Review C.

3.2.3 Investigation of the D-state of \( ^6\text{Li} \) using \( (^6\text{Li}, d) \) and \( (^6\text{Li}, \alpha) \) Reactions

K. D. Veal, Z. Ayer, C. R. Brune, H. J. Karwowski, E. J. Ludwig, A. J. Mendez, A. Eiro\(^1\), F. D. Santos\(^1\), P. Green\(^2\), K. Kemper\(^2\), P. Kerr\(^2\) and I. J. Thompson\(^3\)

Although \( ^6\text{Li} \) D-state parameters are expected to be smaller than those for lighter nuclei, their determination can be quite interesting, since D-state effects arise from both the tensor forces and from n- and p-orbitals outside the \( ^4\text{He} \) core. Three-body (aNN) models of \( ^6\text{Li} \) predict a small and positive \( \eta( ^6\text{Li} ) \), but also predict the wrong sign for the quadrupole moment [Leh90]. Other models predict a negative \( \eta( ^6\text{Li} ) \) [Nis83]. The \( (d, ^6\text{Li}) \) and \( (^6\text{Li}, d) \) reactions can provide a means of determining the d-\( \alpha \) component of \( \eta( ^6\text{Li} ) \). However cross section, VAP, and TAP angular distributions obtained at TUNL for the \( ^{64}\text{Zn}(d, ^6\text{Li})^{60}\text{Ni} \) reaction, have revealed that direct \( \alpha \) transfer cannot always be assumed to be the predominant reaction mechanism [Bow92]. Analyses of these data show that excitation of the low-lying 3\(^+\) state in \( ^6\text{Li} \) contributes significantly to the reaction mechanism at deuteron

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Figure 3.2–1: Theoretical predictions for $T_{20}$ for $^{58}\text{Ni}(^{6}\text{Li}, d)^{62}\text{Zn}$ and $^{28}\text{Si}(^{6}\text{Li}, d)^{32}\text{S}$ at 50 MeV assuming a negative D- to S-state ratio (solid curve) of -0.0145 or positive ratio of the sample magnitude (dashed curve). A direct $\alpha$-cluster transfer is assumed.
energies below 20 MeV. In contrast, data at 45 MeV show angular distribution patterns consistent with direct $\alpha$ transfer [Jac79].

We have now identified suitable target nuclei, such as $^{58}$Ni and $^{28}$Si, which can be used to study the ($^6$Li, d) reaction with higher-energy, polarized $^6$Li beams obtained at Florida State University. At energies between 30 and 50 MeV, a simple, direct-reaction mechanism is expected to predominate and facilitate the determination of D-state parameters. Our exact finite-range DWBA calculations, using the computer code FRESCO, have indicated that quantities such as $T_{20}$ show a clear dependence on the magnitude and sign of the $\eta$ parameter, as shown in Figure 3.2–1. Information about the reaction mechanism obtained from VAP and TAP measurements for ($^6$Li, d) will also aid in establishing the validity of spectroscopic factors extracted for this reaction assuming a direct-alpha transfer. Discrepancies are apparent between the spectroscopic factors obtained for the various alpha-transfer reactions [Chu78].

Additional information about the $^6$Li D-state can be obtained from ($^6$Li, $\alpha$) reactions. These reactions might be measured simultaneously with ($^6$Li, d) using an appropriate combination of transmission and stopping detectors. Preliminary calculations for this reaction reveal a considerable sensitivity to magnitude and sign of the D-state parameters. They also have the advantage that there are no spin-dependent optical-model potentials in the exit channel.

A recent study of detector systems designed for measurement of the reaction products from $^6$Li-induced reactions has been conducted at Florida State. It appears that telescopes consisting of silicon $\Delta E$ detectors along with CsI-photodiode E detectors will provide an excellent system for measuring the deuterons of interest.

3.3 Photon-Induced Reactions on Very Light Nuclei

3.3.1 The $^4$He($\gamma$, d)$^2$H Reaction at $E_\gamma = 150–250$ MeV

The four-nucleon system serves as a critical testing ground for much of the theory of few body systems. Recent advances in few-body calculation techniques, which require accurate data to test the theory, have illuminated the paucity and/or inconsistency of data in certain systems at or above pion threshold. The $^4\text{He}(\gamma, d)^2\text{H}$ reaction with $E_\gamma = 150–250$ 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, ORi95].

We have designed, constructed, and tested an experimental setup at the Saskatchewan Accelerator Laboratory (SAL) with the goal of producing a definitive measurement of this cross-section. SAL contains a six-section linear accelerator with a Pulse Stretcher Ring (PSR) capable of producing 300 MeV electrons with a tagged $\gamma$-ray production of $10^8$ photons/second and more than 100 times greater untagged flux. We used a 7.5 cm diameter cylindrical liquid helium cell suspended vertically from a LHe cryostat to provide a large number of target nuclei. The detectors, pictured in figure 3.3–1, were BC-400 plastic scintillators organized into “arms” to the left and right of the incident beam direction. One arm consisted of seven plastic $\Delta E$-E telescopes centered about the target cell. The other arm, composed of a 1.5 meter plastic bar with fourteen thin plastic paddles in front to serve as $\Delta E$’s, was aligned to detect the recoil deuterons. This geometry provided a two-charged-particle coincidence that helped reduce the background from competing channels.

The test run was completed in July 1995. 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 untagged and tagged 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 additional kinematics information, was taken to provide background estimates for the competing channels. Preliminary results indicate reasonably low background as well as good particle identification. Analysis of these data along with data from a production run in the near future should resolve the discrepancy in the measured value of the cross section. These data will be combined with the LEGS analyzing power data in order to extract the multipolarites of the contributing capture amplitudes (see LEGS submission).


3.3.2 The $^4\text{He}(\vec{\gamma}, d)^2\text{H}$ Reaction at $E_\gamma = 185–330$ MeV


Studies of the four-nucleon system over the past 30 years indicate the need for continued research into photonuclear reactions involving this system with center of mass energies of several hundred MeV. One class of studies using polarized beams and the $^2\text{H}(d, \gamma)^4\text{He}$ reaction with $E_d < 100$ MeV [Wel88] stresses the importance of the D-state and the tensor force in this system and merits continued investigation at higher energies. Since 1962, five distinct measurements of the cross section of $^4\text{He}(\gamma, d)^2\text{H}$ (or its inverse) near $E_\gamma = 200$ MeV have resulted in a discrepancy of a factor of 100 [Sil84, ORi95]. This discrepancy coupled with the suggestion that the reaction may be dominated by E1 contributions in the energy regime near $E_\gamma = 213$ MeV [Sil84, Are76] constitute additional justification for further studies of $^4\text{He}$ at these energies.

With these questions in mind we have studied the angular and energy dependence of the reaction $^4\text{He}(\vec{\gamma}, d)^2\text{H}$ over the range of $E_\gamma = 185–330$ MeV. These data were taken at the Laser Electron Gamma Source (LEGS) at Brookhaven National Laboratory and involved

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the use of a liquid helium target developed by a group from the University of Rome. ΔE-E telescopes consisting of plastic scintillator paddles and NaI crystals and arranged into "arms" to the left and right of the incident beam direction were used to measure d-d coincidences. The cross section and vector analyzing power were measured at nine angles from $\theta_{\text{lab}} = 28$ to 130 degrees. These are the first polarized $\gamma$-ray data for this reaction or its inverse in this energy regime.

The analysis of the data is in progress. This analysis has been complicated by poor particle identification in one of the detector arms. Since we are unable to distinguish between a proton and a deuteron in this arm, the npd channel, which is nearly 100 times larger than the dd channel, provides a substantial background to the events of interest. As a result we have had to kinematically reconstruct each event. LEGS is a tagged backscattered photon facility, so we use the incident $\gamma$-ray energy and information from one reaction particle (including particle identification, kinetic energy, and reaction angle) to reconstruct events. Unfortunately, the second reaction angle is not known precisely, so pd background remains in the dd kinematic region. The final step, depicted in Figure 3.3–2, involves fitting the pd background and subtracting this from the data to obtain a good dd event count.

The extraction of cross section and vector analyzing power data as functions of energy and angle is nearing completion. Preliminary results provide an upper limit of 2 to 9 nb/sr
differential cross section, narrowing the discrepancy in cross section measurements from a factor of 100 to less than a factor of 10. We expect to be able to comment definitively on the question of E1 contributions as soon as analysis of the cross section and analyzing power data is complete. Once final results have been obtained we will perform a transmission matrix element (TME) analysis to determine the importance of the D-state in this energy regime.


3.4 Radiative-Capture Reactions with Polarized Beams

3.4.1 Radiative Capture of Polarized Protons by Deuterium in the Energy Range $E_p(\text{lab}) = 80–0$ keV

G. J. Schmid, R. M. Chasteler, M. A. Godwin, C. M. Laymon, R. M. Prior, B. J. Rice, D. R. Tilley and H. R. Weller

The D($\vec{p}$, $\gamma$)$^3$He reaction has been studied in the energy range $E_p(\text{lab}) = 80–0$ keV ($E_{cm} = 53.3–0$ keV). The quantities measured were the cross-section, $\sigma(\theta,E)$, the astrophysical S-factor, $S(\theta,E)$, the vector analyzing power, $A_y(\theta,E)$, and the $\gamma$-ray polarization $P_\gamma(\theta)$. The primary goal of the present work has been to extract, with better accuracy than previous results [Gri63], the D($p$, $\gamma$)$^3$He electric dipole (E1) and magnetic dipole (M1) cross-section and S-factor components over the energy region $E_p(\text{lab}) = 80–0$ keV. The novel contributions of the current work include the following: the use of polarized beams for the purpose of measuring $A_y(\theta)$ (sensitive to E1/M1 mixing); and the use of a high purity germanium (HPGe) $\gamma$-ray detector. The high intrinsic resolution of the HPGe detector (4.2 keV at $E_\gamma = 5.5$ MeV) has allowed us to directly observe the energy dependence of the D($p$, $\gamma$)$^3$He reaction in our spectra. By measuring angular distributions with this detector, we have thus been able to obtain the $\sigma(\theta)$, $S(\theta)$, and $A_y(\theta)$ observables as a function of $E_p(\text{lab})$.

In the present D($\vec{p}$, $\gamma$)$^3$He experiment, the procedure followed was to stop an 80 keV proton beam in a heavy water (D$_2$O) ice target. This created a range of incident beam energies from $E_p(\text{lab}) = 80–0$ keV. For an HPGe lab angle of 90°, this spread in incident beam energies translated into a spread of outgoing $\gamma$-ray energies from $E_\gamma = 5.49$ to 5.54
Figure 3.4–1: \( \text{D}(\vec{p}, \gamma)^3\text{He} \) full energy peak spectrum (for \( \theta_{\text{lab}} = 90^\circ \)) shown along with a convolution fit (solid curve).

MeV. Figure 3.4–1 shows a typical HPGe full energy peak spectrum acquired for the \( \gamma \)-rays in \( \text{D}(\vec{p}, \gamma)^3\text{He} \). This particular spectrum was acquired at \( \theta_{\text{lab}} = 90^\circ \) (other spectra were acquired at \( \theta_{\text{lab}} = 0, 30, 60, 105, \) and \( 120^\circ \)). The sloping of the peak on the low energy side is due to the energy dependence of the \( \text{D}(\vec{p}, \gamma)^3\text{He} \) yield. In order to extract the energy dependence of the \( \text{D}(\vec{p}, \gamma)^3\text{He} \) S-factor, \( S(E_{\text{cm}}) \), two separate data analysis procedures were undertaken. The first involved simply binning the full energy peak into a series of energy regions based on incident beam energy. The yields acquired for each energy bin were then used (along with information about the proton stopping cross section, the HPGe detector efficiency, etc.) to calculate cross sections, S-factors and vector analyzing powers for each energy region. The second data analysis method used was a convolution fit to the raw spectrum as shown by the solid line in Figure 3.4–1. In the convolution fit procedure, the effects of the HPGe detector response function were removed from the raw spectra in order to create “deconvoluted” yield spectra. These deconvoluted yield spectra could then be used in order to fix the absolute magnitude and slope of a linear \( \text{D}(\vec{p}, \gamma)^3\text{He} \) S-factor function.

Figure 3.4–2 shows by the solid data points the S-factor results of the binning analysis on the raw spectra. The solid line in Figure 3.4–2 shows the results of the deconvolution analysis. The open points in Figure 3.4–2 are the previous results of Griffiths et al. [Gri63].

One important thing to notice about Figure 3.4–2 is that the current results lie 41–52% lower than the previous results over the energy region studied. Although erroneous stopping cross section values in the Griffiths et al. analysis should lower their quoted S-factor values by 10–15% over the energy region studied, this correction will not be sufficient to resolve the
Figure 3.4–2: The current binning results (solid points) and the current deconvolution results (solid line) for D(\vec{p}, \gamma)^3\text{He} are shown along with the previous experimental results (open points) and the theoretical calculations of Schiavilla et al. (dashed and dotted curves). Systematic error is included in the data points.

discrepancy with the current results [Sch95a]. The dotted curve in Figure 3.4–2 represents the preliminary results of a three-body calculation for the D(\vec{p}, \gamma)^3\text{He} reaction [Shi95] which includes only the nucleonic degrees of freedom in the electromagnetic operator (i.e. the impulse approximation). The dashed line in Figure 3.4–2 is the same calculation whereby the non-nucleonic degrees of freedom (i.e. the meson-exchange current effects) have been added in. Disagreement between the full theoretical S-factor result and the current experiment S-factor result is clearly indicated. The concordance between theory and experiment with regards to the vector analyzing power is somewhat better, as shown in Figure 3.4–3.

By performing a transition matrix element fit to the current total S-factor and vector analyzing power data for D(\vec{p}, \gamma)^3\text{He}, the E1 and M1 S-factor components can be extracted. A three-body calculation for the M1 S-factor at zero energy has been done [Fri91], and can be compared with our extracted value. The three-body calculation predicts an M1 S(0) of $0.108 \pm 0.004$ eVb. This is significantly higher than the currently extracted value of $0.079 \pm 0.008$ eVb (including systematic error).

The importance of the D(p, \gamma)^3\text{He} reaction in protostellar evolution has been described by Stahler [Sta88]. The fact that our measured D(\vec{p}, \gamma)^3\text{He} S-factor is 41–52% lower than currently believed could affect astrophysical calculations dealing with protostellar evolution.
The D(p, γ)³He reaction rate should not be of importance in main-sequence solar fusion because of the bottleneck caused by the weak p-p fusion reaction [Rol88].

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3.4.2 T²₀ Measurements for ¹H(d, γ)³He and the P-Wave Component of the Nucleon-Nucleon Force

G. J. Schmid, R. M. Chasteler, A. C. Fonseca, M. A. Godwin, D. R. Lehman, D. R. Tilley, H. R. Weller
Measurements of $T_{20}(\theta_{\text{lab}} = 90^\circ)$ for $^1\text{H}(\vec{d}, \gamma)^3\text{He}$, in the energy range $E_{d(\text{lab})} = 12.7$–19.8 MeV, have been compared with the results of new exact three-body Faddeev calculations using separable versions of the Paris and Bonn-A nucleon-nucleon (NN) potentials. A strong sensitivity of the $T_{20}$ observable to the NN P-waves is noted. In particular, we find that for $T_{20}$ in $^1\text{H}(\vec{d}, \gamma)^3\text{He}$, the $^3P_1$ component is the dominant NN P-wave piece. This contrasts with the results of polarized n-d scattering experiments, whereby the $^3P_0$ component has been shown to be the most important NN P-wave piece [Tor91].

Figure 3.4–4 shows the current $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ data from 12.7 to 19.8 MeV plotted along with a previous point at 10 MeV [Goe92]. The point at 19.8 MeV has been averaged with a previously existing point [Vet85]. The dashed curve is a three-body calculation which neglects the NN P-wave force, while the solid curve is the same calculation which includes the NN P-waves. The importance of the NN P-waves in determining this observable is clearly noted. Furthermore, Table 3.4–1 shows the results of a series of calculations done at 8 MeV which separately turn on the NN P-wave components (in the intermediate rescattering state) in order to identify the dominant NN P-wave piece (the NN P-waves in the ground state and continuum state do not play a very important role here). Turning on the $^3P_1$
3 Dynamics of Very Light Nuclei

Table 3.4–1: Results of Faddeev calculations for $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ at $E_{\text{d}_{\text{lab}}} = 8$, done to identify the dominant NN P-wave piece.

<table>
<thead>
<tr>
<th>Calculation</th>
<th>$T_{20} (\theta_{\text{lab}} = 90^\circ)$</th>
<th>$\Delta$ (rel. to calc. #3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No NN P-waves</td>
<td>-.0563</td>
<td>——</td>
</tr>
<tr>
<td>2. NN P-waves in gnd. state only</td>
<td>-.0559</td>
<td>——</td>
</tr>
<tr>
<td>3. NN P-waves in gnd. state &amp; continuum</td>
<td>-.0455</td>
<td>——</td>
</tr>
<tr>
<td>4. (–)+ $^1P_1$ in int. rescatt. state</td>
<td>-.0497</td>
<td>-.0042</td>
</tr>
<tr>
<td>5. (–)+ $^3P_0$ in int. rescatt. state</td>
<td>-.0359</td>
<td>.0097</td>
</tr>
<tr>
<td>6. (–)+ $^3P_1$ in int. rescatt. state</td>
<td>-.0302</td>
<td>.0153</td>
</tr>
<tr>
<td>7. (–)+ $^3P_2$ in int. rescatt. state</td>
<td>-.0432</td>
<td>.0023</td>
</tr>
<tr>
<td>8. (–)+ $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$ in int. rescatt. st.</td>
<td>-.0221</td>
<td>.0235</td>
</tr>
</tbody>
</table>

component clearly has the largest effect on the $T_{20}$ observable and is thus identified as the dominant NN P-wave piece.

---


### 3.4.3 The $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ Reaction at 80–0 keV


Over the past two years the Radiative Capture Group at TUNL has been studying the reaction $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ with incident beam energies of 80–0 keV, corresponding to center-of-mass energies 54–0 keV [Sch95a, Sch95b]. Recent low-energy few-body calculations [Fri91] have highlighted the role of meson-exchange currents (MEC) in this system. The goal of our research is to test the current theory and motivate the generation of improved theories.

In order to further our understanding of the $^3\text{He}$ system at very low energies we have begun studying the reaction $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ using both tensor polarized and unpolarized deuterons with incident lab energies of 80–0 keV, or center of mass energies 27–0 keV. This range of energies was obtained by stopping an 80 keV deuteron beam in an H$_2$0 ice target. The emitted gamma rays were detected using two large high-purity germanium detectors with 4 keV resolution at 5.5 MeV. We have measured angular distributions of both the cross section (from 0 to 90 degrees) and the tensor analyzing power $T_{20}$ (from 0 to 150 degrees).
Figure 3.4-5: $T_{20}(\theta)$ data for the $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ reaction at $E_{d} = 80-0$ keV. The curves are the results of simultaneous TME fits (using E1 and M1 terms only) to $T_{20}$ and cross section data from this reaction and $A_{Y}$ and cross-section data from the $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ reaction at $E_{p} = 40-0$ keV. The curves highlight the sensitivity of the M1 terms to the asymmetry in $T_{20}$. 
We have begun a transition matrix-element (TME) analysis of these data simultaneously fitting them together with the cross-section and vector analyzing power data from the reaction $^2\text{H}(\vec{p}, \gamma)^3\text{He}$ at lab energies 40–0 keV (center-of-mass energies 27–0 keV). Preliminary results indicate that E1 transitions to the S- and D-states of $^3\text{He}$ as well as M1 transitions must be included in order to fit the data. We have used a recent three-body Faddeev calculation [Leh94] of the $^3\text{He}$ system to impose constraints upon our fitting routines. This calculation gives essentially equal amplitudes and phases for the $^2\text{P}_2$ and $^2\text{P}_4$ E1 transition amplitudes. The best fits to the data (using E1(l=1) and M1(l=0) terms only) under these constraints give M1 contributions to the total cross section as large as 30%.

Since we have $T_{20}$ data that extend from 0 to 150 degrees, we have been able to determine the fore-aft asymmetry of $T_{20}$, which in turn provided information on the distribution of M1 strength among the s-wave amplitudes. Fore-aft asymmetry in $T_{20}$ must arise from interference between radiations having opposite parity (in this case E1 and M1), and between interfering terms whose s and s’ triangulate to 2. Preliminary results (see figure 3.4–5) suggest that the $^4\text{S}_4$ strength accounts for one half or more of the total M1 strength. This result is especially important since this ratio is sensitive to the detailed treatment of meson-exchange currents in the calculations. We hope in the near future to compare this interesting result with ongoing theoretical calculations using a variational technique that includes both Coulomb and MEC effects [Sci95].

References


3.4.4 Measurement of Vector and Tensor Analyzing Powers for $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ at Very Low Energies

Lijun Ma, H. J. Karwowski, C. R. Brune and E. J. Ludwig

Measurement of the analyzing powers of the $^1\text{H}(\vec{d}, \gamma)^3\text{He}$ reaction plays an important role in understanding low-energy few-body capture reaction mechanisms, especially meson-exchange current effects and Coulomb effects. The reaction is also interesting because it serves as one of the leading reactions in proton-proton chain burning process in the standard solar model.
Figure 3.4–6: The energy dependence of $A_{zz}$ at $90^\circ$ and $0^\circ$. 
We have measured full angular distributions of $A_y$, $A_{yy}$ and $A_{zz}$ for this reaction. A vapor-condensed ice target was bombarded by 330 keV deuterium ions, which were accelerated through the upgraded Low Energy Beam Facilities (LEBF). The reaction gamma rays were measured using two large volume high-purity germanium detectors which have efficiencies of 127% and 145%. We placed detectors symmetrically and used the fast spin-flip scheme to determine analyzing powers independently. The energy dependence was extracted using the MINUIT fitting routine [Ma94] at each measured lab angle i.e. 0°, 35°, 60°, 90°, 120°, 135°.

The measured energy dependence of $A_{zz}$ at 0° and 90° is shown in Figure 3.4–6. The error bars on the data points correspond to the one-sigma confidence level. For center-of-mass energies from 35 keV to 110 keV, $A_{zz}$ is negative at 90°, while at 0°, it is consistently positive. More data analysis and theoretical calculations based on the refined resonating group model are now in progress.


3.4.5 Low-Energy Polarized-Proton Capture on $^6$Li

C. M. Laymon, R. M. Prior, R. M. Chasteler, M. A. Godwin, G. J. Schmid, D. R. Tilley, H. R. Weller

Previous [Cha94] and ongoing (described elsewhere in this report) studies of the $^7$Li($\vec{p}, \gamma_0$)$^8$Be reaction at 80 keV in this laboratory reveal large analyzing powers and the presence of a considerable p-wave contribution to the reaction. As part of a systematic investigation of the low-energy radiative-capture process, we have used 80 keV protons directly from the TUNL Intense Polarized Ion Source to measure cross-section and analyzing power angular distributions for the reaction $^6$Li($\vec{p}, \gamma$)$^7$Be. Data were acquired using two large high-purity germanium detectors, one of which was kept fixed at 90°. The other detector had an active NaI shield and was used to acquire data at 5 angles from 0 to 120 degrees. A thick target of enriched $^6$Li was used to stop the beam so that integrated yields were obtained. Figure 3.4–7 illustrates the results for capture to the ground state of $^7$Be. The angular distribution of $\gamma$-rays, illustrated in part A of the figure, is nearly isotropic and the analyzing power, displayed in part B, varies only slightly from zero. The cross-section and analyzing power angular distributions for the $^6$Li($\vec{p}, \gamma$)$^7$Be reaction are similar. These results can be contrasted with $^7$Li($\vec{p}, \gamma_0$)$^8$Be reaction studies in which 20% anisotropies and analyzing powers of about 0.4 (at 90°) are seen.

Values of $A_y(\theta = 90°)$ other than zero and cross-section asymmetries between angles symmetric about $\theta = 90°$ are the result of interference between amplitudes of opposite parity. No such interference is required to explain the current data. However, we have performed several transition matrix element (TME) analyses of the $^6$Li($\vec{p}, \gamma_0$)$^7$Be reaction.
An analysis in which the number of contributing TME’s was reduced to a single E1-s-wave and an M1-p-wave amplitude by making some reasonable assumptions results in a best fit, shown in Figure 3.4–7, that contains only a $(1 \pm 0.1)\%$ M1 contribution to the cross section. If one makes a different, less reasonable, two amplitude assumption, in which the TME’s are chosen to yield a large M1 contribution, the same fit results with a $(4 \pm 4)\%$ M1 contribution. In these two-amplitude analyses, there is a quadratic ambiguity between the E1 and M1 matrix elements. We have assumed that the M1 TME has the smaller amplitude.

Our results are in agreement with simple direct capture calculations that predict insignificant M1-p-wave strength. At these low energies, the p-wave contribution to the direct proton capture reaction in other p-shell systems, $^7$Li($p, \gamma$)$^8$Be for example, is generally predicted to be negligible. A difference between the $^7$Li($p, \gamma$)$^8$Be reaction in which evidence for a large p-wave contribution is seen and the present reaction which does not require any p-wave strength for its description is the relative widths and positions of p-wave resonances in the product nuclei. We are currently performing calculations to compare the effects of resonant tails in these two reactions.
3.4.6 The $^7\text{Li}(\vec{p}, \gamma)^8\text{Be}$ Radiative Capture Reaction at 80 keV


Over the last year we have been studying the $^7\text{Li}(\vec{p}, \gamma)^8\text{Be}$ reaction at energies $E_p = 80–0$ keV. We have been most interested in examining proton capture to the isospin-mixed $2^+$ states (16.62 and 16.92 MeV) in $^8\text{Be}$ in order to examine the p-wave contributions in this reaction. This reaction is closely related to the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction since the $2^+, T = 1$ ground state of $^8\text{B}$ is the isospin analog of the $T = 1$ part of the $2^+$ states in $^8\text{Be}$. Of these two excited states, the 16.62 MeV state is expected to be much more dominant than the 16.92 MeV state [Man81] in our reaction. We have studied the radiative capture to the 16.62 MeV state of $^8\text{Be}$ by stopping an 80 keV proton beam in our $^7\text{Li}$ target. The spectrum of gamma rays produced (which will be spread out due to the stopping of the beam) is dominated by the 108 keV width of the final state. This excited state of $^8\text{Be}$ subsequently decays to two alpha particles virtually 100% of the time.

The spectrum shown in Figure 3.4–8a depicts $\gamma$-ray events detected by the large (128%) high purity germanium (HPGe) detector when run in singles mode for approximately 100 hours with 25 $\mu$A of polarized proton beam on a thick $^7\text{Li}$ target. Note that no evidence for the third excited state ($E_\gamma = 698$ keV, $\Gamma \approx 110$ keV) is seen. In order to separate the associated $\gamma$-ray from background we are performing a coincidence experiment, detecting the 698 keV $\gamma$-ray and one alpha particle simultaneously. When this coincidence with the alpha-scintillator is required the result is Figure 3.4–8b. This requirement substantially reduces the background, and we are left with a peak depicting the third excited state. The data have been fit using a least-squares procedure based on Minuit, by applying a quadratic exponential background and a Breit-Wigner shaped resonance to the spectra. Thus, yields may be extracted for the various angles where the experiment has been performed. Shown in Figure 3.4–9a is the relative cross section for capture to the third excited state, normalized to yields going to the ground state, while Figure 3.4–9b shows the analyzing power data extracted from these yields. A transition matrix element (TME) analysis of the data has been performed, including one s-wave, E1 and one p-wave, M1 partial wave. The results are shown as a dashed curve in Figure 3.4–9. Because of the quadratic nature of the equations involved, two solutions are found, both of which are mathematically valid. One consists of 0.1% M1 admixture, the other 0.1% E1.

In order to distinguish between these we wish to measure the polarization of this 698 keV $\gamma$-ray. When a photon of this energy enters the germanium detector, it will sometimes lose a portion of its energy due to Compton scattering. The plan is to detect the scattered gamma ray in the NaI annulus and detect the residual energy in the HPGe detector. With
Figure 3.4–8: a) $\gamma$-ray spectrum obtained in detector system. b) Same spectrum as part a) but in coincidence with an alpha event in the scintillator.

Figure 3.4–9: Data gathered for a) the relative cross section and b) the analyzing power for the $^7\text{Li}(\vec{p}, \gamma)^8\text{Be}$ reaction at $E_{\text{lab}} = 80-0$ keV. The dashed curves represent a TME fit to the data.
this we may measure an up-down, left-right asymmetry, and thus deduce the polarization of the incident radiation. This project is currently underway.

To conclude, we have begun a detailed study of proton capture to the $2^+, T = 0 + 1$ states of $^8\text{Be}$. The reaction is related to the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction since the $2^+, T = 1$ ground state of $^8\text{B}$ is the isospin analog of the $T = 1$ part of the $2^+$ states in $^8\text{Be}$ and must therefore possess the same space-spin wavefunction. Unfortunately, the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction is very difficult to measure and no experiments have been performed involving the direct detection of $\gamma$-rays. By detecting alpha particles from $^8\text{B}$, cross-section measurements exist as low as $E_p = 134$ keV [Fil83]. Our experiment allows us to study a closely related reaction at much lower energies. In addition, we use a polarized beam, measure $\gamma$-rays directly, and can even measure the polarization of these $\gamma$-rays. A detailed study of our reaction should lead to a deeper understanding of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction, and thus a more reliable extrapolation of low-energy cross sections and the astrophysical S-factor.


3.4.7 The $^7\text{Li}(p, \gamma)^8\text{Be}$ Radiative Capture Reaction to the Ground and First Excited States


In addition to data for the third excited state, we have also obtained new data using our 128% HPGe detector for capture to the ground and first excited states of $^8\text{Be}$. Shown in Figure 3.4–10a and Figure 3.4–10b are the relative cross-section and analyzing power data vs. lab angle for the $\gamma_0$ transition. The circles represent the previously published NaI data of Chasteler et al. [Cha94]. At energies of 100 keV or less, it has been assumed in previous work [Cec92] that s-wave capture (E1) would dominate the reaction. It is clear from the anisotropic behavior of the cross section and the non-zero analyzing powers that multipole radiation other than E1 is involved. In fact, analysis of the data shows the presence of significant p-wave strength, which could reduce the astrophysical S factor by 7%–38%. Our preliminary new measurements reproduce these analyzing power data, with significant statistical improvement. Figure 3.4–10c and Figure 3.4–10d show the same observables for capture to the first excited state. The previously unpublished data of Chasteler et al. [Cha94] are again shown as circles. Here the data indicate no unusual behavior; the cross section is uniform and the analyzing power is zero. Our preliminary new data show the same effects.
Figure 3.4–10: Shown here are the cross-section and analyzing power data for capture to the ground state and first excited state of $^8$Be. In all four pictures the NaI data of Chasteler et al. are shown as circles and the preliminary HPGe data are shown as squares. The curves represent the TME fit of Chasteler.
Since the proton beam stops in the target, this data represents an integrated yield from 80–0 keV. Proton energies of 20 keV or less are significant for astrophysics (in fact the astrophysical S factor is a representation of the zero-energy cross section), and thus it would be quite interesting to examine these observables at lower energies. The measured width of the ground state is quite small ($\Gamma_{c.m.} = 6.8$ keV), and is clearly separated from natural background ($E_\gamma \approx 17.3$ MeV). Because of these properties and because of the excellent energy resolution of the large HPGe detector that we are using, we plan to deconvolute (or at least bin) the $\gamma_0$ data and obtain analyzing power and cross-section data as a function of energy as well as angle. A similar procedure has been successfully employed by Schmid [Sch95] for the $^2$H(p, $\gamma$) reaction and is soon to be published.


3.4.8 Comment on the $^7$Li(p, $\gamma$)$^8$Be Reaction at Energies of Astrophysical Interest

H. R. Weller and R. M. Chasteler

The results of two recent publications [Rol94, Zah95] are reconsidered. These papers argue that the p-wave effects seen in the $^7$Li(p, $\gamma$)$^8$Be reaction below $E_p = 80$ keV, reported in [Cha94], can be accounted for by considering the low-energy tail of the p-wave resonance at $E_p = 441$ keV. It is shown that the cross section and analyzing power data require an order-of-magnitude more p-wave strength when considered together.

Recently reported polarized proton capture data on $^7$Li indicated a substantial p-wave contribution to this reaction at energies below $E_p = 80$ keV [Cha94]. These results are important in that they could impact the manner in which cross sections are extrapolated below $E_p = 100$ keV in order to obtain astrophysical S-factors.

There have been two recent papers which have addressed this result [Rol94, Zah95]. These papers argue that the results of [Cha94] can be accounted for by considering the p-wave contribution near 80 keV due to the tail of the $1^+$ resonance at $E_p = 441.4$ MeV. It is argued in [Rol94], for example, that the interference of this resonance-tail p-wave strength with the s-wave direct-capture stength (E1) can account for the results of [Cha94]. This paper was written to point out that this is not the case. It is also pointed out in this paper that there was an error in [Rol94] in their equation for $a_1$. In the work of [Zah95] only the angular distribution of the cross section was considered and when the analyzing power, $A_y$, is considered simultaneously their results are not sufficient.
In summary, this note has shown that the data of [Cha94] cannot be accounted for by the
tail of the $1^+$ p-wave resonance at $E_p = 441$ keV in the $^7\text{Li}(p, \gamma)^{8}\text{Be}$ reaction. The fore-aft
asymmetry in the cross section along with the measured analyzing power at 90° require at
least an order-of-magnitude more p-wave strength than that expected from the tail of this
resonance. The physical origin of this anomalous p-wave strength remains unaccounted for.


### 3.4.9 Low-Energy Proton Capture on $^9\text{Be}$

**R. M. Prior, C. M. Laymon, E. A. Wulf, M. A. Godwin, D. R. Tilley, H. R. Weller**

Continuing our investigation of low-energy radiative capture on light elements, we are
beginning a study of $^9\text{Be}(p, \gamma)^{10}\text{B}$. Because of nearby levels of $^{10}\text{B}$ it is expected that
there may be effects on the analyzing power of $^9\text{Be}(p, \gamma)^{10}\text{B}$. Data will be acquired for the excitation of several excited states of $^{10}\text{B}$.

The first data will be taken in the summer of 1995. Polarized protons from the intense
polarized ion source will be accelerated to 80 keV by the source high voltage. The beam
energy at the target will be increased to 100 keV by biasing the target to -20 kV. This is necessary because the cross section for $^9\text{Be}(p, \gamma)^{10}\text{B}$ is over an order of magnitude less than the previously studied reactions with Li targets. Increasing the beam energy from 80 keV to 100 keV increases the reaction yield by a factor of 5. Data will be taken with 2 high-efficiency, high-purity germanium detectors. Beam intensity and the target condition will be monitored by detecting with solid state detectors the alpha particles and deuterons from the $^9\text{Be}(p, \alpha)^6\text{Li}$ and the $^9\text{Be}(p, d)^8\text{Be}$ reactions.

### 3.4.10 Fluctuation Effects in Radiative Capture to Unstable Final States:
A Test via the $^{89}\text{Y}(\vec{p}, \gamma)^{90}\text{Zr}$ Reaction at $E_p = 19.6$ MeV

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The work on this experiment has been completed and has been published in the July 1995 issue of Physical Review C. The abstract is listed below. In short, the γ-ray spectra from proton capture on $^{90}$Zr has been extensively studied, utilizing a 19.6 MeV polarized beam from the TUNL tandem accelerator. The purpose of this experiment was to examine radiative capture reactions leading to bound and continuum final states which have excitation energies above those for which direct-semidirect (DSD) processes dominate, but below the statistical region. Non-zero values of the analyzing power and fore-aft asymmetry above a γ-ray energy of 15 MeV suggest the presence of direct reactions. An extended DSD theory has been developed, central to this is the inclusion of fluctuation effects. This corresponds to compound nuclear damping of single-particle states formed during radiative capture. The results for capturing to final states at higher excitation energies may be explained by including both direct-semidirect and Hauser-Feshbach mechanisms. No large contributions from multistep processes are observed in this work, although the effects of these mechanisms are not fully explained.

We have developed an extended direct-semidirect (DSD) model for fast nucleon capture to virtual single-particle configurations that subsequently damp into the compound nucleus or (at sufficiently high excitation energies) escape into the continuum. The inclusion of final-state fluctuation effects is an important feature in this model. To test the model we have measured the spectra of gamma rays from approximately 10 MeV to the endpoint in the $^{89}$Y($\bar{p}, \gamma$)$^{90}$Zr reaction with 19.6 MeV polarized protons from the TUNL tandem accelerator. Gamma spectra were measured with a pair of 25.4 cm x 25.4 cm anti-coincidence shielded NaI detectors at angles of 30°, 55°, 90°, 125° and 150° with respect to the incident beam. The spectra show significant analyzing powers and forward peaking of the angular distributions. These features allow for discriminations between compound processes and direct processes. Analyzing powers and fore-aft asymmetries were observed for gamma energies below those associated with direct-semidirect transitions to known bound final states. We have also performed Hauser-Feshbach calculations of the statistical component of the gamma emission, which dominates below approximately 15–16 MeV. The extended DSD model reproduces the spectral shapes and analyzing powers above this energy quite well. There is no evidence in the present reaction that additional mechanisms, such as multistep compound or multistep direct emission, are required.