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The $^4\text{He}(\gamma,\text{dd})$ Reaction at $E_\gamma = 150-250$ MeV

by

Bryan Joseph Rice

Department of Physics
Duke University

Date: 3/6/98

Approved:

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Berndt Müller

Calvin R. Howell

Alfred M. Lee

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

1998
ABSTRACT

(Physics – Nuclear)

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ABSTRACT

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

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We have performed a measurement of the cross section for the $^4\text{He}(\gamma,\text{d})^2\text{H}$ reaction with $E_\gamma=150$-250 MeV at the Saskatchewan Accelerator Laboratory (SAL). The experiment was performed using bremsstrahlung $\gamma$ rays produced by a 273 MeV electron beam. The target was liquid helium contained in a simple cryostat. Two detector arms consisting of plastic scintillator telescopes were utilized to detect both reaction particles in coincidence. We obtained relative and absolute cross sections at six angles in two energy bins (150-190 and 190-250 MeV).

The angular distribution of the cross section shows peaking behavior at $90^\circ$ in the center-of-mass frame. A Legendre polynomial fit to the data shows this distribution can be described by a $\sin^2\theta$ angular distribution. This distribution suggests the presence of electric dipole or E1 radiation, but isospin selection rules and identical bosons in the exit channel forbid the dominant $\Delta S=0$ E1 transition. Performing a transition-matrix element (TME) analysis using only strictly allowed transitions, we found that the observed angular distribution could be described by the constructive interference of just two TME's: electric quadrupole (E2) s- and d-wave capture to the D-state of $^4\text{He}$.

We performed a direct-capture calculation in order to determine if the D-state could contribute to such a high degree to the cross section. Our calculations, which used an optical model potential from elastic scattering data at lower energies, yielded the result that 90% of the cross section arises from capture to the D-state. The calculation, however, places all capture strength to the D-state into g-wave capture and, as a result, fails to reproduce the observed $\sin^2\theta$ angular distribution. The lack of existing theoretical work for this system
at these energies conspires to keep the mechanism for this angular distribution unclear, but we hope this result will motivate four-body theorists to extend their calculations to this energy range in the near future.
Acknowledgements

The work you hold in your hands represents the culmination of 23 years of education. I knew from a very early age that I wanted to be a “scientist.” My parents encouraged me from the start by patiently answering the countless questions of an inquisitive child, and I am sure that was the source of my fascination with learning and discovery—the trademarks, in my opinion, of true scientists. So to my parents and brothers, thanks for all your support!

Other people have nurtured my love of learning. Although the list is too long to enumerate here, many of my high school teachers nudged me toward math and physics. To all of them, a very heartfelt thank you. Once I had made my decision to major in physics at Georgia Tech, I found that my hunger for knowledge required a varied diet. Luckily, there were lots of professors in other fields ready with suggestions about how I should appease that hunger. To all my non-physics professors I also say thank you.

Graduate school has been a great challenge. For helping me to get through with my sanity (mostly) intact I want to thank my classmates, especially Bret Crawford, Jay Dittmann and Steve Lautenschlager. On the research end of things I would like to thank Bob Chasteler, Greg Schmid, Eric Wulf, Eric Schreiber, Shane Canon, John Kelley, Ron Tilley and Dick Prior. To my SAL colleagues Jerry Feldman, Norm Kolb, and Rob Pywell—you guys are the best. A very special thanks to Chip Laymon for hours of physics discussions. Also, special thanks to Mark Godwin, my officemate and chief cohort in lead brick stacking. And thanks to Henry Weller, my advisor, for his patience and support over the years.

Finally, I'd like to thank Lucy Saunders. I could not have done this without you.
For my parents
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Chapter 1

Historical Perspective and Introduction

1.1 The Electromagnetic Probe in Nuclear Physics

In 1911, Rutherford hypothesized the existence of the atomic nucleus to explain the results of his gold foil experiments. This event arguably marked the genesis of a new branch of science: nuclear physics. In the first half of the twentieth century, nuclear physicists led the search for understanding of the fundamental components of matter and the interactions between them. With the passage of time nuclear physics gave birth to particle physics and took a less prominent role in the search for new particles. At present, the goals of nuclear physics are to study the extrinsic properties of nuclei and to probe their internal structure in a search for better understanding of the interactions between nuclear constituents.

Many techniques have been employed to study nuclei and their internal structure since the early α-particle experiments of Rutherford. One class of techniques involves the use of electromagnetic probes to induce nuclear reactions. The photodisintegration of the deuteron by Chadwick and Goldhaber [Cha34] in 1934, where γ rays were used to break the deuteron into its constituent proton and neutron, represents the first experiment...
in photonuclear physics. The sister field of electronuclear physics began in 1951 when Lyman [Lym51] performed the first electron-nuclear scattering experiment.

The motivation for the development of real photon and virtual (i.e. electron) photon probes to study the nucleus was intimately related to progress in the theoretical understanding of the electromagnetic interaction. The development of quantum electrodynamics (QED), from the discovery of the Dirac equation in 1928 to the Nobel prize winning work of Feynman, Schwinger and Tomanaga, and beyond, yielded an unprecedentedly successful calculational framework for understanding the electromagnetic interaction. The result was that the electromagnetic component of the photo- and electronuclear reactions was well understood.

The implication of this is clear: with the electromagnetic interaction of the photon or electron understood, study of the hadrons-only interaction is possible. In addition to the solid understanding of the electromagnetic probe granted by QED, the relative weakness of the EM interaction compared to the nuclear interaction between nucleons makes applicable the techniques of perturbation theory. Furthermore, the large mean free path of the electromagnetic probes provides access to the entire volume of the studied nucleus, as opposed to hadronic probes which tend to interact at the surface of nuclei. For these reasons, the electromagnetic probe is one of the most reliable and useful tools for studying the nucleus.

Over the past fifty years, electron- and photon-based studies of nuclei have contributed to advances in the understanding of nuclear structure. The results of early elastic and inelastic electron scattering experiments led to the emergence of the picture of a nucleus as a collection of nucleons moving in a self-consistent mean-field potential. Photonuclear reactions led to the discovery of the giant dipole resonance [Bal47], which is due to the collective motion of the protons against the neutrons in a nucleus [Gol48]. Total photoabsorption experiments [Ahr75] exposed the inadequacy of theories based solely on nucleonic degrees of freedom and indicated the importance of meson-exchange currents (MEC's). This ushered in an era of electro- and photoproduction of pions which continues today. The dis-
covery of the EMC effect [Col83], the observation that nucleons behave differently in the vacuum than in the nuclear medium, has led to increased interest from nuclear physicists in deep inelastic scattering, once solely the domain of particle physicists.

The topics sketched in the last paragraph are meant only to indicate the importance of electromagnetic probes to the advancement of nuclear physics. The interested reader is urged to consult the references mentioned in the preceding paragraphs. In addition, an early but illuminating discussion of photonuclear reactions is given by Hayward [Hay70]. A more modern text dealing primarily with electron scattering by Boffi et al. [Bof96] is also very informative.

1.2 Modern Photonuclear Physics

The past twenty years have seen tremendous advances in facilities available for nuclear physicists studying photonuclear reactions. In the early days of photonuclear physics, the primary source of photon beams was bremsstrahlung radiation, positron annihilation, or radiative capture γ rays. For the first two cases, an electron beam is incident on a radiator which produces a continuous spectrum of γ rays (bremsstrahlung) or positrons. In the case of the positrons, they can be analyzed by a magnet and directed toward an annihilation target, producing annihilation γ rays. In the radiative capture sources, protons or neutrons are directed at the appropriate nuclear targets which emit monochromatic capture γ rays.

Of these techniques, only the bremsstrahlung technique remains viable as the required γ-ray energy increases. In particular, the γ-ray yield from positron annihilation lags that of the bremsstrahlung method by 10^5. In radiative capture, the cross sections drop off rapidly with increasing beam energy leading to decreased γ-ray yield at higher energies. The bremsstrahlung technique has its own attendant problems, however. Since the spectrum is continuous, not monochromatic, determination of cross sections as a function of γ-ray energy is difficult. Furthermore, normalization of the overall bremsstrahlung flux incident upon a nuclear target can be quite difficult and can lead to sizable systematic
errors.

A solution to both the $\gamma$-ray energy and bremsstrahlung flux determination problems was proposed and implemented by O'Connell [O'C62]. His bremsstrahlung monochromator, depicted in Fig. 1.1, consisted of the standard bremsstrahlung setup of electron beam, photon radiator, sweep magnet, and nuclear target, but also included a recoil electron detector and coincidence logic. The electron detector was placed such that electrons emitting bremsstrahlung $\gamma$ rays of the desired energy were deflected by the sweep magnet into the detector. Signals from this electron detector were counted to determine the total incident $\gamma$ ray flux and were sent to coincidence logic connected to the output of the nuclear radiation detector setup. A coincidence event indicated a nuclear event caused by an incident $\gamma$ ray of the selected energy, aside from the occasional accidental coincidence. This technique was dubbed photon tagging.

![Bremsstrahlung monochromator](image)

Figure 1.1: The bremsstrahlung monochromator of O'Connell [O'C62]

Several photon tagging facilities have been constructed since O'Connell's pioneering work. The newer facilities have improved upon his original setup in various ways. Most
have implemented a multi-channel tagging system which allows the tagging of photons over a broad range of energies with resolutions of 1-5 MeV. The photon tagging facility at the Saskatchewan Accelerator Facility has been operating since 1989 and was upgraded to 62 channels in 1993 with a γ-ray energy resolution of less than 1 MeV [Vog93]. The photon tagging spectrometer at the University of Mainz uses coherent bremsstrahlung from an aligned diamond radiator crystal to produce linearly polarized photons with up to 60% linear polarization. The photon tagger in Hall B at the Continuous Electron Beam Accelerator Facility (CEBAF) consists of a 384 channel tagging spectrometer capable of tagging photons in a range 800 MeV wide.

Another technique for producing high energy photons that has emerged in the past fifteen years involves the Compton scattering of laser light from high-energy electrons. The laser photons are backscattered as γ rays with energies that depend upon the electron energy. The first such facility was constructed at Frascati in 1980, which produced both linearly and circularly polarized photons of up to 80 MeV. The technique was duplicated at Brookhaven National Laboratory with the LEGS project which can provide γ rays having energies of up to 470 MeV.

A related technique is currently being developed at Duke University's Free Electron Laser Laboratory. In this process, electrons in an electron storage are caused to emit photons of a few eV by wiggler magnets in an optical cavity. Mirrors at the end of the cavity reflect the photons so that their position coincides with the original electrons after each pass of the electrons through the ring. This creates a lasing gain (the free electron laser) which increases the photon density significantly. A second bunch of electrons, 180 degrees out of phase with the first packet, interacts with the laser photons producing inverse Compton γ rays with essentially 100% polarization. This technique promises an increase in flux of three orders of magnitude over the Compton backscattering technique employed at LEGS.

Accelerator technology advances have accompanied the improvements in photon
creation methods. The early electron accelerators were pulsed beam accelerators which created intense bursts of electrons (and consequently, photons) which would inundate an experiment's detectors for brief periods of time, followed by comparatively long periods of inactivity. A measure of the pulsed nature of an accelerator is given by its duty cycle, defined as the time width of a single pulse divided by the time between pulse starts. Typical early linear accelerator duty cycles were on the order of 0.1%. Such pulsed beams create problems in experiments where multiple reaction particles must be detected in coincidence. As the beam intensity increases for a given duty cycle, the chance of detecting accidental coincidences between reaction particles from two or more distinct nuclear events increases rapidly. The result is that the experimental detectors impose limitations on the beam flux significantly below the accelerator's capabilities in order to keep the accidental coincidence rate at acceptably low levels.

The solution to this problem is to create a high duty cycle accelerator that can deliver a continuous beam instead of a pulsed one. Multiple techniques exist for creating continuous beams. The first is to inject a continuous electron beam into a racetrack-shaped microtron and then recirculate the beam sequentially through the accelerating sections until the desired energy is achieved. This method has been employed at the Thomas Jefferson National Accelerator Facility's CEBAF, which can provide up to three continuous beams simultaneously. Another technique is to append a pulse stretcher ring (see Sec. 2.1.3) to the linear accelerator. In this case, beam is extracted from the ring in a continuous fashion between injections from the linear accelerator. The first such ring was completed at the Saskatchewan Accelerator Laboratory in 1986.

The combination of photon tagging and accelerator technology available today makes possible high precision studies of low count-rate coincidence reactions which could not be obtained previously. In the next section we will discuss the history of the application of this technology toward measuring the $^4\text{He}(\gamma,dd)$ system.
1.3 Previous Measurements of $^4\text{He}(\gamma, dd)$

The $^4\text{He}$ system has been the subject of a great deal of experimental and theoretical study in the past thirty years. On the experimental side, searches for charge-symmetry breaking have been conducted by measuring the ratio of the $(\gamma, n)$ and $(\gamma, p)$ cross sections near threshold (see [Lag94] and references contained therein) and by measurements looking for $(dd, ^4\text{He} \pi_0)$ [Hen69]. The observation of a non-zero tensor analyzing power $T_{20}$ [Wel84] indicated that the $^2\text{H}(d, \gamma) ^4\text{He}$ reaction is sensitive to the $D$-state, and hence tensor force effects, in the ground state of $^4\text{He}$. Measurements of the $^2\text{H}(d, \gamma)$ reaction at deuteron energies below 80 keV [Kra92] yielded unexpected (and unexplained) observation of $p$-wave strength in this system. The interested reader is directed to the data compilation work on $^4\text{He}$ [Til92] for a complete list of references.

The results of these experiments have sparked intense theoretical work in many different areas. Again, the reader is referred to Ref. [Til92] for an exhaustive listing of publications. Advances that are particularly relevant for the present work involve studies of the tensor force in the context of sophisticated treatments of the four-body system. The microscopic coupled channels resonating group model (MCCRG) has been successful in describing the cross section and analyzing power data at deuteron energies below 50 MeV [Unk92]. Green's function Monte Carlo (GFMC) [Sch86] and pair-correlated hyperspherical harmonic (PHH) variational techniques [Car97] offer nearly exact calculations of the ground and scattering states in the presence of realistic nuclear potentials. Finally, Faddeev calculation techniques, which are exact in nature (to the extent that the NN potentials are correct), have begun to be extended to the four-body [Fon86, Elk96] system.

Although at higher energies the emphasis in studying reactions involving $^4\text{He}$ has been on the $(\gamma, n)$ and $(\gamma, p)$ single nucleon knockout reactions, some interest has arisen in the $(\gamma, dd)$ reaction. Since 1962, no less than five measurements of this cross section have been attempted at or near $E_\gamma=200$ MeV. These results are shown in Fig. 1.2 and summarized in Table 1.1. Note that the cross sections quoted in the figure and given in
the text below are with respect to the photodisintegration reaction and, where appropriate, results from the inverse reaction have been corrected for detailed balance. A summary of absolute total cross section measurements is also shown in Fig. 1.3.

![Graph showing data for $\frac{d\sigma}{d\Omega}$ for $^4\text{He}(\gamma,dd)$](image)

Figure 1.2: World $\frac{d\sigma}{d\Omega}$ data for $^4\text{He}(\gamma,dd)$.

The earliest attempt to measure this cross section was made by Akimov et al. [Aki62] using the $^2\text{H}(d,\gamma)^4\text{He}$ reaction with $E_d = 404$ MeV, corresponding to $E_\gamma = 225$ MeV. One data point was obtained at $\theta = 42^\circ$ giving a differential cross section $d\sigma/d\Omega = 80 \pm 25$ nb. The next measurement was performed by Asbury and Loeffler on the $^4\text{He}(\gamma,dd)$ reaction at $E_\gamma = 221$ MeV. Again, one data point was obtained, giving the differential cross section at $\theta = 52^\circ$ to be $8.0 \pm 2.5$ nb, fully an order of magnitude smaller than the radiative capture measurement. Another photodisintegration experiment was conducted by Arends et al. with $E_\gamma = 213$ MeV (and higher energies). This time four data points were obtained, indicating a cross section more than an order of magnitude smaller than the Asbury measurement with an angular distribution maximum at $90^\circ$. The radiative capture reaction
Figure 1.3: World $\sigma_{TOT}$ data for $^4\text{He}(\gamma, dd)$ with $E_\gamma$ above 30 MeV. Data are from Akimov [Aki62], Asbury [Asb65], Meyerhof [Mey69], Arkatov [Ark73], Arends [Are76], and Pitts [Pit63].

was remeasured by Silverman et al. at an equivalent energy of $E_\gamma=213$ MeV. Two data points were acquired at $\theta=73^\circ$ and 91° indicating a flat angular distribution with a differential cross section about twice the magnitude of the Arends measurement. Finally, a very recent measurement of the photodisintegration for $E_\gamma=200$ MeV yielded two data points suggesting an angular distribution with a strong minimum at 90°.

A glance at the summary of these measurements shows that there exists a discrepancy of approximately three orders of magnitude in the cross section. Furthermore, for those measurements with more than one data point, the angular distribution shape is either flat, minimum at 90°, or maximum at 90°. Although it might be justifiable to omit the first two measurements of single data points described above, even the most recent measurements are in distinct disagreement about both the magnitude and shape of the cross section.
Table 1.1: World data for $^4\text{He}(\gamma, dd)$.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Fig 1.2 symbol</th>
<th>$E_\gamma$ (MeV)</th>
<th>$\theta$ (°)</th>
<th>$d\sigma/d\Omega$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akimov et al.</td>
<td>▲</td>
<td>225</td>
<td>42</td>
<td>80 ± 25</td>
</tr>
<tr>
<td>Asbury et al.</td>
<td>♦</td>
<td>221</td>
<td>52</td>
<td>8.0 ± 2.5</td>
</tr>
<tr>
<td>Arends et al.</td>
<td>●</td>
<td>213</td>
<td>46</td>
<td>0.22 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>61</td>
<td>0.35 ± 0.09</td>
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<td></td>
<td></td>
<td></td>
<td>73</td>
<td>0.41 ± 0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>87</td>
<td>0.54 ± 0.10</td>
</tr>
<tr>
<td>Silverman et al.</td>
<td>■</td>
<td>213</td>
<td>73</td>
<td>0.82 ± 0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>0.89 ± 0.39</td>
</tr>
<tr>
<td>O'Rielly</td>
<td>▼</td>
<td>200</td>
<td>50</td>
<td>1.3 ± 0.6</td>
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<td></td>
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<td></td>
<td>78</td>
<td>0.08 ± 0.24</td>
</tr>
</tbody>
</table>

1.4 Motivation for the Present Work

Discovering the true nature of the shape and magnitude of the cross section is the motivation for the present work, which describes a new measurement of the $^4\text{He}(\gamma, dd)$ reaction for $E_\gamma$=150-250 MeV. As discussed in the previous section, the discrepancy in the absolute cross section among the measurements reported is several orders of magnitude. Even the most recent measurements disagree by a factor of ten. The primary goal of this work is to accurately determine the absolute total cross section.

Of more interest from a theoretical point of view, however, is the question of the true shape of the angular distribution. The Arends [Are76] and Silverman [Sil84] measurements suggest that the angular distribution is peaked at 90° in the center-of-mass frame and follows, more or less, a $\sin^2 \theta$ shape. This is intriguing because such an angular distribution shape is indicative of the dominance of electric dipole (E1) or magnetic dipole (M1) radiation. As will be discussed in the next section, identical bosons in the exit channel and isospin selection rules conspire to greatly limit E1 (and M1) radiation in this system. The result is that one expects electric quadrupole (E2) radiation to dominate. However, the characteristic shape of an E2 angular distribution is $\sin^2 2\theta$, which is peaked at 45° and
135° and minimum at 90°.

The apparent contradiction between the naive theory and the results of these two measurements has generated some debate. Silverman [Sil84] has suggested that the E1 shape implies the presence of meson-exchange current effects in this reaction. Another possibility involves D-state (tensor force) effects. The D-state of $^4\text{He}$ is discussed in the next section and it's role in the $\gamma, dd)$ reaction is discussed in Chapters 5, 6, and 7.

To summarize, the motivations for the present work are

- Determine the absolute total cross section.
- Measure the angular distribution and determine if it is maximum or minimum at 90°.
- Investigate the role of $^4\text{He}$ D-state (tensor force) effects in this system at these energies.
- Motivate the four-body theorists to account for any unexplained behavior.

In the next section we describe both the nature of the $^4\text{He}$ ground state and the symmetries governing the $^4\text{He}(\gamma, dd)$ reaction in order to place these motivations in a clear context.

1.5 A $^4\text{He}(\gamma, dd)$ Primer

In the simplest model, the $^4\text{He}$ nucleus can be treated as the combination of two deuterons. This so-called d-d cluster model treats the constituent deuterons as point particles with spin-parity $J^\pi=1^+$, isospin 0, channel spin $S$ (the coupling of the two deuteron spins) and relative orbital angular momentum $L$. Since the overall spin-parity of $^4\text{He}$ is $J^\pi=0^+$, the ground state consists of two allowed configurations: $^1S_0$ and $^5D_0$ (where we use the notation $^{2S+1}L_J$ for the bound state (the ground state of $^4\text{He}$)). In the L=0, or S-state, the two deuterons have zero relative orbital angular momentum and the spins of the deuterons are anti-aligned. In the L=2, or D-state, the two deuterons have relative orbital angular momentum of 2 and the spins of the deuterons are aligned.
The presence of a $D$-state in the ground state of a nucleus indicates the importance of the non-central, or tensor, component of the nuclear force which binds the nucleus. Although the $D$-state admixture in the ground state of $^4\text{He}$ is relatively small, approximately 5-17\% [Whi93], its effect is pronounced. Manifestations of the $D$-state include a 40\% contribution from the nuclear tensor force to the binding interaction [Ger42] of $^4\text{He}$. The non-zero tensor analyzing power $T_{20}$ for the $^2\text{H}(d,\gamma)^4\text{He}$ reaction [Wei84] also results from tensor force effects. The importance of the $D$-state to the present work will be discussed both in the following paragraphs and in Chapters 5-7.

With this picture of the helium ground state in hand, we can write down the allowed electromagnetic transitions for the $^4\text{He}(\gamma,dd)$ reaction. We recall that total angular momentum must be conserved and that for electromagnetic transitions the parity is given as $(-1)^k$ for electric transitions and $(-1)^{k+1}$ for magnetic transitions, where $k$ represents the multipolarity of the electromagnetic transition. In addition, the presence of identical bosons in the exit channel means that Bose-Einstein statistics apply. Since the overall scattering state (the post-photodisintegration state consisting of two deuterons) wavefunction must be even under particle exchange, this means that the product of the space and spin wavefunctions must be symmetric, i.e., $\ell+s=\text{even}$. Here, $\ell$ represents the relative orbital angular momentum between the two deuterons in the scattering state, and $s$ represents the channel spin, or the coupling of the two deuteron spins, in the scattering state. We further limit ourselves to those transitions whose bound and scattering state channels spins differ by zero or one unit, the so-called $\Delta S=0,1$ transitions. We define our allowed transitions to be those which obey the $\ell+s=\text{even}$ and $\Delta S=0,1$ rules. The allowed dipole and quadrupole transitions are shown in Table 1.2.

Investigating the permitted transitions, we can make several observations. First, the only remaining electric dipole (E1) transition has $\Delta S=1$, since the $\Delta S=0$ E1 transition is forbidden by $\ell+s=\text{even}$. The spin-dependent component of the E1 operator is much weaker than the spin-independent part (see Sec. 6.2) so we expect this transition contribution to
Table 1.2: Allowed (see discussion in text) electromagnetic transitions for $^4$He($\gamma, dd$)

<table>
<thead>
<tr>
<th>Ground State $^{2S+1}L_J$</th>
<th>Scattering State $^{2s+1}L_J$</th>
<th>Multipolarity $\pi^k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0,^5D_0$</td>
<td>$^3p_1$</td>
<td>E1</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5d_1$</td>
<td>M1</td>
</tr>
<tr>
<td>$^1S_0$</td>
<td>$^1d_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5s_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5d_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5g_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^1S_0,^5D^0$</td>
<td>$^3p_2$</td>
<td>M2</td>
</tr>
<tr>
<td>$^1S_0,^5D^0$</td>
<td>$^3f_2$</td>
<td>M2</td>
</tr>
</tbody>
</table>

be small.

Before discussing the other multipolarities, some words about isospin in this reaction are in order. Since $^4$He and the deuteron are both isospin 0, any isospin conserving transitions in this system are manifestly isoscalar. Having said this, we note that the general isospin selection rule for E1 transitions is that $\Delta T = 0,1$ (i.e. isoscalar $\Delta T=0$ or isovector $\Delta T=1$) [War69]. In addition, for self-conjugate nuclei (nuclei containing equal numbers of protons and neutrons) there is a selection rule forbidding $\Delta T=0$ E1 transitions. This latter selection rule does not apply to the spin-dependent component of the E1 operator, however, so the (isoscalar) spin-flip amplitude discussed above is, in fact, permitted.

Moving on to magnetic dipole (M1) transitions, we note that the only allowed M1 transition (having $\Delta S=0,1$) is from the D-state of $^4$He, which is a small component of the ground state wavefunction (approximately 4% of the two point deuteron $^4$He ground state [Whi93]. We recall that magnetic transitions are weaker than electric transitions of the same order by roughly a factor of 10. Furthermore, isoscalar M1 transitions in self-conjugate nuclei are suppressed by a factor of about 100 from normal. These three conditions imply that the contribution from M1 radiation will be small.

There are four permitted $\Delta S=0$ electric quadrupole (E2) transitions. Of these
transitions, one is from the $S$-state and three are from the $D$-state of $^{4}\text{He}$. The naive expectation would be for the transition from the $S$-state to dominate the E2 contributions. Since no other restrictions apply to these transitions, E2 radiation is expected to play an important role in this reaction.

Finally, two magnetic quadrupole transitions are permitted. These are $\Delta S=1$, so they will be suppressed in the same manner as the spin-flip E1 term above. Just as in the case of M1 there is an isospin selection rule that suppresses isoscalar M2 transitions in self conjugate nuclei. The result is that we expect these M2 transitions to contribute much less than the E2 transitions.

To summarize, analysis of the allowed dipole and quadrupole electromagnetic transitions indicates that E2 transitions should dominate in this reaction. Small contributions from the M1 and spin-flip E1 transitions might also be expected. M2 radiation is not expected to be important. The characteristic shape of an angular distribution arising from pure E2 capture to the $S$-state of $^{4}\text{He}$ would be $\sin^2 2\theta$. As mentioned in the previous section, however, this simple prediction is in disagreement with two recent measurements [Are76, Sil84] which show distributions with approximately $\sin^2 \theta$ shapes. One possible reconciliation of this contradiction involves assuming pure E2 capture to the $D$-state of $^{4}\text{He}$. Such a solution can yield an angular distribution which is peaked at $90^\circ$ in the center-of-mass frame. This topic is discussed in Chapter 5.

1.6 This Experiment

In the summer of 1993, our collaboration from Triangle Universities Nuclear Laboratory descended upon Brookhaven National Laboratory's Laser Electron Gamma Source (LEGS) with the hope of measuring the $^{4}\text{He}(\gamma,dd)$ reaction at $E_\gamma=180-330$ MeV. The opportunity arose for us to piggy-back on a Compton scattering experiment being performed by an Italian group. The hope was that we would be able to obtain both cross section and analyzing power data for this reaction—a significant improvement upon all previous
measurements in that it would be the first measurement of polarization observables in this reaction at these energies. Unfortunately, the Fates were unkind.

Specifically, there were two main problems. The first was a flaw in the design of the experiment. The \((\gamma, dd)\) experiment was a coincidence experiment where both deuterons were detected in coincidence with an energy-tagged polarized photon. Unfortunately, a strong \((\gamma, npd)\) background occupied much of the phase space of the \((\gamma, dd)\) events of interest. This would not have been much more than an inconvenience if we had had good particle identification in both detector arms. In one of the detector arms, however, particle identification was extremely poor, leading to an inability to distinguish between protons and deuterons. This made it impossible to discriminate the \(dd\) counts from the \(npd\) counts on an event-by-event basis. This alone would not have doomed the experiment, however. Background subtraction would have been feasible—given sufficient statistics.

We were unable, however, to obtain the requisite statistics. The Compton scattering count rate was significantly in excess of the best guess for the \((\gamma, dd)\) rate. The result was that the primary experimenters obtained twelve total data points over the course of the run. From hindsight and a liberal dash of guesses, our experiment might have succeeded if we had measured only two angles. As it stood, the total data set contained too few statistics at any one angle to allow for the emergence of a \(dd\) signal peak from the \(npd + dd\) sea.

Not to be thwarted, we became involved with a University of Illinois proposal to perform the \(^4\text{He}(\gamma, dd)\) measurement for \(E_\gamma=70-150\) MeV at the Saskatchewan Accelerator Laboratory (SAL) using the \(4\pi\) detector LASA. As time went by, Illinois removed itself from the proposal and the remaining collaborators opted to forego the use of LASA in favor of discrete detectors we would construct ourselves and arrange in a coplanar formation. A test experiment produced inconclusive yet promising results in the summer of 1995. The production run began in November 1996. The run was plagued by a host of accelerator and photomultiplier tube problems, but in the end yielded over three weeks of usable data.

The accelerator facility, detector setup, and ancillary equipment used in the SAL
experiment are detailed in Chapter 2. A comprehensive discussion of the analysis of the SAL data follows in Chapter 3. The LEGS experimental setup and data analysis are described in Chapter 4. The results of both analyses are presented in Chapter 5. A comparison of the data with the results of a direct capture calculation is given in Chapter 6. Finally, the findings of this dissertation are summarized and some conclusions drawn in Chapter 7.
Chapter 2

Experimental Setup

The data presented in the main body of this dissertation were obtained at the Saskatchewan Accelerator Laboratory (SAL) in Saskatoon, Saskatchewan, Canada. The photons used in the thesis experiment were emitted via bremsstrahlung from 273 MeV electrons generated by SAL's linear accelerator. The photons were then incident upon a liquid $^4$He target where they (rarely) interacted to produce two deuterons in coincidence. These reaction particles were then detected using plastic scintillator detector telescopes arranged in two detector arms so as to detect both coincident deuterons. Energy and timing signals from the detectors were then converted into digital signals and stored on compact discs for later analysis.

In this chapter we discuss the equipment associated with each phase of the experiment described above. We begin with the primary beam of electrons in Section 2.1. Next we describe the creation of the photon beam in Section 2.2. Descriptions of the target (Section 2.3) and the detectors (Section 2.4) follow. Finally, we discuss the electronics utilized to process the detector signals (Section 2.5) and the data acquisition software used to sort and record the experimental data (Section 2.6).
2.1 The Facility

The Saskatchewan Accelerator Laboratory (SAL), shown in Fig. 2.1 houses an electron Linear Accelerator (LINAC). Electron bunches from the LINAC are sent through an Energy Compression System and then injected into a Pulse Stretcher Ring. The result is an electron beam that can be extracted continuously between LINAC injections and directed via a switchyard of dipole, or bending, magnets to one of two experimental areas.

2.1.1 The linear accelerator

The SAL LINAC (see Fig. 2.1) consists of six radio frequency (RF) cavities. Each section is capable of accelerating electrons by as much as 50 MeV. This yields a total possible electron energy of 300 MeV. The acceleration process begins with μs long pulses of 220 keV electrons produced by an electron gun at the rate of 180 pulses per second. These long pulses are sent through a wave prebuncher and a traveling wave buncher to produce 360 ns long bunches. These electron bunches are then injected into the first acceleration section. Within the RF cavities energy is transferred to the electrons through a microwave traveling wave at 2856 MHz, yielding an acceleration of approximately 15 MeV/m. After the last acceleration section the bunches have an energy spread of approximately 1%.

2.1.2 The energy compression system

In order to reduce the energy spread of the beam, the electrons are passed through an Energy Compression System (ECS). The ECS consists of three dipole magnets and a short RF accelerating section (see Fig. 2.1). The dipoles increase the spread of the packet longitudinally and, together with the accelerating section, effectively reduce the energy spread by passing only those electrons within a particular energy acceptance. The resulting bunch has the same time structure (360 ns) as the incident bunch but is energy compressed to an energy spread of 0.1% [Lax80].
Figure 2.1: The Saskatchewan Accelerator Laboratory. Shown are the LINAC, ECS, PSR, and experimental areas (EA2 and EA3).
2.1.3 The pulse stretcher ring

The electron beam exiting the ECS consists of bunches of electrons separated by 5.6 ms and is said to be pulsed. Although this pulsed beam could be used, it is advantageous (see the Section 2.1.4) to deliver the beam to the experiment in a continuous fashion. The Pulse Stretcher Ring (PSR) takes the pulsed beam from the ECS and provides a nearly continuous wave (CW) beam that can be directed to the experimental areas.

The electron bunches from the ECS are injected into the PSR through a 180° injection line (see Fig. 2.1). The injection line dipole magnets act as an energy analyzer and further reduce the energy spread of the beam to a (nearly) monochromatic 0.01%. The PSR itself is an electron storage ring with dipole (bending) and quadrupole (focusing) magnets (see Fig. 2.1). In addition, the ring contains sextupole and octupole magnets to excite instabilities in the beam. The PSR parameters are set to the so-called one-third resonance tune which increases the (transverse) spatial extent of the beam relative to a resonance (i.e. stable) tune. An electrostatic septum is then used to extract the beam by siphoning a fraction of the electron bunch during each pass. The result is a CW beam which can be directed through a switchyard of dipole magnets to Experimental Area 2 or 3 (see Fig. 2.1). For a detailed description of the PSR the reader is referred Dallin [Dal90].

2.1.4 Pulsed versus Continuous Wave Beams

As mentioned above, the pulsed beam generated by the ECS could be utilized in nuclear physics experiments. In the early days of linear accelerators, in fact, nuclear physicists were limited to such pulsed beams. With pulsed beams, all of the beam particles arrive at the experimental target in a temporally short burst which is then followed by a temporally long period of inactivity. This creates very high instantaneous rates in the experimental detectors which in turn causes accidental events to swamp the true events of interest. One solution to this problem is to reduce the current of electrons altogether, but this correspondingly reduces the experimental count rate. The more elegant solution is to
provide smaller bunches of beam particles with less time between the bunches. In the limit of this approach a constant beam current would be supplied to the target—hence the term continuous wave beam.

The degree to which a beam is pulsed or continuous is often characterized by its *duty factor*. The duty factor is approximately equal to the percentage of time that beam is being delivered to the experimental target. Accordingly, a delta-function beam would have a duty factor of 0% and a perfectly steady beam would have a duty factor of 100%. In the case of beam exiting the ECS, the duty factor is 360 ns/5.6 ms ≈ 0.01%. During the production runs for this experiment, the duty factor of beams extracted from the PSR ranged from 40-80%.

### 2.2 Photon Production

The CW electron beam extracted from the PSR was directed through the switchyard toward Experimental Area 2 or EA2 (see Fig. 2.2). The electron beam energy used throughout the experiment was approximately 273 MeV with beam currents varying between 600 nA and 3 μA. In EA2, the electron beam was incident on a thin aluminum radiator. The majority of the electrons passed through the radiator with minimal energy loss, but a small fraction radiated bremsstrahlung γ rays. These γ rays were used as the photon beam for this experiment and proceeded downstream toward the experimental target (Section 2.3).

#### 2.2.1 Bremsstrahlung

Bremsstrahlung comes from the German for “braking radiation.” This name aptly describes the phenomenon where a charged particle collides with an atom and is subjected to acceleration by the field of the nucleus or its electrons. The particle radiates a photon whose energy can be any value in a continuum that ranges from 0 to the *end-point energy*. The end-point energy is equal to the incident particle energy minus the rest mass of the incident particle.
Figure 2.2: Experimental Area 2 and the setup for the present experiment (EXP055).
For the present experiment, the primary electron beam was incident on a thin aluminum foil called a *radiator*. The bremsstrahlung spectrum resulting from the interaction of the beam with the radiator is shown in Fig. 2.3. This spectrum was generated using the relativistic, thin radiator formula of Schiff [Sch51] with an incident electron energy of 273 MeV.

![Graph showing calculated bremsstrahlung spectrum for incident electron energy of 273 MeV using the Schiff relativistic, thin-radiator formula.](Figure 2.3)

The radiator used in this experiment was 115 μm thick. Thicker radiators would produce higher photon intensity for the same electron beam current, but would be susceptible to undesirable effects such as multiple scattering and ionization energy loss. This thickness was chosen since it allowed production of the photon flux necessary to acquire adequate counting statistics within the allotted beam time while minimizing the adverse thick-radiator effects.
2.2.2 Photon tagging and the SAL tagger

A significant problem with bremsstrahlung experiments is the difficulty of obtaining an accurate measurement of the number of photons incident upon a target. One solution to this problem is to employ the technique known as photon tagging. In this process, electrons that have emitted bremsstrahlung γ rays are bent by a tagging magnet into an array of detectors called the tagging focal plane. Detection of these recoil electrons allows a precise determination of the number of photons, or flux, in (a portion of) the bremsstrahlung spectrum. Furthermore, detailed knowledge of the tagging magnet’s magnetic field together with precise measurements of the location of detectors that count the recoil electrons allows the determination of the recoil electron energy. Since conservation of energy gives

\[ E_\gamma = E_{\text{incident } e^-} - E_{\text{recoil } e^-}, \]  

(2.1)

the energy of the coincident bremsstrahlung photon can be calculated. The photon is said to have been tagged.

The photon tagging facility at SAL is shown in Fig. 2.4. It consists of a radiator wheel containing the 115 μm radiator (among others), a clam-shell tagging magnet, a dump magnet, a beam dump, and a tagging focal plane array. In addition to its role in the tagging process, the tagging magnet prevents beam electrons and other charged particle contaminants from proceeding downstream toward the target and detectors. The dump magnet sweeps these particles into the beam dump. The beam dump is a lead walled area designed to shield the experiment from background radiation resulting from the deceleration of the primary beam. The tagging focal plane array consists of 63 plastic scintillator detectors or counters.

Although it is possible, in principle, to design a tagging system capable of detecting recoil electrons for the entire range of bremsstrahlung photon energies, in practice only a portion of the spectrum is tagged. For the electron energy and tagging magnet settings in this experiment, the range of photons that were tagged extended from 171 to 212 MeV.
Figure 2.4: SAL photon tagging system.
(see Fig. 2.3). The correspondence between photon energy and each detector channel (see below) in the tagger for a typical run is detailed in Table 2.1.

A simple diagram of the focal plane array is shown in Fig. 2.5. It consists of two planes of detectors containing 31 in the front plane and 32 in the back plane. A detector channel is defined as the coincidence between a detector in the front plane and a detector in the back plane. Channel one represents a coincidence between focal plane counters one and two, channel two a coincidence between counters two and three, etc. This definition removes spurious signals arising from dark current in the counter photomultiplier tubes.

![Diagram of the SAL tagging focal plane array.](image)

Figure 2.5: The SAL tagging focal plane array.

Counts in each channel were accumulated in electronics modules called scalar. A plot of the scalar distribution versus tagger channel is shown in Fig. 2.6. One interesting characteristic of this spectrum is the unequal distribution of counts in the odd versus the even channels in the focal plane. This odd-even effect arises from variation in the tagger channel acceptance. The overlap of the tagger counters in the front plane with those in the back was chosen to yield equal acceptance for odd and even channels for an electron.
Table 2.1: Photon energies of the 62 tagger channels for the tagged runs in this experiment.

Standard (62 channel) tagger focal plane. Date: December, 1996
Shifted by -16.0 channels, -208.0 mm. Ring Energy Loss: 0.50 MeV/c
Electron beam momentum: 271.68 MeV/c B301/2: 273.00 MeV/c
Central tagger momentum (P0): 84.90 MeV/c Dial: 87.12 MeV/c
Setting number: 640 Tagger Field (B0): 5.448 kG (T = 169.5 A)

<table>
<thead>
<tr>
<th>Chann. No.</th>
<th>Central Momentum (%)</th>
<th>Momentum Spread (MeV/c)</th>
<th>Photon Energy Spread (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-29.29</td>
<td>60.03 ± 0.29</td>
<td>211.64 ± 0.29</td>
</tr>
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<tr>
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<td>67.20 ± 0.31</td>
<td>204.48 ± 0.31</td>
</tr>
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<td>203.86 ± 0.31</td>
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<td>-17.92</td>
<td>69.68 ± 0.31</td>
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<td>78.76 ± 0.33</td>
<td>192.92 ± 0.33</td>
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</tbody>
</table>
beam with a 45° angle of incidence. This is approximately true for channels 31 and 32. Channels with an electron angle of incidence less than 45° (channel numbers less than 31) exhibit higher counts in the odd numbered channels, while channels with an electron angle of incidence greater than 45° (channel numbers greater than 32) show higher counts in the even numbered channels.

Figure 2.6: Tagger channel scalar spectrum.

2.2.3 Design Considerations and the Choice of a Primary Run Mode

The choice of a primary mode of operation—tagged versus untagged bremsstrahlung—was influenced by two design considerations. The first was that the $^4\text{He}(\gamma, dd)$ cross section is likely quite small. The three most recent measurements [Are76, Sil84, O'R97] put the differential cross section at or considerably below a nanobarn per steradian. The second was the presence of high concurrent background from several competing nuclear reaction channels. At $E_\gamma=70$ MeV, the highest energy for which accurate data are available for
all channels [Ark74], the total cross sections of nuclear reactions involving only protons, deuterons, and tritons are listed in Table 2.2. The \( dd \) channel resembles the proverbial needle in a haystack.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Total Cross Section, ( E_\gamma = 70 \text{ MeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (\gamma, dd) )</td>
<td>( \sim 1 \mu b )</td>
</tr>
<tr>
<td>( (\gamma, pt) )</td>
<td>0.2 mb</td>
</tr>
<tr>
<td>( (\gamma, n)^3\text{He} )</td>
<td>0.25 mb</td>
</tr>
<tr>
<td>( (\gamma, npd) )</td>
<td>0.12 mb</td>
</tr>
<tr>
<td>( (\gamma, nnpp) )</td>
<td>0.04 mb</td>
</tr>
</tbody>
</table>

The tagger focal plane detectors and electronics are limited to approximately 1.5 MHz average rate of operation [Vog93] per tagger counter. This rate, while substantial, requires production beam time on the order of months to allow measurement of cross sections at the sub-nanobarn scale. Since the present experiment was limited to about four weeks of beam time, the decision was made to run in an untagged bremsstrahlung mode for the bulk of data taking. The experimental detector count rates permitted an untagged photon flux equivalent to 7.5 MHz average tagger counter rate. Daily tagged runs, in addition to several longer tagged runs, were performed to provide accurate flux normalization data (see the next section 2.2.4). The bulk of the beam time, approximately two and a half weeks, was allotted to untagged operation. The usable untagged flux extended from 150-250 MeV and provided the experimental data reported in this dissertation.

### 2.2.4 Un-tagged mode flux determination

As described above, one of the major advantages of running a tagged experiment is that it allows for accurate determination of the total photon flux incident upon the experimental target. In order to retain this accurate flux normalization, we positioned two beam current monitor paddles (BCMP’s) adjacent to the tagging focal plane detectors on the high energy photon side. These paddles were approximately five times narrower than
the tagger counters. One consequence of this narrower profile was that the BCMP's could continue to count electrons (and therefore photons) accurately even at the higher rates associated with the untagged mode of operation. This, in turn, allowed for a solution to the problem of untagged flux normalization.

Specifically, several day-long tagged runs as well as short daily tagged runs were performed in addition to the untagged runs. During both tagged and untagged modes the BCMP's remained in operation. For the tagged runs, the detection of photons over the entire tagged range allowed for a highly accurate 62-point normalization of the bremsstrahlung spectrum. The total flux seen by the BCMP's was likewise recorded during the tagged runs. This allowed the BCMP flux measurements to be cross normalized to the full tagging focal plane flux measurements. During untagged operation, when the tagging focal plane detectors were powered off, the BCMP's remained in operation, providing an accurate measurement of the bremsstrahlung spectrum. The normalization factor between the BCMP's and the tagging focal plane is shown in Fig. 2.7. The ratio remained steady throughout the course of the experiment.

2.2.5 Photon beam efficiency

The photon flux described above is a measurement of the number of bremsstrahlung photon created by the electron beam-radiator interaction. For this experimental setup, however, there is not a one-to-one correspondence between the tagging focal plane (or BCMP) flux and the flux incident upon the experimental target. The reason is that the photon beam passes through two collimators prior to reaching the target. The location of the primary and secondary collimators is shown in Fig. 2.4. For this experiment, the collimator sizes were 15 mm and 20 mm, respectively. These sizes were chosen to restrict the beam spot size at the target to be approximately 75% the width of the target.

Since some tagged photons do not reach the target, the percentage of photons which do reach the target must be measured. This percentage is known as the tagging efficiency.
To measure the tagging efficiency we reduced the photon rate to approximately 100 Hz. We then placed a lead glass detector in the photon beam at a point downstream—past the collimators. This lead glass detector was thick enough to be essentially 100% efficient at detecting the photons. We then measured all hits in the tagging focal plane and looked for coincident hits in the lead glass detector. To first order, the tagging efficiency is given by

$$\epsilon = \frac{\text{hits in lead glass}}{\text{hits in tagging focal plane}} \times 100\%.$$  \hfill (2.2)

This equation ignores room background effects, however. In order to determine the contribution to lead glass events from room background, we also ran with the photon radiator rotated out of the electron beam. The radiator-out corrected efficiency is given by

$$\epsilon_{\text{corrected}} = \frac{N_{in} - RN_{out}}{F_{in} - RF_{out}} \times 100\%$$  \hfill (2.3)

where $N_{in}$ and $N_{out}$ are the counts in the lead glass detector with the radiator in and out, $F_{in}$ and $F_{out}$ are the tagging focal plane fluxes with the radiator in and out, and $R$ is the
ratio of livetime with the radiator in to the livetime with the radiator out. The livetime is simply a measure of the time data was actually being taken.

The tagging efficiency was calculated as a function of photon energy by performing the calculation for each tagger channel. Fig. 2.8 shows a typical plot of tagging efficiency versus tagger channel. Tagging efficiency runs were performed daily throughout the course of the run. Fig. 2.9 shows the average tagging efficiency across the tagging focal plane versus run number. The efficiency remained relatively stable throughout the course of the experiment.

![Tagging Efficiency Per Channel](image)

Figure 2.8: Tagging efficiency versus tagger channel.

### 2.3 The Target

The most recent measurements of the $^4\text{He}(\gamma, dd)$ cross section [Are76, Sil84, O'R97] near $E_\gamma=200$ MeV all place the differential cross section at or about one nanobarn. Several approaches to measuring such a small cross section are possible. O'Rielly [O'R97] utilized a 1.5 meter gas target in conjunction with a $4\pi$ detector. An alternative method involves using a liquid target in conjunction with discrete detectors. The present experiment adopted
the second method. In this section we describe the target cell and cryostat assembly.

2.3.1 The target cell

Fig. 2.10 shows the target cell used in this experiment. The cell was a five centimeter diameter cylinder which was suspended vertically from a liquid $^4$He dewar. The cell walls were constructed of mylar and were 150 $\mu$m. The seam in the cylinder was positioned on the downstream side to reduce photon beam attenuation. The top and bottom of the cell were glued to aluminum caps using a low temperature epoxy. The top cap contained a neck with a knife-edge fitting. Using an indium seal, the neck was attached to a similar fitting on the bottom of the liquid helium dewar.
2.3.2 The cryostat

The cryostat, pictured in Fig. 2.10, consisted of a liquid helium dewar, a liquid nitrogen jacket, a vacuum pump-out, the target cell, a radiation shield and a target chamber. The liquid helium dewar had a capacity of twenty liters and occupied the center of the dewar. Surrounding this was a layer of superinsulation followed by a cylindrical liquid nitrogen dewar, or jacket. Another layer of superinsulation went between the liquid nitrogen jacket and the cryostat’s outer wall. The lower portion of the cryostat was housed by the target chamber and pumped out to approximately $10^{-6}$ torr by a diffusion pump. The liquid helium cell, acting as a cryopump, maintained the vacuum after the pump out valve was closed.

Connected to the cryostat from below were the radiation shield and target chamber. Fig. 2.11 shows a top view of the lower portion of the cryostat. Surrounding the target cell at a diameter of fifteen centimeters, the radiation shield was thermally connected to the liquid nitrogen jacket and then wrapped in mylar superinsulation. This presented a liquid nitrogen-temperature shield to the liquid helium target cell, effectively limiting the boiloff rate. Surrounding the target cell and radiation shield, the target chamber itself was connected with an O-ring vacuum seal to the cryostat assembly. Both the radiation shield and the target chamber had beam and reaction particle entrance and exit windows to keep particle and energy losses at a minimum. The target chamber windows were covered with kapton to maintain vacuum integrity.

The cryostat performed admirably throughout the experiment. Liquid helium dewar levels were monitored using a superconducting level sensor. The time between liquid nitrogen jacket fills was approximately eight to twelve hours, while the time between liquid helium fills was an excellent five days.
Figure 2.10: Target cell and cryostat assembly.
Figure 2.11: Top view of the target chamber.

2.4 The detectors

Since the bulk of the present experiment was carried out using untagged bremsstrahlung, it was necessary to measure both the reaction particles in coincidence in order to be kinematically complete. To accomplish this we utilized two sets of detectors, or detector arms, which defined the reaction plane. Figs. 2.12 and 2.13 show both arms from the top and side.
Figure 2.12: Top view of experimental setup.
Figure 2.13: Side view of experimental setup.
2.4.1 The telescope arm

The telescope arm consisted of six collimated detector telescopes. A telescope is an arrangement of detectors that places one or more thin, or $\Delta E$, detectors in front of a thick, or $E$, detector. The telescopes used here are of the $\Delta E$-$E$ variety. The motivation for using this geometry is to provide a method of particle identification, allowing the experimenter to differentiate between particles with different charge and mass (see Fig. 2.14). Particle identification is discussed in detail in Sec. 3.1.

![Typical raw spectrum for a telescope detector.](image)

Figure 2.14: Typical raw spectrum for a telescope detector.

The $\Delta E$ detectors consisted of a 10 cm $\times$ 10 cm $\times$ 2 mm block of plastic scintillator. This was glued to a lucite light guide which was in turn optically connected (using optical coupling grease) to a 5 cm photomultiplier tube (PMT). A PMT base containing high
voltage and signal connections along with various electronics was connected to the PMT. The integrity of the light guide-PMT junction was maintained by using a spring-loaded cannister to hold the PMT-base assembly flush against the light guide. The $E$ detectors were 10cm × 10cm × 7.6cm blocks of plastic scintillator. Aside from the size of the scintillating block and light guide, the $E$ detector was identical to the $\Delta E$ detector.

Fig. 2.13 shows a single telescope in profile to the left of the cryostat assembly. Not shown in the figure is the ringstand used to support the $\Delta E$ detector and cannister. Located in front of the $\Delta E$ detector is a 35 mm lead collimator. The collimator contained a conical bore with a half-angle of approximately six degrees that illuminated the back face of the $E$ detector. This collimation determined the solid angle acceptance of each telescope. The six detectors were positioned at $\theta_{lab} = 38.8^\circ$, 55.0°, 81.0°, 98.1°, 115.1°, and 132.2° throughout the course of the experiment.

2.4.2 The recoil arm

The recoil detector arm consisted of a long plastic scintillator bar with fourteen $\Delta E$ detectors in front and a long, thin veto detector behind. The bar detector was 1.5 m long by 15 cm high by 7.6 cm thick. Lucite lights guides and 12.5 cm PMT’s were connected to the bar at each end. The $\Delta E$ detectors were identical to those discussed in the previous section, with the exception of a bend in the lucite light guides. This bend was added to allow the PMT cannisters for the fourteen $\Delta E$’s to be supported by a rack attached to the bar detector assembly (see Fig. 2.12). The veto detector was a 1.5 m × 15 cm × 2 mm plastic scintillator with light guides and PMT’s at both ends. Typically used to allow the experimenter to discriminate between charged and uncharged particles (hence the term veto), the veto detector was used here to select high-energy charged particles whose total energy was not depositied in the bar detector.

Since the telescope arm detectors determine the acceptance of the experiment, the recoil arm’s purpose is to detect any (coplanar) particle in coincidence with a hit in the
telescope arm. The size and placement of the recoil arm assembly were determined by the end telescope detectors and the finite size of the target. The recoil arm was positioned so that for any $dd$ event where one deuteron was detected in a telescope, the recoil deuteron would be detected in the recoil arm—provided it was energetic enough not to be stopped in the intervening layers.

### 2.4.3 Scintillator Detectors

All of the detectors described in the previous two sections are organic, or plastic, scintillator detectors. The detectors operate by converting kinetic energy from particles passing through the detector material into light. The mechanism for this conversion of energy into light involves two steps. First, an energetic charged particle that is to be detected undergoes a large number of interactions with the atoms in the detector. The result of these collisions is that many atomic electrons are raised to excited states. The second step is that the excited states de-excite and emit photons, or fluoresce.

Since the scintillator is transparent to these photons, the experimenter can use reflective material and other transparent materials called light guides to direct the photons toward photomultiplier tubes. The photomultiplier tube (PMT) uses the photoelectric effect to convert the photons to electrons. The PMT consists of a series of electrodes called dynodes, with a potential difference of about 100-200 V between adjacent dynodes. Photoelectrons which are emitted from one dynode and are accelerated produce many new secondary electrons per incident electron upon interacting with the next dynode. This cascade effect produces a signal that is proportional to the energy of the charged particle incident upon the scintillator and which can be processed by various electronics modules. For a more detailed description of scintillator detectors and photomultiplier tubes see Krane [Kra88] or Leo [Leo94].
2.5 The Electronics

This section describes the various electronics used to acquire the experimental data. Individual components consisted of both NIM and CAMAC modules. The bulk of the NIM modules were coincidence logic units, logic and linear fans, and discriminators. The ADC's, TDC's and coincidence registers used were CAMAC modules. The electronics controlling the tagger consisted of NIM, CAMAC, and custom-built modules and are described in Ref. [Vog93].

As discussed in the previous section, our experimental detectors were arranged in two arms designed to detect two deuterons in coincidence. The electronics for each detector arm are discussed in the following two sections. The electronics that determine whether or not a $dd$ candidate event was detected are discussed in the Sec. 2.5.3.

2.5.1 Telescope arm electronics

A simple schematic of the telescope arm electronics circuit is shown in Fig. 2.15 for a single telescope. This circuit contained three sections: $E$, $\Delta E$, and sum threshold.

The $E$ and $\Delta E$ sections were identical. Each circuit took a PMT pulse from the detector and created two copies using a passive splitter. One pulse was sent to an analog-to-digital converter (ADC) which recorded the pulse height of the signal. The other copy was sent to a constant fraction discriminator (CFD). This module compared the amplitude of the (analog) input signal to a threshold voltage and rejected those signals which were below the threshold. Signals above the threshold caused the generation of a logic pulse. This logic pulse was fanned out with a logic fan-out and sent to a scalar (Scal) module, a coincidence register (CoReg), a time-to-digital converter (TDC), and some coincidence logic units. The scalar module simply counted the number of signals passing the CFD threshold and allowed us to track the detector count rates during the runs. The coincidence register recorded a 32 bit word each time an event fired. Each bit in this register had a one-to-one correspondence with a particular $E$ or $\Delta E$ and was used offline as an efficient way to determine which
detectors fired during a particular event. The TDC was used to help reject random (in time) coincidence events. The coincidence logic monitored the signals coming from the $E$ and $\Delta E$ and generated a logic pulse if both signals arrived in coincidence with each other and in coincidence with the signal coming from the *sum threshold* logic.

One problem with running with high incident energy beams is that a tremendous number of low-energy electrons are produced. These electrons are easy to distinguish from heavier particles if one looks at a $\Delta E$-E plot for a telescope detector as they tend to occupy a locus in the low channels of both detectors. The real difficulty is that they cause the trigger electronics to fire, which causes the data acquisition system to record the ADC values—a relatively time-consuming process. While busy recording these values the data acquisition is inhibited and cannot process other events. Since the electron events are many times more likely than the deuteron events, the computer would always be busy recording the wrong type of events. In order to allow our data acquisition system to be more selective about the events it recorded we implemented a *sum threshold* cut.

The *sum threshold* cut was composed of a linear fan-in and a leading edge discriminator (LED). The idea behind the sum threshold is illustrated graphically in Fig. 2.16. The linear fan-in sums the pulse heights from the $\Delta E$ and $E$ detectors and the LED compares this sum against a fixed threshold. Events passing this threshold generate a logic pulse which is sent on to the telescope coincidence logic. Events which fall below this threshold are rejected, causing the "folded corner" cutoff in the lower left corner of Fig. 2.16.

The coincidence logic for the telescope arm is a simple three-fold logic *AND*. If a hit in the $\Delta E$ is above threshold, a hit in the $E$ detector is above threshold, and together these hits pass the *sum threshold*, then that particular telescope is said to have fired. A six-way logic *OR* takes the output from the coincidence logic for each telescope. If any one telescope fires, the telescope arm (TELE trigger) is said to have fired.
2.5.2 Recoil arm electronics

The recoil arm electronics, shown in a simple schematic in Fig. 2.17, are very similar to the telescope arm electronics. Fourteen paddles located in front play the role of ΔE's. The bar detector acts as the $E$ detector. Since the bar had a PMT on each end, a valid hit in the bar was defined as the $\text{AND}$ of both bar ends. Lack of sufficient electronics modules prevented us from instrumenting a sum threshold on the recoil arm. A valid recoil arm trigger (BAR trigger) was generated if any one of the fourteen paddles fired in coincidence with both ends of the bar.
2.5.3 Trigger electronics

In order to record the pulse height and timing information from the ADC and TDC modules, as well as the hit pattern stored in the coincidence register, these modules require a logic gate. This gate was generated by the trigger logic shown in Fig. 2.18. Whenever a valid telescope arm trigger and recoil arm trigger occurred in coincidence, the master trigger logic would generate a logic pulse called the XREF. This was used to gate the ADC's, TDC's, and coincidence register.

During the tagged mode of operation, the XREF signal was also sent to the tagging focal plane electronics. In this case, a valid trigger was defined as a coincidence between the XREF and any tagger channel. In some cases an XREF could be generated without
an accompanying hit in the tagger. Rather than record an event coming from an unknown source, the tagger electronics generated an *AUTO Clear* signal which was sent the the ADC's, TDC's, and coincidence register. This signal causes the modules to stop converting and reset—a process which is much quicker than reading out and clearing the modules.

Several other features were included in the trigger logic. First, after a valid trigger is received but before the modules have been read-out, all of the ADC's, TDC's, scalars, and coincidence registers are inhibited. This prevents additional signals from piling up on top of the initial event. The inhibit was wired through the tagger module but was in effect in both tagged and untagged modes of operation.

In addition, at times it was convenient to change the triggering level to record data arising from single arm events. Rather than having to request an access to the experimental hall we wired the triggering logic so that the output of a computer-controlled output register
was included as an input to the master trigger. In single arm mode this line was always true, so a valid master trigger was generated each time a TELE trigger or a BAR trigger was received.

![Trigger electronics diagram](image)

**Figure 2.18: Trigger electronics.**

### 2.6 The Data Acquisition and Analysis Systems

All ADC's, TDC's and coincidence register modules used in this experiment were CAMAC modules. The crates containing these modules were controlled by a single-board MVME167 VME computer. This computer was in turn controlled by software running on Sun Sparcstation computers connected to the VME computer via ethernet. The VME computer was connected to the master trigger. Upon receiving a valid trigger it would execute code which had been downloaded to it from the data acquisition software running on the Sun. Rates as high as a few kHz were obtained during singles runs.

The data acquisition package in use at SAL is called LUCID. This software contains a state-of-the-art graphical user interface front-end system which is both powerful and easy to use. The package allows the user to import sophisticated online analysis routines written in C or Fortran as well as providing a full-functional native LUCID language. Multidimensional
histograms may be defined, making online investigation of data quick and painless even for experimental setups composed of many detectors.

The data were initially stored to hard disk while beam was on target. After each run the data files were compressed using the standard Unix compression tool gzip. Compression ratios of 4:1 were obtained on average. The compressed data files were then transferred to an IBM-compatible PC running Linux, the public domain Unix platform. This PC contained a writable CD-ROM drive. Once approximately 650 megabytes of compressed data were acquired, a data CD was burned. Two copies of each data set were burned. The data were verified after the burn process using the LucidView utility. After two error-free CD’s were created the data files on the hard disk were deleted.

The total data set for the running period from late November to late December consisted of 16 CD’s. Usable data constituted approximately 22 gigabytes (uncompressed).
Chapter 3

Data Analysis

Now that we have described the motivations for the experiment and the specifics of the experimental apparatus, we turn to a detailed account of the analysis of the data that were acquired during the experimental production runs. In the first two sections we discuss methods used to identify particle types (Sec. 3.1) and particle energies (Sec. 3.2) in the various detectors. In Sec. 3.3.1 we describe the kinematic reconstruction of two-body events leading to the selection of a pool of dd candidate events. Sec. 3.4 we cover the process of selecting events from competing reaction channels. This information is used in Sec. 3.5 to allow the subtraction of background events from the dd candidate pool. The remaining yield of good dd events becomes the basis for the determination of the absolute differential cross sections. Calculation of the differential cross sections is described in Sec. 3.6.

3.1 Linearization of $\Delta E-E$ Plots

One of the benefits of the $\Delta E-E$ detector geometry employed in this experiment is the ability to graphically select particles of different mass and charge. Fig. 3.1, a typical $\Delta E-E$ plot, shows the bands that are formed by the various products of the photodisintegration reactions observed in this experiment—protons, deuterons, and tritons. An approximate
expression for the energy lost in the $\Delta E$ detector is [Jel90]

$$\frac{dE}{dx} = -aM Z^2 / E,$$

(3.1)

where $M$ and $Z$ are the mass and charge of the particle, $E$ is the incident energy of the particle, $\Delta x$ is the thickness of the detector, and $a$ is a constant dependent upon the detector material. In the ideal case, detected particles of a given type form bands in the shape of hyperbolas (characterized by $aM Z^2$) when displayed on a $\Delta E$-$E$ plot.

![Figure 3.1](image)

Figure 3.1: Typical raw spectrum showing the particle separation.

Unfortunately, this simple parameterization was inadequate for spectra from the detectors used in the present experiment. For the PMT voltage range at which the detectors were operated, the detector response was observed to be non-linear in the low deposited energy region. Rather than implementing a less physical parameterization, it was decided...
to exhaustively map the form of each particle band (proton and deuteron). First, generous graphical regions were drawn containing each particle band for each detector telescope. Gain shifts (see the next section) in one or more detectors necessitated additional regions for different blocks of experimental runs. Next, the spectrum was divided into 128 bins, each containing eight ADC channels. Finally, the centroid $\Delta E$ ADC channel was recorded for each $E$ ADC bin. One can think of this information as tracing out the "ridgeline" of the "mountain range" formed by the particle bands depicted in Fig. 3.1.

This detailed information about the shape of each particle band was employed to construct a *linearized particle identification (PID)* plot. For a given detector telescope, the linearized PID was calculated as

$$
Lin.PID = (\Delta E \text{ Channel}) - \frac{1}{2} \left( \frac{\text{Proton } \Delta E \text{ centroid} + \text{Deuteron } \Delta E \text{ centroid}}{\text{Proton } \Delta E \text{ centroid} - \text{Deuteron } \Delta E \text{ centroid}} \right) + 1.5.
$$

\hspace{1cm} (3.2)

The normalization employed here arbitrarily centers protons around 1.0 and deuterons around 2.0. Since it is not possible to straighten three particle bands simultaneously, the tritons appear centered around 2.5 instead of 3.0.

The light output (see the next section) measured in the $E$ detector was plotted against linearized PID quantity. A typical linearized PID plot is shown in Fig. 3.2. Although various alternate quantities were calculated, including linearized PID's that used the deuteron band or the proton band exclusively, Eq. 3.2 produced the stabllest and straightest results.

### 3.2 Gain Shifts Tracking and Detector Calibration

The linearization process described above, while straightforward, required a great deal of time and effort. Why was so much work done to change the shape of the particle bands from roughly hyperbolic to linear? One reason was that the high detector rates created gain shifts both in the $E$ detectors. Without a simple parameterization of each band,
Figure 3.2: Linearized particle id spectrum.

correcting for these gain shifts is very difficult. With the linearized PID plots, however, any shift in gain was characterized simply by a change in the endpoint of each particle band. In other words, the particle bands stretched or shrunk in only one dimension.

The point used to track the gain shifts in the detectors was the proton bendback point. Protons of sufficiently high incident energy (greater than 101 MeV) did not deposit all of their energy in the $E$ detector. Such energetic protons are said to punch through the detector. From Eq. 3.1 we see that $dE/dx$ decreases with increasing incident particle energy $E$. Up to the point where the protons begin to punch through, the proton band is monotonically decreasing in $\Delta E$ ADC channel and increasing in $E$ ADC channel. When the proton energy exceeds 101 MeV, however, the $E$ ADC channel begins to decrease. The
result is that the proton band begins to bend back. The point at which this bending back occurs is the proton bendback point (shown in Fig. 3.3).

![Proton bendback](image)

Figure 3.3: Proton bendback point in a $\Delta E-E$ spectrum.

Since the resolutions of the detectors are finite, the various particles form broad bands as opposed to infinitesimally thick curves. Consequently, protons at or near the punch-through energy yield a distribution of $E$ ADC channels rather than a single value. To determine the bendback point, we first restricted ourselves to protons within a generous region placed around the entire proton band. The data were then placed in eight channel by eight channel bins. Next, for each $\Delta E$ bin the centroid $E$ value was calculated. The location with the highest value for this centroid was chosen to be the proton bendback point. The $\Delta E$ and $E$ channels for the location of the proton bendback point were recorded for each detector telescope for each run.
This information was used to calibrate the detectors. For each detector, the gain of the detector-PMT-ADC system was defined as

\[
gain = \frac{\text{proton bendback } \text{ADC channel}}{\text{light output of bendback proton}},
\]

(3.3)

where the light output of 101 MeV bendback protons is 85.1 MeV for 7.6 cm of plastic scintillator. The light output is a quantity proportional to the energy deposited in a detector which takes into account differences in the ionization characteristics of the incident particle. In the case of plastic scintillator, the light output from a 101 MeV deuteron is 77.4 MeV, compared with 85.1 for a 101 MeV proton. The bottom line is that the ADC channel is proportional to the light output of the detector independent of particle type. Using the gains obtained in this fashion it is possible to calculate the light output deposited in a detector (again— \textit{independent of particle type}) by

\[
\text{light output} = \frac{\text{ADC channel}}{\text{gain}}.
\]

(3.4)

With the detector gains in hand, the normalization of the linearized PID spectra becomes trivial. As shown in Fig. 3.2, the y-axis is labeled in terms of the light output in the \( E \) detector. Since each detector is calibrated in each run, spectra from different runs can be summed to produce a single plot representing data from the entire experiment.

### 3.2.1 PID cuts

Another benefit of the linearized PID plots is the simplicity with which particle identification cuts can be applied. If we project the two-dimensional linearized PID plot onto one dimension, we obtain a plot that shows peaks for the various particle types. Fig. 3.4 shows the 1D linearized PID spectra for all untagged production runs in one telescope arm and one recoil arm detector, respectively. Peaks for the protons and deuterons are shown, along with a shoulder for the tritons which is clearer in the telescope arm detector.

The process of determining the type of particle detected involves applying a simple cut on linearized PID. As an example, Fig. 3.5 shows typical deuteron cut ranges. The
Figure 3.4: Linearized PID spectra for telescope arm (top) and recoil arm (bottom) detectors.
data were analyzed with several choices for the limits on cuts for protons, deuterons, and tritons. In the end, a deuteron PID cut between 1.5 and 2.3 was employed. The low end of this cut was in the “valley” between the proton and deuteron peaks. The upper limit was chosen to maximize the number of included deuterons while minimizing the number of included tritons. The proton and triton cuts could be made considerably tighter since they were used primarily to determine contamination of the deuteron peak. This is discussed in detail in Sec. 3.4.

3.3 Kinematic Reconstruction

The process of determining whether or not an event contained a deuteron in the telescope arm and a deuteron in the recoil arm was composed of several steps. First, we established particle cuts as detailed in the previous section. This particle identification, however, was not very accurate. The reason is that there are a number of nuclear reactions other than \(^4\text{He}(\gamma, dd)\) that contain two charged particles in the exit channel and which can generate valid hardware triggers. The fact that these channels are as much as 100 times stronger than the \(dd\) channel coupled with the moderate resolution of our detectors leads to a considerable contamination of the linearized PID deuteron cut. Specifically, \(pt\) and \(n \text{pd}\) events with particles that were misidentified as deuterons were present within the \(dd\) PID cuts. In addition to the PID cuts, however, we recorded (on an event-by-event basis) the energy and angle of both detected particles. Additionally, we had detailed information about the intervening layers between the target and the detectors. This allowed us to reconstruct the event and make a better discrimination against non-\(dd\) events.

3.3.1 Two-body kinematics

For a fixed target two-body breakup reaction there are three degrees of freedom after conservation of energy and conservation of momentum have been applied (see A.2). To obtain complete information about the energy and momentum of all particles it is therefore
Figure 3.5: Typical deuteron cut for telescope (top) and recoil (bottom) arm linearized PID spectra.
necessary to measure three independent quantities. One valid method is to measure the angles of both breakup particles and the energy of one of the particles. Another method is to measure both particle energies and just one of the angles.

During the untagged running, we measured the angle and the energy of both particles. Since we obtained more than the minimum amount of information to determine the reaction kinematics, the system is said to be *kinematically overdetermined*. One problem, however, was that the energies measured were not equal to the particle vertex energies (i.e. the particle energy at the point of creation). The reaction products had to traverse several intervening layers of material (called *dead layers*) before reaching the detectors.

### 3.3.2 Energy loss corrections

Fortunately, the energy losses endured by the reaction particles when passing through the various dead layers could be calculated. Table 3.1 shows the thicknesses of the various layers between and including the target and the $E$ detectors. The energy lost by an incident particle traversing an infinitesimal thickness of energy absorbing material is given by the corrected Bethe-Bloch formula

$$\frac{dE}{dx} = \frac{Z}{A} \frac{z^2}{\beta^2} \left( \ln \left( \frac{2m_e \gamma^2 v^2 W_{\text{max}}}{I^2} \right) - 2 \beta^2 - \delta - 2 \frac{C}{Z} \right). \quad (3.5)$$

The parameters used in this equation are: $a$, a combination of fundamental constants equal to 0.1535 MeV cm$^2$/g; $Z$ and $A$, the atomic number and atomic mass of the absorbing material; $z$, the charge of the incident particle; $v$, the velocity of the incident particle; $\beta$, equal to $v/c$ ($c$ is the speed of light) for the incident particle; $\gamma = 1/(1 - \beta^2)^{1/2}$; $\delta$, the density effect correction; $C$, the shell correction, and $W_{\text{max}}$, the maximum energy transfer in a single collision. For a nice discussion of this formula see Chapter 2 of Leo [Leo94].

The density corrections used in the energy loss calculations for the present work come from Sternheimer *et al.* [Ste84], while the shell corrections are from Barkas and Berger [Bar64].

For the particle energies described in this thesis, the density correction is generally negligible while the shell correction is of the order of a few percent.
The calculation of the energy loss in each layer was accomplished by integrating the infinitesimal energy loss from Eq. 3.5 over the thickness $t$ of the layer:

$$E_{\text{loss}} = - \int_0^t \frac{dE}{dx} dx. \quad (3.6)$$

Sec. A.3 gives a discussion of the code used to perform the energy loss calculations.

The deuteron vertex energies were reconstructed by first converting the $E$ detector ADC channel to a light output according to the gain of the detector and Eq. 3.4. This light output was converted into true energy according to the method described in O'Rielly et al. [O'R96]. Using this energy, the energy loss through the preceding layers was deduced from the known thicknesses of the layers. The vertex where the event occurred was assumed to be the center of the target. For the relatively high energy deuterons detected in this experiment ($E_d$ above 50 MeV) and the size of the beam spot being used (about 37.5 mm in diameter), this introduced an error $\delta E \leq 7$ MeV in the detected deuteron energies. Errors in detected proton energies were considerably smaller.

### 3.3.3 Spectrum of $dd$ candidate events

With a method for calculating the vertex energies in hand we proceeded with the kinematic reconstruction. The first step was to select a set of $dd$ candidate events using the PID cuts on the linearized PID spectra as described in Sec. 3.2.1. Deuteron cuts were
employed on both detector arms and only events with particles passing this first PID cut in both arms were selected. Note that this cut contained contaminant events from the \( pt \) and \( npd \) channels where the proton and triton (\( pt \)) or proton (\( npd \)) passed the deuteron cuts.

The next step was to reconstruct the vertex energies of the two particles. Both particles were treated as deuterons for purposes of the energy loss reconstruction described in the previous section. When reconstructing the recoil arm vertex energy we accounted for the effective thickness of those intervening layers parallel to the photon beam by applying a factor of \( 1/\sin \theta_{recoil \, detector} \). \( \theta_{recoil \, detector} \) was taken to be the central angle of the recoil paddle that fired. In addition, the angle of the telescope arm detector that fired was also taken to be the telescope central angle. The telescope detectors were collimated to a half angle of \( 6.5^\circ \), while the angular ranges for the recoil paddles varied between \( \pm 9.4^\circ \) and \( \pm 1.25^\circ \).

Once both vertex energies were calculated, we took advantage of the fact that this system is kinematically overdetermined. Since any three of the four energies and angles constitutes kinematic completeness, the fourth can be calculated. We used both angles and the recoil arm deuteron vertex energy to calculate the telescope arm deuteron vertex energy, \( E_{\text{calc}} \). This number was compared with the reconstructed telescope deuteron vertex energy, \( E_{\text{recon}} \), and the difference was calculated as

\[
E_{\text{diff}} = E_{\text{calc}} - E_{\text{recon}}. \tag{3.7}
\]

The value of \( E_{\text{diff}} \) for all events with a deuteron in a given telescope arm detector (in coincidence with a deuteron in any recoil arm telescope) was recorded in an \( E_{\text{diff}} \) histogram. A typical \( E_{\text{diff}} \) spectrum is shown in Fig. 3.6.

In the ideal case of point detectors with \( \delta \)-function resolutions and a point target, the \( E_{\text{diff}} \) spectrum for a given telescope would be a delta-function at \( E_{\text{diff}} = 0 \) MeV. In this experiment, the finite resolutions of the detectors and the finite size of the target smeared this \( \delta \)-function into a distribution of energies. Effects which contribute to the final shape of this distribution include the detector resolutions, uncertainty in the location of the \( dd \)
vertex, straggling of the deuterons as they exit the target and pass through the intervening dead layers, and uncertainty in the final deuteron angles due to finite detector size. In each case (ignoring small tailing effects) the resulting distribution can be described to a good approximation by a Gaussian.

The distribution resulting from the conglomeration of these effects in a given detector can be estimated by looking at the distribution of energies near the proton bendback point. Since the proton bendback energy is well defined, looking at the proton band at fixed $\Delta E$ ADC channel provides pseudo-monoenergetic protons. The resolution of the detectors is the full width at half maximum of the proton bendback divided by the centroid $E$ energy of the distribution. A typical value for the $E$ detectors used in this experiment is 25%. Looking at an event generated by a 175 MeV $\gamma$ ray we have deuterons with a total of 150 MeV. Detected energies might typically be on the order of 120 MeV. This gives an energy width of about 30 MeV. The reconstruction process multiplies this figure by roughly $150/120 = 1.25$, giving
a final estimated resolution of 38 MeV. The total Gaussian width that can be expected in
our $E_{\text{diff}}$ spectrum is approximately 38 MeV. This Gaussian is shown in Fig. 3.6.

Inspecting the $E_{\text{diff}}$ spectrum, we see that although there is certainly a peak in
the spectrum, there are quite a few events far from zero. These events correspond to $pt$
and $npd$, and even some $ppnn$, events that have survived the initial deuteron PID cuts.
The final step in selecting true $dd$ events was to estimate the contributions from these (and
other) backgrounds.

3.4 Backgrounds to the $dd$ candidate events from competing channels

One valid method for estimating the contributions to the various $E_{\text{diff}}$ spectra from
competing nuclear reaction channels would be to simulate the system with a Monte-Carlo.
This would require detailed information about the absolute and differential cross sections of
all reactions as well as complete characteristics of the physical setup and detector responses.
Unfortunately, the various cross sections are not well known, with considerable controversy
surrounding the angular distribution of the $pt$ channel in particular. For this reason (among
others), we decided to estimate the competing channel contributions to the $E_{\text{diff}}$ spectra
by analyzing our own data.

The hardware trigger, as discussed in Sec. 2.5.3, was a coincidence between a charged
particle in any telescope arm telescope and any recoil arm telescope. This trigger allowed us
to record data on the $pt$ channel, the $npd$ channel, and even the (kinematically incomplete)
$ppnn$ channel in addition to the $dd$ channel. Using the technique described in Sec. 3.2.1, we
selected out events of each type by employing PID cuts in the linearized PID spectra.

The objective was to determine the shape of the background contribution to the
$dd$ $E_{\text{diff}}$ spectrum from the various competing channels. We did this by starting with an
event "known" to be, for example, $npd$. This means that a $p$ was been detected in one
detector and a \( d \) in another detector. We then determined the \( E_{\text{diff}} \) for \( npd \) events, *treating both particles as if they were deuterons* for purposes of energy loss correction. The resulting shape should mirror that of the background contributions to the \( dd \) \( E_{\text{diff}} \) spectrum from \( npd \) events that were misidentified as \( dd \) events by the PID cuts.

One immediate concern is how similar backgrounds generated in this fashion are to the backgrounds in the \( dd \) \( E_{\text{diff}} \) spectrum. Since both data sets used to generate both \( E_{\text{diff}} \) spectra were acquired simultaneously a great number of possibilities, including detector, beam, and target considerations, can be eliminated immediately. Another possibility is that misidentified protons and tritons occupy different regions of phase space from those "known" \( npd \) or \( pt \) events. Specifically, is there some geometric effect causing this misidentification?

To investigate this possibility we consider a particle leaving the target and proceeding through the recoil \( \Delta E \) detector centered at 90° in the lab. This particular detector subtends the largest angle of any \( \Delta E \) detector and serves as a worst case. A particle passing through the \( \Delta E \) of thickness \( t \) with an angle of incidence \( \theta \) will traverse a distance \( t \cos \theta \) of material. Recalling the simplified version of the Bethe-Bloch formula given in Eq. 3.1, we see that the energy deposited by a particle is proportional to its mass and the thickness of the detector. This introduces an ambiguity between thickness traversed and mass of particle. For example, a proton traversing a thickness \( 2t \) deposits as much energy as a deuteron traversing a thickness \( t \). From the detector and target geometry we find that the greatest angle of incidence possible for the 90° recoil \( \Delta E \) detector is 13.9°. This leads to a thickness correction of three percent relative to a particle normally incident to the same detector. Such a minor correction will not cause significant misidentification of particles and can safely be neglected.

Fig. 3.7 shows the shapes of the \( E_{\text{diff}} \) spectra generated from the competing channels. The figure shows curves labeled \( pt \), \( tp \), \( pd \) and \( dp \). The notation for the spectra specifies the type of particle cut applied to telescope arm followed by the type of particle cut applied to the recoil arm. For example, the spectrum labeled \( dp \) represents events which
have a \( d \) in the telescope arm and a \( p \) in the recoil arm. This same spectrum describes the shape of the \( dp \) background in the \( dd \) \( E_{\text{diff}} \) spectrum.

![Figure 3.7: Typical \( E_{\text{diff}} \) shapes from competing background channels.](image)

3.5 Determination of Detector Yields

3.5.1 \( \chi^2 \) minimization technique for competing channel background subtraction

In the previous section we described the method used to determine the \( E_{\text{diff}} \) spectrum shapes for the various reaction channels that compete with \( dd \). To determine the actual number of \( dd \) events we employed a minimization technique using the shapes from the previous section for contributions from the background channels and a Gaussian for the \( dd \) peak. The functional form of our fit was

\[
f = c_1 y_{pd} + c_2 y_{dp} + c_3 y_{tp} + c_4 y_{pt} + c_5 y_{pp} + \text{gauss}(A, a, \sigma),
\]  

(3.8)
where the $c_x$ are scale factors, the $y_{xx}$ are the background shapes, $gauss$ represents a Gaussian function, $A$ is the amplitude of the Gaussian, $a$ is the central value of the Gaussian, and $\sigma$ is the standard deviation. The value that was minimized was the square of the difference between $f$ and the $dd\ E_{\text{diff}}$ spectrum, i.e. the $\chi^2$. The code used to perform the minimization is given in Sec. A.4.

Several pieces of information aided the minimization process. First, it was noted that the likelihood of a four-body event masquerading as a $dd$ was quite small. The primary reason for this is that such a result implies the misidentification of both protons as deuterons. Although this is possible, it will clearly occur less often than events where only a single proton is misidentified. Since the $ppmn$ events represented only a small fraction of background events, this component was omitted from the minimization process.

Another factor influencing the parameters used from telescope to telescope was the incidence of tritons observed in the raw $\Delta E-E$ plots. According to Eq. 3.1, the energy loss experienced by a triton should be greater than that of deuterons and protons of the same energy. Furthermore, the kinematics of the $pt$ reaction indicate that for equivalent incident $\gamma$-ray energies, the tritons ejected at a particular angle will have significantly less energy than deuterons emitted at the same angle. These two properties combine to significantly increase the energy loss experienced by tritons as they pass through the target and intervening layers toward the detectors. The result is that many tritons are not energetic enough to reach the detectors. This is especially true for tritons emerging at lab angles above 90°. Using this information, the $pt$ contributions were ignored for telescope arm detectors at 38.8° and 55.0° (because recoil tritons were not detected) and the $tp$ contributions were ignored for telescope arm detectors 115° and 132° (because the telescope arm tritons were not detected).

An issue which requires clarification is the seeming arbitrariness of including the $pt$ and $tp$ events while excluding the $ppmn$ events. While the proton and deuteron peaks are quite distinct in the linearized PID spectra, the tritons tend to merge with the deuterons. The reason for this is that the tritons experience considerable energy losses in reaching the
detectors. This places them in the non-linear response region for the $\Delta E$ detectors, where the triton and deuteron bands begin to overlap. This results in significant overlap between the triton and deuteron bands.

Results of the minimization process for a typical telescope are presented in Fig. 3.8. Pictured in the figure are the "raw" $dd\ E_{\text{diff}}$ spectrum, the fitted background spectrum, the extracted Gaussian for the $dd$ peak, and the final background + peak result from the fit.

![Graph showing results from the $E_{\text{diff}}$ minimization process.](image)

Figure 3.8: Results from the $E_{\text{diff}}$ minimization process.

3.5.2 Deuteron PID cut corrections

The minimization process described above began with a cut on the linearized PID spectra around the deuteron peak. The low end of this cut was at a PID of 1.5, placing it in the valley between the proton and deuteron peaks. The upper limit was at a PID of 2.3 and was chosen so as to maximize the number of included deuterons while minimizing the
number of included tritons. Clearly this cut does not include all of the deuterons in either arm.

One method for estimating the number of deuterons excluded by our PID cuts is to fit the linearized PID spectra in both arms and calculate the percentage of omitted deuterons. Fig. 3.9 shows the results of a gaussian fit to the various particle peaks in the spectra. The fits were good, with $\chi^2/\nu$ of 0.574 and 0.349 for the telescope and recoil arms, respectively. Using the results of the fits, we find that a 1.5 to 2.3 PID cut corresponds to a 2.5 (telescope arm) and 2.0 (recoil arm) standard deviation cut. Since such a cut includes 98.76% of the deuterons in the telescope arm and 95.45% of the deuterons in the recoil arm, the percentage of $dd$ events included by our PID cut is $98.76\% \times 95.45\% = 94.26\%$. Consequently, 5.73% of the $dd$ events have been excluded by our PID cut.

This simple method presupposes that the deuteron peak in the PID spectrum is, in fact, a gaussian. One effect that is significant at these energies, however, comes from secondary nuclear reactions between the deuterons to be detected and the plastic scintillator that comprises our detectors. In particular, the inelastic cross section of deuterons on carbon can cause the pulse-height yielded for a particular deuteron to be spuriously low. This manifests itself as a long tail extending from a PID of 2.0 (i.e., the center of the deuteron peak) toward lower PID values. Measday and Schneider [Mea66] have studied this effect for a range of deuteron energies incident upon plastic scintillator. Specifically, they calculated (by integrating the corrected Bethe-Bloch energy-loss formula) the likelihood for a deuteron pulse height to fall more than 10 MeV below the nominal, full-energy pulse height. For the deuteron energies used in this experiment, their results predict that one of the deuterons in a $dd$ event will fall outside this 10 MeV cut for 14% of the mid-energy bin $dd$ events and 29% of the high-energy bin $dd$ events. Our deuteron PID cuts, however, were significantly broader than the 10 MeV cut employed in this calculation. Unfortunately, details of how this calculation changes with different cutoff energies are not available.

We shall take the results from these two methods to be lower and upper bounds
Figure 3.9: Triple gaussian fits to typical telescope arm (top) and recoil arm (bottom) linearized PID spectra.
on the deuteron PID cut correction. Averaging the two methods we find that 9.4% of the mid-energy bin $dd$ events and 17% of the high-energy bin $dd$ events have been excluded by our PID cut. These corrections were applied to the yield given in Sec. 3.5.1. We take the uncertainty in this correction to be half the difference between the two methods. For the mid-energy bin this is 4.6%, and for the high-energy bin this is 11.7%. It is important to note that this error is systematic in nature, and as such we did not include it when propagating the error on the yields. The total systematic error for the present measurement is discussed in Sec. 3.6.1.

### 3.5.3 Empty target contributions

Several empty target runs were performed during the experiment. Since we did not employ a pressurized target that could be emptied on command, we monitored the target level in two ways. First, a superconducting level sensor was used to read the liquid helium level in the dewar. When this dropped off scale, however, helium remained in the target cell. At this point a close watch was kept on the trigger rate histogram. This histogram pictured in Fig. 3.10, tracked the number of two-arm coincidence triggers as a function of time. When the target level reached the height of the beam, a drop in trigger rate was observed. When the rate stabilized at a new, lower rate the target was considered "empty."

The empty target runs were summed and analyzed using the $E_{diff}$ spectrum technique described above. In the region of overlap with the $dd$ Gaussian, the spectrum was observed to be, for the most part, flat. The yield in this region was determined and recorded for each telescope arm detector. Comparison of the count rates showed the background count rate to be approximately $20.6\% \pm 0.7\%$ of the target full rate. This background was subtracted from the yield given in Sec. 3.5.1.
3.5.4 Uncorrelated contributions

Although the two-arm coincidence trigger is fairly restrictive, occasionally particles from two different nuclear reactions can cause a coincidence. These uncorrelated events are known as accidental coincidences and constitute another background to the true $dd$ yield.

A simple method exists to estimate this accidental coincidence rate. Fig. 3.11 shows the TDC spectrum for the recoil arm $E$ detector. Every two-arm coincidence event caused this detector to fire, so every event was recorded in this spectrum. The central peak represents correlated or true coincidences arising from a single event. Surrounding this is a true peak timing cut which must be satisfied in order for the offline analysis code to process the event. Events occurring outside this peak were uncorrelated. Using the true peak timing cut and applying an off peak timing cut, the accidental rate is given by

$$\text{acc. rate} = \frac{\text{off peak counts} \times \# \text{true peak channels}}{\# \text{off peak channels} \times \text{true peak counts}}$$

(3.9)
This gives the rate of accidental coincidences falling within the true peak timing cut. The accidental rate observed in this experiment was approximately 7.50%. An $E_{\text{diff}}$ analysis of the uncorrelated data yielded a background in the $dd$ region that was $2.90\% \pm 0.10\%$ of the true + accidental $dd$ yield, indicating that most uncorrelated background fell outside the region of kinematic acceptance for the $dd$ events. These accidental counts were subtracted from the yield given in Sec. 3.5.1.

![Typical $E_{\text{diff}}$ spectrum](image)

**Figure 3.11: Typical $E_{\text{diff}}$ spectrum**

### 3.6 Determination of Absolute Differential Cross Sections

The differential cross section for a two-body reaction is given by

\[
\frac{d\sigma}{d\Omega} = Y \frac{A}{N_A} \frac{1}{\epsilon N_\gamma} \frac{1}{\Delta \Omega \rho t'}
\]  

(3.10)

where $Y$ is the $dd$ yield after background, empty target, and accidental subtraction, $A$ is the atomic mass of $^4\text{He}$, $N_A$ is Avogadro's number, $\epsilon$ is the tagging efficiency, $N_\gamma$ is the flux
of gamma rays, \( \rho \) is the density of liquid helium, and \( t \) is the target thickness.

The flux of \( \gamma \) rays incident upon the target was obtained from the recorded beam current monitor paddle fluxes. As described in Sec. 2.2.5, the BCMP’s were cross normalized to the fluxes obtained across the entire tagging focal plane. The tagging focal plane measured the total flux of \( \gamma \) rays with energies between 171 and 212 MeV. The \( dd \) data were divided into bins with (reconstructed) \( \gamma \) ray energies between 150 and 190 MeV (the mid-energy bin) and between 190 and 250 MeV (the high-energy bin). Data below 150 MeV (the low-energy bin) were also collected, but particle energy losses made this data unusable. In order to obtain total fluxes for the mid- and high-energy bins, the bremsstrahlung spectrum was integrated for both these bins and for the tagged energy bin according to the Schiff thin-radiator bremsstrahlung formula (see Sec. A.1). The flux in the mid-energy bin was determined to be 1.117 times the total tagged bin flux, while the flux in the high energy bin was found to be 1.546 times the total tagged bin flux.

The target density was taken to be a constant 0.125 g/cm\(^3\) throughout the run. This assertion assumes that the target remains in liquid form throughout the target cell. The target boiloff rate was tracked with and without beam on target. To within 2-3\%, no change in the boiloff rate was observed. Based on this we conclude that no gas bubbles (to the 2-3\% level) were created in the target by the beam.

The effective target length was calculated using a Monte-Carlo routine. The beam profile was treated as a double Gaussian with a width determined by the Schiff bremsstrahlung formula as a function of angle. The 50 mm cylindrical target cell was bombarded by \( \gamma \) rays with a circular beam spot of diameter 37.5 mm as defined by the primary beam collimator. The effective target length was determined to be 47.3 mm ± 1 mm. This uncertainty was estimated by moving the beam spot center ± 3 mm. This limit in the motion of the beam spot corresponds to the precision of measuring the beam spot center on polaroid film at the 15 mm collimator using a ruler with millimeter demarcations.

The detector acceptances were determined using the 6.5° half-angle of the telescope.
arm collimators. This provides a $\Delta \Omega$ of 40.4 msr. The detection efficiencies were also modeled using a Monte-Carlo. Every location in the target cell accessible by the incoming photon beam was treated as a source for $dd$ events. Using a 150 MeV $\gamma$ ray, $dd$ events were then specified with one deuteron directed at each telescope and the recoil deuteron appropriately directed at the recoil arm. Energy losses through the intervening layers were included, as well as a detector threshold determined from the $\Delta E-E$ plots. For every detector, all $dd$ events generated could be detected, so the detection efficiency was 100%.

In order to quote differential cross sections in the center of mass it is necessary to multiply by the Jacobian $d\sigma_{\text{cm}}/d\sigma_{\text{lab}}$. The Jacobian was calculated using the kinematics code RKIN for each detector angle at $E_\gamma = 170$ MeV and $E_\gamma = 220$ MeV. The results of the calculation are given in Table 3.2.

<table>
<thead>
<tr>
<th>Telescope $\theta_{\text{lab}}$</th>
<th>$\theta_{\text{cm}}$</th>
<th>$J(\theta_{\text{lab}})$</th>
<th>$\theta_{\text{cm}}$</th>
<th>$J(\theta_{\text{lab}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.8°</td>
<td>44.7°</td>
<td>0.790</td>
<td>45.4°</td>
<td>0.770</td>
</tr>
<tr>
<td>55.0°</td>
<td>62.7°</td>
<td>0.843</td>
<td>63.6°</td>
<td>0.828</td>
</tr>
<tr>
<td>81.0°</td>
<td>90.3°</td>
<td>0.964</td>
<td>91.4°</td>
<td>0.962</td>
</tr>
<tr>
<td>98.1°</td>
<td>107.3°</td>
<td>1.06</td>
<td>108.4°</td>
<td>1.07</td>
</tr>
<tr>
<td>115.1°</td>
<td>123.5°</td>
<td>1.17</td>
<td>124.4°</td>
<td>1.19</td>
</tr>
<tr>
<td>132.2°</td>
<td>138.9°</td>
<td>1.27</td>
<td>139.7°</td>
<td>1.31</td>
</tr>
</tbody>
</table>

**Final $d\sigma/d\Omega$ formula**

Unifying the results of the previous discussions we obtain

$$
\frac{d\sigma}{d\Omega}(\theta) = Y(\theta)J(\theta)f,
$$

(3.11)

where $f$ is a constant given by 0.813 pb/sr for the mid-energy bin and 0.617 pb/sr for the high-energy bin. These formulas were used in conjunction with the observed background-subtracted yields for each telescope to provide a cross section angular distribution for both energy bins. The results of this analysis are presented and discussed in Chapter 5.
3.6.1 Estimate of systematic errors

There are several sources of systematic error in this experiment. First, during untagged production mode the incident \(\gamma\)-ray energy is not known \emph{a priori} and must be reconstructed. The uncertainty in the energy of the detected particles introduces an error into the reconstructed \(\gamma\)-ray energy. This error has components arising primarily from the detector resolution and the energy straggling of the detected particles through the target and intervening layers. As discussed in Sec. 3.3.3, this is approximately 25\%. Consequently, the cuts on reconstructed \(\gamma\)-ray energy used to sort the data into bins are uncertain. Investigating the effect of a 25\% shift in the \(E_\gamma\) cut, we find that uncertainty in the total flux is approximately 3.3\%. The reason for the smallness of this number is that the bremsstrahlung spectrum is relatively flat in this energy region.

Another source of systematic error comes from placement of the deuteron linearized PID cuts. This was discussed in Sec. 3.5.2. We found that the systematic error introduced by our PID cuts is 4.6\% for the mid-energy bin and 11.7\% for the high-energy bin.

As discussed in Sec. 3.6, motion of the beam spot relative to the target contributes a systematic uncertainty of 2.0\% to the effective target length. The uncertainty in the target density is taken to be 2.5\%. The tagging efficiency measurement also introduced a systematic error. Looking at the variation in efficiency measurements from run to run (61.9\% to 65.6\%), we estimate this to be approximately 2.8\%.

There exists some debate at to the proper method for combining systematic uncertainties. One school of thought is that the individual errors should be summed. According to this method, the total systematic uncertainty becomes 15\% for the mid-energy bin and 22\% for the high-energy bin. Another method for combining the uncertainties is to add them in quadrature. Using this technique we obtain a final systematic uncertainty of 7.1\% for the mid-energy bin and 13\% for the high-energy bin. This second technique implies a normal distribution to the total systematic uncertainty and corresponds to one standard deviation. We shall quote this second value throughout the remainder of this work, with
the implication that this value is a one standard deviation limit on the systematic error.
Chapter 4

The LEGS Experiment

The first incarnation of our attempt to measure the $^4\text{He}(\gamma, dd)$ reaction took place at the Laser Electron Gamma Source (LEGS) beamline facility at the National Synchrotron Light Source (NSLS), which is located at Brookhaven National Laboratory. This experiment used linearly polarized $\gamma$ rays to measure both the cross section and analyzing power for $E_\gamma = 185 - 310$ MeV. As discussed in Sec. 1.6, a lack of statistics and poor particle identification prevented an accurate determination of the differential cross section or the total cross section. One of the great strengths of analyzing power measurements, however, is their independence from many of the normalization difficulties encountered by cross section measurements. As a result, we have been able to extract analyzing powers from the data. This chapter describes the LEGS experiment and the analysis of the analyzing power data—the first such data at these energies. The results will be given in Chapter 5.

4.1 The Facility

The NSLS (shown in Fig. 4.1) was, at the time of this experiment in the summer of 1993, the site of 2.5 GeV and 750 MeV electron storage rings. The 2.5 GeV ring produced synchrotron radiation in the x-ray region and so was dubbed the x-ray ring. The smaller ring produced UV synchrotron radiation and was known as the UV ring. Both rings have since
been upgraded to higher nominal electron energies, but the primary use of both remains unchanged–material science research. All the beam legs shown in Fig. 4.1 are devoted to this research–except beam line X5.

X5 belongs to the LEGS facility. The facility, pictured in Fig. 4.2, Compton scatters 100% plane polarized laser light from the 2.5 GeV electrons in the x-ray ring to produce linearly polarized γ rays. Our experiment used an Argon-Ion laser tuned to either 488 nm or 351 nm, which produced γ-ray energies 185-237 MeV and 185-310 MeV, respectively. In the present work we will present only those data from the 488 nm runs.

### 4.1.1 Compton Backscattering

The idea of producing high-energy photons from the Compton-scattering of low-energy photons from relativistic electrons was first proposed by Arutyunian and Tumanian in 1963 [Aru63]. They showed that the photons coming from star light could be boosted considerably in energy by Compton scattering from high energy electrons and suggested that this was the source of many observed cosmic γ rays. In the lab frame the energy of a Compton-backscattered γ ray is given by [Aru63]

\[
E_\gamma = h\nu = \frac{\gamma^2 E_L (1 + \beta \cos \phi)(1 + \beta \cos \theta')}{1 + \frac{\gamma E_L}{mc^2}(1 + \beta \cos \phi)(1 + \cos(\theta' + \phi'))},
\]

where

\[
\gamma = \frac{E_e}{mc^2} = \sqrt{1 - \beta^2}, \beta = v/c,
\]

\(E_e\) is the electron kinetic energy, \(m\) is the electron mass, \(\phi\) is the angle between the incident photon and the initial electron momentum, \(\theta\) is the angle between the recoil gamma ray and the initial electron momentum, \(E_L\) is the energy of the laser photon, and the primed quantities are in the electron rest frame.

Eq. 4.1 can be simplified somewhat by taking into account the extreme relativistic nature of the electrons. The backscattered γ rays fall into a forward peaked cone with a half-angle of approximately 1 mrad. Expanding in angles we need only retain the lowest
Figure 4.1: The NSLS floorplan.
Figure 4.2: The LEGS beamline and experimental hall.
order terms. Next, for this experiment $\gamma$ is about 5000, so we need only keep terms in order $1/\gamma$. The resulting equation is

$$E_\gamma = \frac{4\gamma^2 E'_L}{1 + \frac{4\gamma E'_L}{mc^2} + \theta^2 \gamma^2}$$

(4.2)

where $E'_L = E_L(1 + \cos \phi)/2$. The maximum $\gamma$-ray energy that can be produced for a given incoming photon energy occurs when the angle between the incident photon and the recoil photon is $180^\circ$. This is called the Compton edge. For the 488nm (2.5 eV) laser line interacting with a 2.53 GeV beam, the Compton edge corresponds to approximately 237 MeV.

The Compton scattering spectrum is relatively flat compared to the bremsstrahlung spectrum. Fig. 4.3 shows the spectra for Compton backscattering using the 488 nm line and the 351 nm laser line. Collimators were placed such that only $\gamma$ rays with $E_\gamma > 185$ MeV were permitted to proceed toward the target.

![Figure 4.3: The Compton backscattering spectrum for the 488 nm and 351 nm laser lines. Collimators pass $\gamma$'s with $E_\gamma > 185$ MeV only.](image-url)
4.1.2 The Laser

As mentioned above, this experiment used an Argon-Ion laser to produce nearly 100% plane polarized photons. The polarization state of the photons could be selected using a polarization rotator. In this experiment we ran with the polarization at $0^\circ$ and $90^\circ$, where $0^\circ$ corresponds to being in (||) the reaction plane defined by the experimental detectors and $90^\circ$ corresponds to being perpendicular ($\perp$) to this plane. Fig. 4.4 shows the coordinate system for linearly polarized $\gamma$ rays used in this work. In order to reduce systematic errors the polarization state was flipped often, with an average of 300 seconds spent in each polarization state. After visiting both polarization states, bremsstrahlung measurements lasting approximately 20 seconds were also made. The laser polarization was measured several times during the experiment. It was observed to be a stable 99.0% and 99.7% for the $||$ and $\perp$ states, respectively.

![Diagram](image)

Figure 4.4: Coordinate system XYZ in which the polarization state of the beam ($\gamma$ rays) is described. The incident beam $k_{in}$ is along $+Z$. The normal to the plane $k_{in} \times k_{out}$ is along $+Y$. The photon polarization vector $\epsilon$ has azimuthal angle $\phi$ measured between $+X$ and the vector $\epsilon$ [Wel92].

These laser photons were directed through a vacuum window into the NSLS ring where they interacted with electrons somewhere along the straight section shown in Fig. 4.5. The recoil $\gamma$ rays were boosted in energy and backscattered through the laser mirrors along
a vacuum beamline toward the LEGS experimental hall and the target. The energy of the \( \gamma \) rays and the thickness of the mirrors and their backings made attenuation of the \( \gamma \) beam by the mirrors negligible.

### 4.1.3 The LEGS Tagger

The \( \gamma \) ray energies were determined on an event by event basis by tagging the recoil electrons in a tagging focal plane similar to the one described in Sec. 2.2.2. The electrons lost energy equal to the energy of the recoil \( \gamma \) ray. As a result, the recoil electrons could be separated via dipole magnets from the primary beam packet. A series of four dipole magnets, shown in Fig. 4.5, were used to perform this separation. The electrons were directed into a focal plane cave containing a tagging focal plane array. This array was composed of two planes of plastic scintillator counters very similar to the SAL tagger. The tagger consisted of 64 channels, each defined as a coincidence between a front scintillator and an overlapping back scintillator. Since the incoming electrons were approximately perpendicular to the detectors, the geometric acceptance problems experienced at SAL were not encountered here. For a complete description of the tagging spectrometer the interested reader is referred to Ref. [Tho89].

The tagger was calibrated twice during the running period. The calibration process involved using six different laser lines and recording the Compton edge. Since both the ring energy and laser photon energies were well known, the Compton edge \( \gamma \)-ray energies could be calculated. These six points were then fit using a cubic polynomial to provide a tagger calibration. It's important to note that this technique was insensitive to misalignments between the laser and ring electron packets. An incident laser photon angle of as much as 1\(^\circ\) (where perfect alignment implies an angle of incidence of 0\(^\circ\)), which is much larger than the divergence of either laser or electron beam, changes the Compton edge energy by only 20 keV.
Figure 4.5: The LEGS tagging spectrometer.
Tagging Efficiency at LEGS

Although the detectors in the tagging focal plane closely resemble those employed at SAL, the technique for determining the total $\gamma$-ray flux is markedly different. A beam monitor was placed in the photon beam downstream of the target in front of the LEGS beam dump. This beam monitor, designated CG3, consisted of a charged particle veto, a thin copper $\gamma$-ray converter, and a plastic scintillator to detect $e^{\pm}$ pairs. A set of scalar electronics modules was wired so as to increment a counter for each tagger channel that fired in coincidence with a hit in the CG3 detector. This setup obviates the need for correction of total $\gamma$-ray flux due to losses in the $\gamma$-ray collimators. The efficiency for $e^{\pm}$ pair creation by the $\gamma$-rays, however, must still be measured.

The CG3 conversion efficiency was measured periodically throughout the experiment by placing a 100% efficient NaI in the beam. The $\gamma$-ray flux was reduced to a few kHz by narrowing the collimation slits. The flux rate observed by the NaI was compared with the $e^{\pm}$ detection rate in CG3 and a $\gamma$-ray detection efficiency was deduced. The average CG3 efficiency for our experiment was 6.50% $\pm$ 0.03%.

4.1.4 $\gamma$-ray Polarization

For relativistic electrons, the spin-flip probability for Compton scattering at 0° (between the outgoing $\gamma$ ray and the initial electron momentum) goes to zero. If the incoming laser photons are 100% plane polarized, then $\gamma$'s Compton backscattered at 0° will be 100% polarized as well. For recoil angles other than 0°, the polarization of a $\gamma$ is given by

$$f = 1 - (\Delta \theta \gamma)^2,$$

where $\theta$ is the angle between the outgoing $\gamma$ and the initial electron momentum.

Determining the polarization of the beam at the target is more complicated. The cross section is a complex function of $\theta$, the electron energy, and the $\gamma$ ray energy. This
cross section is given by the Klein-Nishina formula

$$\frac{d\sigma}{d\Omega}(E_\gamma, E_e) = \frac{2\pi r_0^2}{E_e^2 y^2} \left( \frac{2\gamma}{1 + x^2} \right) \left[ y + \frac{1}{y} - \left( \frac{2x}{1 + x^2} \right)^2 \right],$$

(4.4)

where

$$x = \theta \gamma = \left[ 4\gamma E_L \left( \frac{\gamma}{E_\gamma} - \frac{1}{mc^2} \right) - 1 \right]^{1/2},$$

(4.5)

and

$$y = 1 + \frac{4\gamma E_L}{(1 + x^2)mc^2},$$

(4.6)

and where $E_\gamma$ is the energy of the recoil $\gamma$ ray, $E_e$ is the initial energy of the ring electron, $E_L$ is the energy of the laser photon, $r_0$ is the classical electron radius, $m$ is the electron rest mass, and $c$ is the speed of light. A Monte-Carlo simulation was performed by Keith Mize (see Ref. [Miz92]) to determine the effective polarization of the $\gamma$-ray beam at the target. Results of this simulation are presented in Table 4.1 as $P_\perp^C$ and $P_\parallel^C$.

Unfortunately, synchrotron radiation damage to the laser optics introduces some depolarization effects into the process. The primary source of problems comes from the vacuum window mounted on the light source ring. When the laser and the NSLS are operating, the window absorbs power on the order of a few watts. This creates a temperature gradient in the material which causes the window to act as a lens. This depolarization could be determined by measuring the polarization of the laser light after the light had passed through the interaction region and exited a non-radiation-damaged exit port on the ring. This was done and the laser polarizations were measured to be $P_\parallel^L = 97.8\% \pm 1.3\%$ and $P_\perp^L = 96.5\% \pm 1.3\%$ where the error has been estimated from knowledge of the measurement device and methods [Miz92].

In addition, bremsstrahlung radiation from interactions between the electron beam with residual gas in the ring provides an unpolarized contribution to the observed $\gamma$-ray flux. A correction for the presence of these unpolarized $\gamma$'s can be made. For $\gamma$'s produced when using the 488 nm laser line this correction was calculated to be $P_B = 0.992 \pm 0.011$ [Miz92].
Finally, the $\gamma$ ray polarization of the beam at the target can be calculated as

$$P^\gamma_a = P_B [P_a^L P_a^C - 1/2(1 - P_a^L)(P_a^C - P_a^C)]$$

where the subscript $a$ denotes either the $\parallel$ (0°IRC) state or the $\perp$ (90°) state. The calculated values for various $\gamma$-ray energies are listed in Table 4.1.

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>$P_a^C(\pm)$</th>
<th>$P_a^C(\pm)$</th>
<th>$P_\parallel^C(\pm)$</th>
<th>$P_\perp^C(\pm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>229</td>
<td>0.993(.001)</td>
<td>0.994(.001)</td>
<td>0.951(.017)</td>
<td>0.964(.017)</td>
</tr>
<tr>
<td>226</td>
<td>0.998(.001)</td>
<td>0.997(.001)</td>
<td>0.955(.017)</td>
<td>0.967(.017)</td>
</tr>
<tr>
<td>222</td>
<td>0.995(.001)</td>
<td>0.996(.001)</td>
<td>0.952(.017)</td>
<td>0.966(.017)</td>
</tr>
<tr>
<td>218</td>
<td>0.995(.001)</td>
<td>0.995(.001)</td>
<td>0.952(.017)</td>
<td>0.965(.017)</td>
</tr>
<tr>
<td>214</td>
<td>0.993(.001)</td>
<td>0.992(.001)</td>
<td>0.951(.017)</td>
<td>0.962(.017)</td>
</tr>
<tr>
<td>211</td>
<td>0.988(.001)</td>
<td>0.988(.001)</td>
<td>0.946(.017)</td>
<td>0.959(.017)</td>
</tr>
<tr>
<td>207</td>
<td>0.982(.001)</td>
<td>0.983(.001)</td>
<td>0.940(.017)</td>
<td>0.954(.017)</td>
</tr>
<tr>
<td>203</td>
<td>0.979(.001)</td>
<td>0.977(.001)</td>
<td>0.937(.017)</td>
<td>0.948(.017)</td>
</tr>
<tr>
<td>199</td>
<td>0.972(.001)</td>
<td>0.970(.001)</td>
<td>0.931(.017)</td>
<td>0.941(.017)</td>
</tr>
<tr>
<td>195</td>
<td>0.961(.001)</td>
<td>0.960(.001)</td>
<td>0.918(.016)</td>
<td>0.931(.017)</td>
</tr>
<tr>
<td>191</td>
<td>0.949(.001)</td>
<td>0.949(.001)</td>
<td>0.908(.016)</td>
<td>0.921(.016)</td>
</tr>
<tr>
<td>187</td>
<td>0.938(.001)</td>
<td>0.940(.001)</td>
<td>0.898(.016)</td>
<td>0.911(.016)</td>
</tr>
</tbody>
</table>

### 4.2 The Target

The target used in this experiment is pictured in Fig. 4.6. The cell wall was composed of electroformed nickel. The geometry was a torpedo shape with a cylindrical section capped by two hemispherical sections. The cylinder section was 5 cm in diameter and 5 cm long. The end caps had a radius of 2.5 cm. The cell was surrounded by an aluminum heat shield and the entire assembly housed inside an evacuated aluminum beam line.

The target was filled by means of a pressurized system that pumped liquid helium from a large dewar in through an access neck with 12.7 mm diameter. The temperature and pressure of the target were monitored by sensors placed on the target neck. This
information was used to determine the target density, which was found to have the average value of $\rho = 0.140 \pm 0.001 \text{ g/cm}^3$ throughout the target during the production runs. In addition, resistive heating elements in conjunction with various valves allowed the target to be pumped out on demand. This conveniently allowed empty target runs to be performed whenever required.

The presence of the neck made the placement of the target very important. Several beam profile photos were taken to insure that the beam missed the neck. The dimensions of the beam spot at the target were measured (from exposed film) to be approximately 20 mm vertically and 40 mm horizontally. The target was placed with the neck (and helium fill lines) above and out of the beam path.

4.3 The Detectors

A mockup of the detector setup is shown in Fig. 4.7. The setup consisted of three telescopes with plastic scintillator $\Delta E$'s and sodium-iodide (NaI) $E$'s. Two of the detectors were mounted on rotating arms. The smaller of the rotating detectors was a 10 inch by 14 inch NaI with two 0.25 inch plastic paddles serving as $\Delta E$'s. The other rotating detector was a $\Delta E - \Delta E - E$ telescope. The first $\Delta E$ layer consisted of three 0.25 inch plastic paddles. The second layer was a one inch plastic scintillator affectionately known as the turtle. The $E$ was a 19 inch by 19 inch NaI, the largest single-crystal NaI ever fabricated by Bicron Technologies. Both rotating NaI detectors were mounted with lead collimators containing 11.5° half-angle bores. The third telescope consisted of two 0.125 inch plastic paddles in front of a 4 inch by 4 inch by 14 inch NaI bar.

This detector setup allowed us to detect both deuterons from a $dd$ event in coincidence. A two-arm coincidence trigger was defined as

$$(Pad_{14} \cdot NaI_{14} + Turtle \cdot NaI_{19}) \cdot (Pad_{\text{bar}} \cdot NaI_{\text{bar}}),$$

meaning that a charged particle had to be detected in the bar $\Delta E$ and $E$, as well as in both
Figure 4.6: The liquid $^4$He target for the LEGS experiment.
the $\Delta E$ and $E$ in one of the rotating detectors. This constituted a two-charged particle event where both particles were detected in coincidence.

4.4 Analysis

We now turn to an analysis of the data collected during the LEGS experiment. In this section we will only discuss those data acquired while using the visible laser line at 488 nm, corresponding to $\gamma$-ray energies between 185 and 237 MeV.

Coincidence events between either of the rotating detector telescopes and the NaI bar telescope were recorded. $\Delta E$ spectra for the 19 inch arm and the NaI bar are shown in Fig. 4.8. The most striking feature apparent in these spectra is the difference in quality. The rotating arm had extremely good particle identification, whereas the bar arm had extremely poor PID.

The reason for the poor resolution in the NaI bar is that the this arm was located only a few inches from the target. As such, the bar's two $\Delta E$'s could only resolve the incident particle's reaction angle into two bins: $\geq 90^\circ$ and $\leq 90^\circ$. This poor angular resolution translates into uncertainty in the thickness of scintillator traversed by the particle. As indicated by the discussion in Sec. 3.4, such uncertainty in the $\Delta E$ thickness traversed leads to an inability to distinguish between protons and deuterons in the bar $\Delta E$-$E$ plot.

4.4.1 Kinematic Reconstruction

The lack of particle identification in the bar detector arm prevented us from identifying $dd$ events with simple PID cuts. Instead, we identified $dd$ events by performing a kinematic reconstruction of each event. Recalling the discussion of two-body kinematics in Sec. 3.3.1, only three quantities must be measured in order to have complete kinematic information about a particular event. Since this is a tagged experiment, we always have the incoming $\gamma$-ray energy. Additionally, the angle of the rotating detector which fired in a given event is also known. Using the energy deposited in the rotating detector and the
Figure 4.7: The detectors for the LEGS experiment.
Figure 4.8: Typical spectra for the LEGS detectors.
angle of the detector we can reconstruct the vertex energy of that particle. This gives us three pieces of information—the requisite number for kinematic completeness.

Unfortunately, events from the npd channel tend to occupy nearly the same phase space as the dd channel if only one d is measured. The pure phase space distribution for three-body breakup indicates that if we detect a single particle in a given detector the remaining two particles will occupy (within the constraints of momentum conservation) the remaining solid angle with essentially equal probability. Tiller [Til95] has found, however, that the vast majority of npd breakups tend to fall in or near the reaction plane defined by the beam axis and the d detector. In other words, npd breakups tend to lie in the same reaction plane as dd breakups.

Nevertheless, we performed the kinematic reconstruction analysis of our event sets at each angle in the hopes of finding a dd peak. Our first step was to place graphical cuts on the raw spectra (cf. Fig. 4.8) to select deuterons. The cuts in the rotating arms were unambiguous. The cuts in the bar were quite generous and consequently included many protons.

The next phase of the analysis involved producing energy difference plots similar to those discussed in Chapter 3. Specifically, we used the tagged $\gamma$ energy and the reconstructed vertex deuteron energy from the rotating arm to calculate the vertex energy and angle of the recoil deuteron. We then calculated the energy the recoil deuteron would deposit in the bar NaI, taking into account energy losses through the intervening layers and assuming the reaction vertex was in the center of the target. This was our calculated NaI energy. We then compared this to the measured energy deposited in the NaI (obtained from the NaI pulse height and detector energy calibrations). The quantity $E_{diff} = calculated - measured$ was then calculated for each dd candidate event. The $E_{diff}$ spectrum resulting from this analysis for a single rotating detector angle is given in the top plot of Fig. 4.9. With perfect resolution point detectors, one would expect true dd events to appear right around 0 MeV in this spectrum. Clearly, the reconstructed spectrum is centered around ~60 MeV.
Figure 4.9: Sample $E_{diff}$ plots for the LEGS analysis. The top plot is the $dd$ $E_{diff}$ spectrum. The bottom plot is the $E_{diff}$ spectrum from $npd$ events. Notice the absence of events in the $dd$ region in the lower plot.
The source of this background was npd events with a proton in the bar being misidentified as a deuteron. In order to understand this background we performed another reconstruction analysis—this time cutting on deuterons in the rotating detector and protons in the bar. We repeated the energy reconstruction treating the proton as if it was a deuteron for the purposes of energy loss corrections. The resulting spectrum is shown in the bottom plot of Fig. 4.9. This spectrum is very similar to the npd background in the dd $E_{\text{diff}}$ spectrum. Inspecting the dd $E_{\text{diff}}$ spectrum closely one can now interpret the small number of counts near 0 MeV as a dd peak.

4.4.2 Determination of dd yields

The difficulty with extracting meaningful results is that there are simply too few statistics. The varying quality of the $E_{\text{diff}}$ spectra at the different angles (due to low statistics) prevented us from fitting the spectra in a consistent fashion. In the end, we employed a single cut on $E_{\text{diff}}$ between 0 and -20 MeV to arbitrarily specify the true dd events. The raw counts obtained in this fashion are listed in Table 4.2 along with a breakdown according to the laser (and $\gamma$-ray) polarization state.

<table>
<thead>
<tr>
<th>NaI 14° $\theta_{\text{lab}}$</th>
<th>Raw counts</th>
<th>0° state</th>
<th>90° state</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>26</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>38</td>
<td>89</td>
<td>36</td>
<td>53</td>
</tr>
<tr>
<td>78</td>
<td>31</td>
<td>9</td>
<td>22</td>
</tr>
<tr>
<td>90</td>
<td>32</td>
<td>13</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NaI 19° $\theta_{\text{lab}}$</th>
<th>Raw counts</th>
<th>0° state</th>
<th>90° state</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>30</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>45</td>
<td>38</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>72</td>
<td>36</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>90</td>
<td>49</td>
<td>21</td>
<td>28</td>
</tr>
<tr>
<td>110</td>
<td>26</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>130</td>
<td>38</td>
<td>11</td>
<td>27</td>
</tr>
</tbody>
</table>
In order to obtain relative yields from the raw counts given in Table 4.2, we must first normalize to the flux of $\gamma$ rays incident upon the target for the various runs. The flux was measured during each run by the CG3 beam monitor described above. Fluxes for both polarization states were recorded as well. These fluxes are given in Table 4.3.

<table>
<thead>
<tr>
<th>NaI 14&quot; $\theta_{lab}$</th>
<th>0° state(±) ($\times 10^9$)</th>
<th>90° state(±) ($\times 10^9$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>1.008(.005)</td>
<td>0.890(.004)</td>
</tr>
<tr>
<td>38</td>
<td>4.372(.010)</td>
<td>4.651(.010)</td>
</tr>
<tr>
<td>78</td>
<td>1.977(.006)</td>
<td>2.049(.006)</td>
</tr>
<tr>
<td>90</td>
<td>2.474(.007)</td>
<td>2.709(.007)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NaI 19&quot; $\theta_{lab}$</th>
<th>0° state ($\times 10^9$)</th>
<th>90° state ($\times 10^9$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>1.414(.005)</td>
<td>1.611(.005)</td>
</tr>
<tr>
<td>45</td>
<td>1.060(.005)</td>
<td>1.098(.005)</td>
</tr>
<tr>
<td>72</td>
<td>1.008(.005)</td>
<td>0.890(.004)</td>
</tr>
<tr>
<td>90</td>
<td>2.025(.006)</td>
<td>2.147(.007)</td>
</tr>
<tr>
<td>110</td>
<td>1.603(.006)</td>
<td>1.699(.006)</td>
</tr>
<tr>
<td>130</td>
<td>2.721(.008)</td>
<td>2.854(.008)</td>
</tr>
</tbody>
</table>

There are two other sources for corrections to the yields. The first is a contribution from the target cell to the observed yields. Empty target runs were performed for each of the detectors angles used during the 488 nm runs. The amount of empty target running was quite limited, however, and no significant number of $dd$ events was recorded at any given angle. Lacking sufficient information we can make no attempt at an empty target subtraction.

The final correction to the observed $dd$ yield involves subtracting uncorrelated events. Since each two-arm coincidence event was also in coincidence with the tagging focal plane, we can use the tagger TDC signal to estimate the number of random coincidences in our data. Fig. 4.10 shows the LEGS tagger TDC spectrum for the entire tagging
focal plane. The TDC starts when an electron hits one of the plastic scintillator detectors in the tagging focal plane. The TDC stop comes from the detection of a two-arm nuclear event.

![Graph showing TDC spectrum with peak and off-peak regions]

Figure 4.10: LEGS tagger TDC spectrum showing the peaks for true (true peak) and accidental (off-peak) coincidences between the tagger and the nuclear reaction detectors.

Hits in the off-peak region represent accidental coincidences between the tagger and nuclear events generated by photons other than the one which started the tagger TDC. The true peak indicates nuclear events coming from the tagged γ-ray. The true peak also contains some accidental coincidences. By summing the events in the off-peak region and normalizing, we estimated the size of the accidental coincidence contribution to the true peak. The accidental rates measured for the true peak at each detector angle are listed in Table 4.4

Putting it all together we obtain final yields for the $^4\text{He}(\gamma,dd)$ reaction for $E_\gamma = 185$
Table 4.4: Accidental coincidence rates for the LEGS experiment.

<table>
<thead>
<tr>
<th>NaI 14'' θ_{lab}</th>
<th>Accidental Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>0.088</td>
</tr>
<tr>
<td>38</td>
<td>0.071</td>
</tr>
<tr>
<td>78</td>
<td>0.053</td>
</tr>
<tr>
<td>90</td>
<td>0.083</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NaI 19'' θ_{lab}</th>
<th>Accidental Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>0.094</td>
</tr>
<tr>
<td>45</td>
<td>0.063</td>
</tr>
<tr>
<td>72</td>
<td>0.088</td>
</tr>
<tr>
<td>90</td>
<td>0.068</td>
</tr>
<tr>
<td>110</td>
<td>0.070</td>
</tr>
<tr>
<td>130</td>
<td>0.063</td>
</tr>
</tbody>
</table>

- 237 MeV. The yields are listed in Sec. 5.3, where they are used to determine the analyzing power \( A(\theta) \) of this reaction.

### 4.4.3 The Analyzing Power

As mentioned previously, data were accumulated for two different \( \gamma \)-ray polarization states. The breakdown of \( dd \) events according to polarization state is also listed in Table 4.2. Given data in two such states it is possible to define an analyzing power \( A(\theta) \) as [Wel92]

\[
A(\theta) = \frac{\sigma(\theta, \phi = 0^\circ) - \sigma(\theta, \phi = 90^\circ)}{p_\perp \sigma(\theta, \phi = 0^\circ) + p_\parallel \sigma(\theta, \phi = 90^\circ)},
\]

where \( \phi \) is the angle the \( \gamma \)-ray polarization vector makes with the reaction plane of the detectors (see Fig. 4.4), \( p_\perp \) is the fractional \( \gamma \)-ray polarization in the 90° state, and \( p_\parallel \) is the fractional polarization in the 0° state.

This analyzing power is interesting for several reasons. First, the analyzing power and the cross section may both be expressed in terms of the transition matrix elements (TME’s) that contribute to the \( ^4\text{He}(\gamma, dd) \) reaction. The resulting expressions represent two linearly independent combinations of the TME’s. Performing a TME analysis of both
observables allows one to extract more detailed information about the contributing amplitudes and phases than measurement of the cross section alone.

Since the cross sections for both polarization states appear in the numerator and the denominator of Eq. 5.6, the analyzing power is dependent only upon the ratio of cross sections and is independent of the absolute cross section. This is especially significant in the present experiment where the lack of statistics makes the determination of the absolute cross section difficult. The result is that we may express Eq. 5.6 in terms of the yields for each spin state:

$$A(\theta) = \frac{Y_\parallel(\theta) - Y_\perp(\theta)}{p_\perp Y_\parallel(\theta) + p_\parallel Y_\perp(\theta)},$$

(4.9)

where $Y_\parallel$ and $Y_\perp$ are the yields for the 0° and 90° states, respectively. The associated error for the analyzing power is given by

$$dA_y = \left\{ \frac{(Y^+ - Y^-)^2 \left[ (Y^- d_{p^+})^2 + (Y^+ d_{p^-})^2 \right] + (p_+ + p_-)^2 \left[ (Y^- dY^+)^2 + (Y^+ dY^-)^2 \right]}{\left[ p_+ Y^- + p_- Y^+ \right]^2} \right\}^{\frac{1}{2}}$$

(4.10)

Results for the analyzing power $A(\theta)$ for the reaction $^4\text{He}(\bar{\gamma}, dd)$ at $E_\gamma = 185$-237 MeV are presented in Sec. 5.3 in the next chapter. In Sec. 5.5, the analyzing power data are used along with the cross section data from SAL in a TME analysis to extract information about the contributing TME amplitudes and phases.
Chapter 5

Results

In this chapter we present the results of the analysis of the SAL cross section data (Sections 5.1 and 5.2) and the LEGS analyzing power data (Section 5.3). The results of a Legendre polynomial analysis are discussed in Sec. 5.4 and used to determine total cross sections for this reaction. A simultaneous transition-matrix element (TME) analysis performed on both the differential cross section data and the analyzing power data is discussed in Sec. 5.5.

5.1 Mid-energy Bin SAL Results

In this section we present results for the cross sections from the SAL data for $E_\gamma = 150$-190 MeV. Figures 5.1-5.3 show the detailed results of the minimization process described in Sec. 3.5.1. These figures show the results from the kinematic reconstruction process for $dd$ candidate events (dot-dashed curve) and the background from competing nuclear reaction channels (short-dashed curve). The raw spectrum minus the background spectrum (long-dashed curve) is also shown. The yield of true $dd$ events was obtained by integrating the area under the gaussian fit (solid curve) to the $dd$ peak.

The yields obtained from this minimization technique were corrected for empty target backgrounds, accidental coincidences, and lab-to-center-of-mass transformations as
Figure 5.1: Results from the $E_{\text{diff}}$ minimization process in the mid-energy bin with $E_\gamma = 150$-190 MeV for the telescopes at 38.8° (top) and 55.0° (bottom).
Figure 5.2: Results from the $E_{\text{diff}}$ minimization process in the mid-energy bin with $E_\gamma = 150$ to 190 MeV for the telescopes at 81.0° (top) and 98.1° (bottom).
Figure 5.3: Results from the $E_{diff}$ minimization process in the mid-energy bin with $E_\gamma = 150$ to 190 MeV for the telescopes at 115.1° (top) and 132.2° (bottom).
described in Secs. 3.5.3, 3.5.4, and 3.6. The final yields for each telescope arm detector are given in Table 5.1. The differential cross sections (in the center-of-mass) for these detectors, obtained from Eq. 3.11, are also listed in this table.

Since the exit channel of the reaction contains identical particles, the cross section must be symmetric with respect to 90° in the center-of-mass. Accordingly, we have reflected the data about 90°. The resulting data set contains twelve points which are plotted in Fig. 5.4.

The most striking feature of the data is that the angular distribution is maximum at 90° in the center-of-mass frame. This corroborates the results of Arends [Are76] and Silverman [Sil84].

Table 5.1: Yields and differential cross sections for each telescope for the energy bin with \( E_\gamma = 150 - 190 \) MeV. Lab and center-of-mass angles are listed in the table. Since the data must be symmetric about \( \theta_{c.m.}=90° \), a reflected center-of-mass angle \( \theta_{c.m.,refl} \) is also listed. The uncertainties listed are purely statistical and do not include an 7.1% systematic uncertainty.

<table>
<thead>
<tr>
<th>( \theta_{lab} )</th>
<th>( \theta_{c.m.} )</th>
<th>( \theta_{c.m.,refl} )</th>
<th>Yield</th>
<th>( d\sigma_{c.m.}/d\Omega ) (nb/sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.8°</td>
<td>44.7°</td>
<td>135.3°</td>
<td>989 ± 191</td>
<td>0.635 ± 0.123</td>
</tr>
<tr>
<td>55.0°</td>
<td>62.7°</td>
<td>117.3°</td>
<td>1522 ± 193</td>
<td>1.040 ± 0.133</td>
</tr>
<tr>
<td>81.0°</td>
<td>90.3°</td>
<td>87.7°</td>
<td>2455 ± 209</td>
<td>1.920 ± 0.163</td>
</tr>
<tr>
<td>98.1°</td>
<td>107.3°</td>
<td>73.7°</td>
<td>1660 ± 184</td>
<td>1.430 ± 0.159</td>
</tr>
<tr>
<td>115.1°</td>
<td>123.5°</td>
<td>56.5°</td>
<td>1305 ± 150</td>
<td>1.240 ± 0.143</td>
</tr>
<tr>
<td>132.2°</td>
<td>138.9°</td>
<td>41.1°</td>
<td>827 ± 136</td>
<td>0.854 ± 0.122</td>
</tr>
</tbody>
</table>
Figure 5.4: SAL differential cross section for $E_\gamma = 150$ to 190 MeV. Exploiting the symmetry of the system, measured data (circles) have been reflected about $\theta_{c.m.}=90^\circ$ and plotted (squares). The uncertainties shown are purely statistical and do not include an 7.1% systematic uncertainty.
5.2 High-energy Bin SAL Results

In this section we present results for the cross sections from the SAL data for $E_\gamma = 190$-250 MeV. Figures 5.5-5.7 show the detailed results of the minimization process described in Sec. 3.5.1. These figures show the results from the kinematic reconstruction process for $dd$ candidate events (dot-dashed curve) and the background from competing nuclear reaction channels (short-dashed curve). The raw spectrum minus the background spectrum (long-dashed curve) is also shown. The yield of true $dd$ events was obtained by integrating the area under the gaussian fit (solid curve) to the $dd$ peak.

The yields obtained from this minimization technique were corrected for empty target backgrounds, accidental coincidences, and lab-to-center-of-mass transformations as described in Secs. 3.5.3, 3.5.4, and 3.6. The final yields for each telescope arm detector are given in Table 5.2. The differential cross sections (in the center-of-mass) for these detectors, obtained from Eq. 3.11, are also listed in this table.

Since the exit channel of the reaction contains identical particles, the cross section must be symmetric with respect to 90° in the center-of-mass. Accordingly, we have reflected the data about 90°. The resulting data set contains twelve points which are plotted in Fig. 5.8.

Table 5.2: Yields and differential cross sections for each telescope for the energy bin with $E_\gamma = 190$ - 250 MeV. Lab and center-of-mass angles are listed in the table. Since the data must be symmetric about $\theta_{c.m.}=90^\circ$, a reflected center-of-mass angle $\theta_{c.m.,refl}$ is also listed. The uncertainties listed are purely statistical and do not include a 13% systematic uncertainty.

<table>
<thead>
<tr>
<th>$\theta_{lab}$</th>
<th>$\theta_{c.m.}$</th>
<th>$\theta_{c.m.,refl}$</th>
<th>Yield</th>
<th>$d\sigma_{c.m.}/d\Omega$ (nb/sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.8°</td>
<td>45.4°</td>
<td>134.6°</td>
<td>249 ± 192</td>
<td>0.118 ± 0.091</td>
</tr>
<tr>
<td>55.0°</td>
<td>63.6°</td>
<td>116.4°</td>
<td>951 ± 239</td>
<td>0.486 ± 0.122</td>
</tr>
<tr>
<td>81.0°</td>
<td>91.4°</td>
<td>88.6°</td>
<td>1977 ± 242</td>
<td>1.17 ± 0.144</td>
</tr>
<tr>
<td>98.1°</td>
<td>108.4°</td>
<td>71.6°</td>
<td>1394 ± 198</td>
<td>0.921 ± 0.131</td>
</tr>
<tr>
<td>115.1°</td>
<td>124.4°</td>
<td>55.6°</td>
<td>771 ± 133</td>
<td>0.566 ± 0.097</td>
</tr>
<tr>
<td>132.2°</td>
<td>139.7°</td>
<td>40.3°</td>
<td>735 ± 133</td>
<td>0.594 ± 0.107</td>
</tr>
</tbody>
</table>

The results of the minimization process for the high-energy data are less satisfying
Figure 5.5: Results from the $E_{\text{diff}}$ minimization process in the high-energy bin with $E_\gamma = 190$ to 250 MeV for the telescopes at 38.8° (top) and 55.0° (bottom).
Figure 5.6: Results from the $E_{\text{diff}}$ minimization process in the high-energy bin with $E_\gamma = 190$ to 250 MeV for the telescopes at 81.0° (top) and 98.1° (bottom).
Figure 5.7: Results from the $E_{\text{diff}}$ minimization process in the high-energy bin with $E_r = 190$ to 250 MeV for the telescopes at $115.1^\circ$ (top) and $132.2^\circ$ (bottom).
Figure 5.8: SAL differential cross section for $E_\gamma = 150$ to 190 MeV. Exploiting the symmetry of the system, measured data (circles) have been reflected about $\theta_{c.m.}=90^\circ$ and plotted (squares). The uncertainties shown are purely statistical and do not include a 13% systematic uncertainty.

than those for the mid-energy bin. The large amount of scatter in the data most likely stems from a decrease in $d\sigma/d\theta$ counts relative to background for this energy bin. Nevertheless, the observed maximum at $\theta_{c.m.} = 90^\circ$ of the data corroborates that of the mid-energy bin data as well as the Arends [Are76] and Silverman [Sil84] measurements. These data, which correspond to $E_\gamma = 213$ MeV, are shown along with our high-energy bin data in Fig. 5.8.
5.3 LEGS Analyzing Power Data

We now present the results from the LEGS experiment. Table 5.3 shows the yields in the detectors at each angle for each γ-ray linear polarization state (denoted 0° and 90°; see Sec. 4.1.2. These yields have been corrected for accidental coincidences. The data in the unpolarized yield column were generated by summing the counts in both polarization states. Since the polarizations of both states were roughly equal, and since the total incident flux in both states was also nearly equal, summing the individual states provided a good approximation of the unpolarized yield.

These yields were then normalized according to the total γ-ray flux incident upon the target. The flux-normalized yields are shown (in arbitrary units) in Table 5.3 in the relative yield column. Note that the relative yields have been corrected for the lab to center-of-mass transformation by applying the appropriate Jacobians. These yields are plotted in Fig. 5.9. The poor statistics make conclusions difficult, but the data seem to support an angular distribution consistent with a maximum at 90° in the center-of-mass frame. This corroborates the results from the SAL data discussed in the previous two sections.

Table 5.3: The accidental-subtracted yields for both polarization states and unpolarized data from the LEGS experiment with $E_\gamma = 185$-237 MeV. The flux-normalized yield is shown in the Relative Yield column (in arbitrary units).

<table>
<thead>
<tr>
<th>$\theta_{c.m.}(°)$</th>
<th>0° State Yield(±)</th>
<th>90° State Yield(±)</th>
<th>Unpolarized Yield(±)</th>
<th>Relative Yield(±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.6°</td>
<td>25.5(5.1)</td>
<td>25.4(5.0)</td>
<td>50.9(7.1)</td>
<td>0.776(.109)</td>
</tr>
<tr>
<td>48.3°</td>
<td>52.1(7.2)</td>
<td>66.1(8.1)</td>
<td>118(11)</td>
<td>0.825(.076)</td>
</tr>
<tr>
<td>84.9°</td>
<td>22.2(4.7)</td>
<td>40.0(6.3)</td>
<td>62.2(7.9)</td>
<td>0.974(.124)</td>
</tr>
<tr>
<td>100.3°</td>
<td>31.5(5.6)</td>
<td>43.5(6.6)</td>
<td>75.0(8.7)</td>
<td>0.816(.094)</td>
</tr>
<tr>
<td>119.6°</td>
<td>5.6(2.4)</td>
<td>18.6(4.3)</td>
<td>24.2(4.9)</td>
<td>0.845(.172)</td>
</tr>
<tr>
<td>137.8°</td>
<td>10.3(3.2)</td>
<td>25.3(5.0)</td>
<td>35.6(6.0)</td>
<td>0.823(.138)</td>
</tr>
</tbody>
</table>

Finally, we present the results of the analyzing power $A(\theta)$ in Table 5.4 and Fig. 5.10. The first thing to notice is that the $A(\theta)$ data are not symmetric about 90° in the center-
of-mass. The presence of identical particles in the exit channel, however, requires that any observable be symmetric with respect to $\theta_{c.m.} = 90^\circ$. This is a consequence of momentum conservation which requires that the two deuterons emerge from the nuclear reaction back-to-back in the center-of-mass frame.

Table 5.4: The analyzing power $A(\theta)$ data for the LEGS experiment with $E_\gamma = 185$-237 MeV.

<table>
<thead>
<tr>
<th>$\theta_{c.m.}(^\circ)$</th>
<th>$dd \ A(\theta)$</th>
<th>$npd \ A(\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.6</td>
<td>0.019 ± .147</td>
<td>0.054 ± .047</td>
</tr>
<tr>
<td>48.3</td>
<td>-0.097 ± .096</td>
<td>0.101 ± .025</td>
</tr>
<tr>
<td>84.9</td>
<td>-0.310 ± .129</td>
<td>-0.107 ± .03</td>
</tr>
<tr>
<td>100.3</td>
<td>-0.130 ± .119</td>
<td>-0.188 ± .027</td>
</tr>
<tr>
<td>119.6</td>
<td>-0.540 ± .185</td>
<td>-0.278 ± .055</td>
</tr>
<tr>
<td>137.8</td>
<td>-0.425 ± .163</td>
<td>-0.154 ± .097</td>
</tr>
</tbody>
</table>

The most likely source for the asymmetry in the analyzing power data is contami-
Figure 5.10: The analyzing power $A(\theta)$ data for the $dd$ and $npd$ channels from the LEGS experiment with $E_\gamma = 185$-237 MeV. Errors are purely statistical.

nation from the $npd$ reaction. In order to investigate this possibility we extracted $A(\theta)$ for those $npd$ reactions where a $d$ was detected in the rotating arm and a $p$ was detected in the bar arm. The $npd$ $A(\theta)$ data are listed in Table 5.4 and are plotted in Fig. 5.10.

Looking at the data, we see that the $dd$ $A(\theta)$ data are generally more negative than the $npd$ data for the same angle. Contamination of the $dd$ data by $npd$ data would tend to raise the observed $dd$ analyzing powers. Since the poor statistics do not allow a rigorous method for determining this contamination, we conclude that the measured $dd$ analyzing powers represent an upper limit on the actual analyzing powers. Furthermore, since there is no a priori reason to assume the amount of $npd$ contamination is consistent from angle to angle, we have chosen not to quote a systematic error.

The final data set includes twelve points (after reflection about $\theta_{c.m.} = 90^\circ$) and is plotted in Fig 5.11. The uncertainties shown in the figure are purely statistical. We reiterate
that these data almost certainly contain sizable contamination from the \textit{npd} channel. As such, we feel they represent a best guess at an upper limit and an appropriate degree of caution is urged when using them. The strongest justifiable conclusion that can be made is that the analyzing powers are (most likely) uniformly negative.

![Graph](image)

Figure 5.11: $dd$ (circles) and reflected (squares) $A(\theta)$ data from the LEGS experiment. Errors are purely statistical.

5.4 Legendre Polynomial Analysis and Total Cross Sections

The angular distributions of the cross sections presented in Secs. 5.1 and 5.2 may be used to estimate the total cross section. One technique for determining the total cross section involves expanding the angular distribution, $\sigma(\theta)$, in terms of the Legendre polynomial functions (see, for example, Arfken [Arf85]). Assuming a point detector geometry, this
expansion is given by

\[ \sigma(\theta) = \sum_k A_k P_k(\cos \theta) \]  \hspace{1cm} (5.1)

where the \( A_k \) are the Legendre polynomial coefficients and the \( P_k \) are the Legendre polynomials. One can account for the finite size of the detectors being used by including a finite geometry correction factor, \( Q_k \) [Ros53]. The corrected cross section expansion then looks like

\[ \sigma(\theta) = A_0 \left( 1 + \sum_{k=1} Q_k a_k P_k(\cos \theta) \right) \]  \hspace{1cm} (5.2)

where we have introduced the \( a_k = A_k / A_0 \). The coefficient \( A_0 \) is the absolute total cross section normalization constant and is directly related to the total (angle-integrated) cross section. Specifically, the total cross section is

\[ \sigma_T = \int \int \sigma(\theta, \phi) \, d\Omega = 4\pi A_0. \]  \hspace{1cm} (5.3)

This definition of the total cross section includes integration over \( 4\pi \) solid angle. For the case of a reaction containing identical particles in the exit channel, however, it is important to note that the total cross section is obtained by integrating over only \( 2\pi \) solid angle [Mey69]. For the present case, with two deuterons in the exit channel, the total cross section is given by

\[ \sigma_{TOT} = 2\pi A_0. \]  \hspace{1cm} (5.4)

We performed a Legendre polynomial analysis of the cross section results presented above. Since identical particles exist in the exit channels, the cross section must be symmetric about \( 90^\circ \) in the center of mass frame. Accordingly, we set the odd Legendre polynomial coefficients to zero (since these polynomials are antisymmetric with respect to \( 90^\circ \)). Good fits to the data were obtained using \( P_0, P_2, \) and \( P_4 \), and were nearly consistent with a pure \( \sin^2 \theta \) distribution (i.e. \( a_2 = -1.0 \)). It is important to note that since we have no data near \( 0^\circ \) or \( 180^\circ \), the cross section is unconstrained in this region. In these fits we arbitrarily
constrained the cross section to be zero at $0^\circ$ and $180^\circ$. The results of the Legendre polynomial fits for the mid-energy and high-energy bins are shown in Fig. 5.12. The coefficients from the fits are summarized in Table 5.5.

Table 5.5: Total cross sections and Legendre polynomial coefficients for the mid- and high-energy bins. The first uncertainty on the total cross section is statistical, while the second represents the systematic uncertainty (7.1% for the mid-energy bin, 13% for the high-energy bin.

<table>
<thead>
<tr>
<th>$E_\gamma$ Bin</th>
<th>$A_0$</th>
<th>$a_2$</th>
<th>$a_4$</th>
<th>$\sigma_{TOT}$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150-190 MeV</td>
<td>1.09 ± 0.04</td>
<td>-1.07 ± 0.08</td>
<td>0.0685 ± 0.0633</td>
<td>6.85 ± 0.25 ± 0.49</td>
</tr>
<tr>
<td>190-250 MeV</td>
<td>0.586 ± 0.031</td>
<td>-1.32 ± 0.14</td>
<td>0.316 ± 0.010</td>
<td>3.68 ± 0.19 ± 0.48</td>
</tr>
</tbody>
</table>

The results for the total cross section are presented, along with the world data for $^4\text{He}(\gamma,dd)$ with $E_\gamma$ greater than 30 MeV, in Fig. 5.13. The figure shows that the results are in agreement with those reported by Arends [Are76] to within about a factor of two. (Note that Arends's total cross section numbers were extracted from Legendre polynomial fits which were constrained, like our fits, to be zero at $0^\circ$ and $180^\circ$.) Taken together, the weight of evidence from recent measurements indicates that the total cross section favors the lower values of those reported in the past 35 years. Although there is room for improvement in the statistics, we are inclined to declare that the discrepancy in the magnitude of the absolute cross section has been resolved.
Figure 5.12: Results from the Legendre polynomial analysis of the $E_\gamma = 150$ to 190 MeV data (top) and the $E_\gamma = 190$-250 MeV data (bottom).
Figure 5.13: World data compared with the results of the present measurements. Uncertainties quoted for the present work are purely statistical error and do not include systematic uncertainty (7.1% for the mid-energy bin and 13% for the high-energy bin).
5.5 Transition-Matrix Element Analysis

It is also possible to express the cross section and analyzing power in terms of reduced transition-matrix elements. The formalism for handling reactions of the form ($\gamma, X$) for linearly polarized $\gamma$ rays has been described by Weller et al. [Wel92]. The key result from that work is

$$\sigma(\theta, \phi) = \left(\frac{\lambda^2}{6}\right) \sum_{t, t'} \left[ (B_{00}^{k0} + \frac{1}{\sqrt{10}}B_{20}^{k0})R_t R_{t'} P_2(\cos \theta) - f \sqrt{\frac{3}{5}} \cos(2\phi)B_{22}^{k2} R_t R_{t'} P_2(\cos \theta) \right].$$

(5.5)

where $\phi$ is the angle between the photon polarization and the reaction plane, $\lambda$ is the wavelength of the incoming photon, $t$ and $t'$ are the quantum numbers for a given transition-matrix element, $R_t$ and $R_{t'}$ are the reduced matrix elements, $P_2$ and $P_2'$ are the Legendre polynomials and second associated Legendre polynomials, respectively, $f$ is the fractional (linear) polarization of the $\gamma$ ray, and the $B_{ab}^{cd}$ are the coefficients containing all the angular momentum coupling information. A full expression of the $B$ coefficients is given in Ref. [Wel92].

The analyzing power for linearly polarized photons can be defined in terms of Eq. 5.5 as

$$A(\theta) = \frac{1}{f} \frac{\sigma(\theta, 0) - \sigma(\theta, \pi/2)}{\sigma(\theta, 0) - \sigma(\theta, \pi/2)}$$

(5.6)

Using Eqs. 5.5 and 5.6, it is possible to express the cross section and analyzing power in terms of the amplitudes and phases of the contributing transition-matrix elements. Table 5.6 shows the allowed transitions (as discussed in Sec. 1.5) for this reaction for E1, M1, E2 and M2 radiations. The code GDDTMFIT (see Sec. A.5) was used to perform a $\chi^2$ minimization fit to both the mid-energy cross section data and the analyzing power data. This code made use of the MINUIT library and its implementation of the SIMPLEX fitting algorithm.

Various transition-matrix element analyses were performed allowing different combinations of the multipole radiations. All permutations of the allowed radiations were
<table>
<thead>
<tr>
<th>Ground State $^2S+^1L_J$</th>
<th>Scattering State $^2s+^1\ell_j$</th>
<th>Multipolarity $\pi k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0, ^5D_0$</td>
<td>$^3p_1$</td>
<td>E1</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5d_1$</td>
<td>M1</td>
</tr>
<tr>
<td>$^1S_0$</td>
<td>$^1d_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5s_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5d_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^5D_0$</td>
<td>$^5g_2$</td>
<td>E2</td>
</tr>
<tr>
<td>$^1S_0, ^5D^0$</td>
<td>$^3p_2$</td>
<td>M2</td>
</tr>
<tr>
<td>$^1S_0, ^5D^0$</td>
<td>$^3f_2$</td>
<td>M2</td>
</tr>
</tbody>
</table>

investigated. We found that M1 radiation contributed only negligibly when other multipole radiations were permitted. When only E1 radiation was permitted, the resulting cross section angular distribution was minimum at 90°. When only M1 radiation was permitted a similar result was observed, but additionally the sign of the analyzing power was positive.

The best fits were found when E2 transitions were allowed. The two best solutions included E2 only and E1, E2, and M2 transitions, respectively. The amplitudes (as a fraction of the total cross section) for these fits are listed in Table 5.7. The cross section and analyzing power results from these fits are displayed graphically in Fig. 5.14, along with the results from an E1-only fit.

Inspecting Fig. 5.14, we see that both the E2-only and the E1-E2-M2 fits are capable of producing cross sections that are peaked at 90 degrees. Outside of the region covered by our data the two fits diverge significantly. The E2-only fit predicts that the cross section drops off at extreme angles. The E1-E2-M2 fit predicts an upturn in the cross section at extreme angles. Looking at the analyzing power data we see that neither fit is very good. In both cases the fits are unable to reproduce the analyzing power near 90 degrees.

Assuming that higher multipole transitions are not present, the inability of the transition-matrix element analysis to simultaneously fit the cross section and analyzing
Figure 5.14: TME analysis results.
power indicates that at least some of the data are in error. Since there are strong indications of \(npd\) contamination in the \(dd\) analyzing power data, we attempted to fit just the cross section data and investigated these fits’ predictions for the analyzing power. Using \(E2\) only and \(E1, E2,\) and \(M2\) transitions we obtained the fits labelled \(no A(\theta)\) in Table 5.7. The analyzing power predictions from these fits are shown in Fig. 5.15

One interesting feature of the fits to the cross section data only is that they both predict analyzing powers which generally agree with the data. However, both fits indicate that the analyzing power near ninety degrees should be large and negative—a trait that is not evident in the measured analyzing power near 90°. One possibility is that the \(npd\) contamination is larger at this angle than other angles. Since the \(npd\) analyzing power is near zero at this angle, contamination of a large, negative \(dd\) analyzing power would tend to raise the observed value dramatically. These fits (to the cross section data only), therefore, suggest that the analyzing power data near 90° are in error. Ignoring these points would result in a consistent data set of cross section and analyzing power data. We feel that the present data cannot be used to state with authority what the correct analyzing power near 90° may be, however. As such, we hope that a remeasurement of this observable can be performed sometime in the future.
Figure 5.15: TME fit to the cross section data only.
Setting aside the inconsistencies with respect to the analyzing power data, the fits to both the cross section and analyzing power data provide detailed information about the distribution of strength among the allowed multipole transitions. The amplitudes (in terms of fraction of $\sigma_{TOT}$) and phases of the transitions used in the E2-only and E1-E2-M2 fits are shown in Table 5.8.

<table>
<thead>
<tr>
<th>TME</th>
<th>E1-E2-M2 fit</th>
<th>E2-only fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{2s+1}\ell_j$</td>
<td>Fraction of $\sigma_{tot}$</td>
<td>Rel. Phase($^\circ$)</td>
</tr>
<tr>
<td>$^1d_2$(E2)</td>
<td>0.000 ± 0.0012</td>
<td>-172.59 ± 360.00</td>
</tr>
<tr>
<td>$^5s_2$(E2)</td>
<td>0.745 ± 0.0339</td>
<td>0.00 ± 49.14</td>
</tr>
<tr>
<td>$^5d_2$(E2)</td>
<td>0.013 ± 0.0083</td>
<td>0.00 ± 56.02</td>
</tr>
<tr>
<td>$^5g_2$(E2)</td>
<td>0.000 ± 0.0000</td>
<td>0.00 ± 360.00</td>
</tr>
<tr>
<td>$^3p_1$(E1)</td>
<td>0.090 ± 0.0255</td>
<td>0.00 ± 17.85</td>
</tr>
<tr>
<td>$^3p_2$(M2)</td>
<td>0.091 ± 0.0304</td>
<td>0.00 ± 19.08</td>
</tr>
<tr>
<td>$^3f_2$(M2)</td>
<td>0.061 ± 0.0310</td>
<td>0.00 ± 18.84</td>
</tr>
</tbody>
</table>

In the E2-only fit, we see that all of the strength is placed into $s$- and $d$-wave capture to the $D$-state of $^4$He. This is surprising because the $D$-state component of the ground state wave function is approximately 2-6%, significantly smaller than the dominant $S$-state component. In addition, TME analyses of data at lower energies for this reaction or its inverse have indicated the presence of $g$-wave capture to the $D$-state. The E2-only fit places no strength into $g$-wave capture, however.

The $s$- and $d$-wave TME's in the E2-only fit have the same phase, indicating that they interfere constructively. It is this interference that gives rise to the observed maximum in the cross section at $90^\circ$.

Results from the E1-E2-M2 fit indicate that E2 $s$- and $d$-wave capture to the $D$-state is still present. In particular, $s$-wave capture still dominates, providing 75% of the total cross section. Spin-flip E1 and M2 radiations are also present, however. Constructive interference between E1 and M2 radiations and between E2 and M2 radiations, causes the
observed maximum at 90° in the cross section angular distribution.

As mentioned above, M1 radiation was found to contribute negligibly if any other multipoles were permitted. The presence of M2 radiation at the 25% level in the E1-E2-M2 fit is therefore interesting. Since the energies involved in this reaction are large, it is not surprising to find it necessary to include the higher multipoles to fit the data. At present we have no explanation for this behavior.

Looking at both fits, we can conclude that between 76% and 100% of the cross section arises from capture to the D-state of $^4$He. This capture is dominated by E2 s-waves. Furthermore, the observed maximum in the cross section angular distribution at 90° arises from E2-E2, E2-M2, and/or E1-M2 constructive interference.
Chapter 6

Theory

As of this writing, no sophisticated theoretical treatment of the $^4\text{He}(\gamma, dd)$ system exists for $\gamma$-ray energies above pion threshold. In the absence of a tenable theory, this chapter's goals are twofold. In Sec. 6.2 we describe the Direct Capture model, a reaction model which can be used to investigate the effects of certain simplifying assumptions upon the reaction dynamics. Section 6.3 then presents the results of a set of direct capture calculations for this reaction, along with its predictions for the total cross section $\sigma_{TOT}$, the cross section angular distribution $\sigma(\theta)/A_0$, and the analyzing power $A(\theta)$ for the $(\gamma, dd)$ reaction. The second goal of this chapter is to discuss the various theoretical treatments of this system at lower $\gamma$-ray energies and comment upon the future applicability of these models when they are extended to higher energies.

6.1 Relationship of the $^4\text{He}(\gamma, dd)$ Reaction to the $d(d, \gamma)^4\text{He}$ Reaction

The Direct Capture model is normally applied to radiative capture reactions. Radiative capture describes nuclear reactions with an initial state consisting of a projectile nucleus incident upon a target nucleus and a final state consisting of an emitted $\gamma$ ray and
a *residual* nucleus. Photodisintegration reactions such as those studied in the present work are the inverse of radiative capture. In photodisintegration the initial state is comprised of a $\gamma$-ray projectile incident upon a target nucleus leading to a final state containing recoil and residual nuclei. The radiative capture and photodisintegration reactions are related, however, by the principle of detailed balance. The reactions

$$a + \gamma \rightarrow d + X \quad \text{and} \quad d + X \rightarrow a + \gamma$$

are related by time reversal invariance. At the same center of mass energy, time-reversal invariance requires that

$$|\langle \psi_i | H' | \psi_f \rangle|^2 = |\langle \psi_f | H' | \psi_i \rangle|^2,$$

where $\psi_i$ and $\psi_f$ represent the initial and final state wave functions, respectively, and $H'$ is the interaction Hamiltonian governing the transition from the initial to the final state. This equation can be abbreviated as

$$|T_{fi}|^2 = |T_{if}|^2,$$

where $T_{fi}$ and $T_{if}$ represent the matrix elements for the forward and inverse reactions. These matrix elements can be used to obtain a transition rate $W_{if}$ for the reaction by applying Fermi's golden rule (number two), which is given by

$$W_{if} = \frac{2\pi}{\hbar} |T_{if}|^2 \rho_f(k),$$

where $\rho_f$ is the density of final states. This rate is proportional to the reaction cross section. Starting with this equation it is straightforward to show (see, for example, Jelley [Jel90]) that

$$g_i \frac{d\sigma_{if}}{d\Omega} k_i^2 = g_f \frac{d\sigma_{fi}}{d\Omega} k_f^2$$

where $k_f$ and $k_i$ are the wavenumbers of the bombarding particles in the final and initial states, respectively, and the statistical factors $g_i$ and $g_f$ are given by

$$g_i = (2I_a + 1)(2I_r + 1) \quad \text{and} \quad g_f = (2I_d + 1)(2I_X + 1).$$
The $(2I + 1)$ factors denote the number of spin substates for each particle. In the case of the present system, the relationship is

$$2(2I_{He} + 1)k_7^2 \frac{d\sigma(\gamma, d)}{d\Omega} = (2I_d + 1)(2I_d + 1)k_2^2 \frac{d\sigma(d, \gamma)}{d\Omega} \quad (6.7)$$

where the leading 2 is the number of spin substates for the photon.

The implication of this result for reactions that are related by detailed balance is that the underlying physics is unchanged by the direction of time. Results obtained from studies of the $d(d, \gamma)^{4}\text{He}$ reaction using the Direct Capture model are therefore applicable to the $^{4}\text{He}(\gamma, dd)$ reaction, provided they are scaled by the appropriate detailed balance factors. The calculations in Sec. 6.3 have been corrected for detailed balance and all results have been presented in terms of the photodisintegration reaction.

### 6.2 The Direct Capture Model

The Direct Capture model describes a nuclear reaction occurring between two particles, the projectile and the target, which are considered to be point-like and structureless. The transition from this two-particle initial continuum state to a final bound state is treated as a one-step, or direct, process that occurs in a very short period of time (approximately $10^{-22}$ seconds). This model assumes that no intermediate compound nuclear state is formed. Reactions that do not involve resonances may therefore be treated as electromagnetic transitions from the initial to the final state. In the initial state the incoming particle is affected only by a nuclear potential and undergoes a radiative transition from this continuum state directly to the final state. The final state is viewed as a single-particle bound state with the particle (formerly the projectile) coupled to a core (formerly the target). The reaction products are therefore this residual nucleus and the emitted $\gamma$ ray. Figure 6.1 shows a graphical representation of direct capture for the $^{2}\text{H}(d, \gamma)^{4}\text{He}$ reaction.

The Hamiltonian for the direct capture process may be separated into two compo-
\[ H = H_0 + H'. \] (6.8)

\[ W_{if} = \frac{2\pi}{\hbar} |T_{if}|^2 \rho_f(k), \] (6.9)

which gives the transition rate between the initial and final state in terms of the unreduced transition matrix elements (TME's) \( T_{if} \) and the density of final states, \( \rho_f(k) \). \( T_{if} \) is defined by

\[ T_{if} = \langle \psi_f | H' | \psi_i \rangle \] (6.10)

where \( \psi_i \) represents the initial (continuum) state wave function and \( \psi_f \) represents the final (bound) state wave function. The cross section is easily expressed as the rate \( W_{if} \) divided
by the flux of incoming particles:

\[ \frac{d\sigma}{d\Omega} = \frac{W_{if}}{\Phi_i}. \]  

(6.11)

Following the work of Tombrello and Parker [Tom63] the differential cross section for direct capture from the continuum to a bound state is given by the equation

\[ \frac{d\sigma}{d\Omega} = \frac{E_\gamma}{2\pi\hbar^2 c u_i(2j_p + 1)(2j_t + 1)} \sum_{m_i m_f P} |T_{if}|^2. \]  

(6.12)

Here \( j_p \) and \( j_t \) are the spins of the projectile and target, respectively. The summation is over all magnetic substates of the initial and final states, and the circular polarization states of the photon.

**Wave Functions**

In order to evaluate equation 6.12, the continuum and bound state wave functions need to be expressed. The continuum wave function shall be considered a product of two terms: a nuclear wave function (describing the target nucleus) and a distorted plane wave (representing the projectile). The bound state wave function is given as a product of three terms: a nuclear wave function (again, representing the target nucleus), a pure single-particle wave function (describing the bound projectile), and the quantity \( \sqrt{S} \), where \( S \) is the spectroscopic factor [Rol73].

The distorted plane wave mentioned above is generated from an optical model potential of the form:

\[ V(r) = V_0 f(r, r_0, a_0) + V_d \frac{d}{dr} f(r, r_d, a_d) + V_c(r), \]  

(6.13)

where \( V_c(r) \) is the coulomb potential, \( V_d(r) \) is the imaginary central potential, and \( V_0(r) \) is the real central potential. The function \( f \) is the standard Woods-Saxon form factor:

\[ f(r, r', a) = \frac{1}{1 + e^{(r-r')/a}}. \]  

(6.14)
The imaginary, or absorptive, term accounts for absorptive processes such as inelastic scattering.

The bound state wave function is calculated by solving the Schrödinger equation for a real Woods-Saxon potential in order to produce a bound single-particle state having the proper quantum numbers and binding energy. In the case of the $^4$He bound state, both an $L=0$ $S$-state and and $L=2$ $D$-state wave function must be calculated. These two wave functions are calculated using potentials of the form

$$V_{\text{bound}}(r) = V_L f(r, r_L, a_L) + V_c(r)$$  \hspace{1cm} (6.15)$$

where the subscript $L$ can have the values $S$ or $D$ and denotes the $L$ of the bound state. The final, conglomerate bound state wave function may be written as

$$\sqrt{1 - \rho^2} |^1S_0\rangle + \rho |^5D_0\rangle = \psi_{\text{bound}},$$  \hspace{1cm} (6.16)$$

where $\rho^2$ is equal to the percentage $D$-state of $^4$He. The value used for $\rho^2$ in all direct capture calculation appearing in Sec 6.3 was 4% [Whi93].

**The Electromagnetic Operator**

The last piece of information needed to evaluate equation 6.12 is the electromagnetic interaction Hamiltonian, $H'$. This may be written as [Laf82]

$$H' = -\frac{1}{c} \int \vec{J} \cdot \vec{A}(r) dr,$$

where $\vec{J}$ is the nuclear current density and $\vec{A}$ is the vector potential of the electromagnetic field. In practice the Hamiltonian is expanded into its multipole components. In this study, only the electric dipole (E1) and electric quadrupole (E2) terms have been calculated. In calculating the electric multipole operators, Siegert's theorem [Sie37] is used to replace the electric current density with the charge density. This allows for the simplification of the radial part of the electric operator, which may be expressed in terms of spherical Bessel functions. The long wavelength approximation is *not* made. Since both the deuteron and
the ground state of $^4$He are isospin zero, only the isoscalar forms of the operators are considered. The operators have both $\Delta S=0$ (non-spin-flip) and $\Delta S=1$ (spin-flip) terms. For multipolarity $L$ we write the non-spin-flip electric operator as $Q_L$ and the spin-flip electric operator as $Q'_L$. The non-spin-flip (reduced) matrix element is given by

$$
\langle \ell_a s_a j_a || Q_L || \ell sj \rangle = (-)^{\ell + \ell_a + j - j_a} e g_L \tilde{\ell}_j I_1(i)^{\ell - \ell_a + L} C(\ell LL_a; 000) W(L \ell j_a s; \ell j) 
$$

(6.18)

$$
I_1 = \frac{(2L + 1)!!}{(L + 1)k_L^L} \int_0^\infty dr \chi_{\ell j a s}^k \left\{ \left[ 1 - \frac{E_r}{2m_p c^2} \right] k_L r j_{L-1}(k_L r) 
- L j_L(k_L r) u_{ij}(r) - \frac{E_r}{2m_p c^2} r j_L(k_L r) \frac{d}{dr} u_{ij}(r) \right\}, 
$$

(6.19)

while the spin-flip matrix element is given by

$$
\langle \ell_a s_a j_a || Q'_L || \ell sj \rangle = (-)^{\ell + \ell_a + L} e g_L \frac{\beta g_s k_L}{L + 1} \left[ L(L + 1)s(s + 1) \right]^{1/2} \tilde{\ell}_j I_2(i)^{\ell - \ell_a + L} 
C(\ell LL_a; 000) X(\ell js; \ell_a js; LL1)
$$

(6.20)

$$
I_1 = \frac{(2L + 1)!!}{k_L^L} \int_0^\infty dr \chi_{\ell j a s}^k j_L(k_L r) u_{ij}(r).
$$

(6.21)

We define the following

- $e = \text{unit charge}$
- $L = \text{multipolarity of operator}$
- $\beta = \text{Bohr nuclear magneton} = eh/2m_p c$
- $g_L = \text{orbital } g\text{-factor of projectile} = 1$
- $g_s = \text{spin } g\text{-factor of projectile} = 1.7585$
- $m_p = \text{mass of proton} = 938.3 \text{ MeV}$
- $r = \text{the distance between the projectile and target}$
• $k_\gamma$ = wavenumber of $\gamma$ ray

• $E_\gamma = k_\gamma \hbar c$

• $j(k_\gamma r) =$ spherical Bessel function with argument $k_\gamma r$

• $\chi_{\ell j}(r) =$ scattering state (radial) wave function

• $u_{\ell j}(r) =$ bound state (radial) wave function

• $\dot{x} = \sqrt{2x + 1}$

• $C(abc; def) =$ Clebsch-Gordan coefficient

• $W(abcd; ef) =$ Wigner 6-$j$ symbol

• $X(abc; def; hij) =$ Wigner 9-$j$ symbol

• $s_a =$ spin of deuteron = 1

• $s =$ spin of deuteron as cluster in the bound state = 1

• $\ell_a =$ angular momentum of the projectile in the continuum state = 0, 2, 4

• $\ell =$ angular momentum of single particle in the bound state = 0, 2

• $j = \ell + s$ and $j_a = \ell_a + s_a$

Normally the spin-flip component is negligible, but since the non-spin-flip E1 term is forbidden by symmetry (see Sec. 1.5), the spin-flip E1 may be significant compared to the E2 strength in this reaction. A calculation of the ratio of the spin-flip to non-spin-flip E1 transition strength for the $d(d, \gamma)^4$He reaction was performed by Weller [Lan89]. This calculation utilized the long-wavelength approximation and found

$$\frac{\langle 1S_0 | E1 \Delta S = 1 | 3p_1 \rangle}{\langle 1S_0 | E1 \Delta S = 0 | 1p_1 \rangle} = \frac{E_\gamma}{1067.4} \quad (6.22)$$

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where the numerator represents the spin-flip TME, the denominator the non-spin-flip TME, and $E_\gamma$ is the energy of the emitted $\gamma$ ray in MeV. For a $\gamma$-ray energy of 170 MeV, this calculation predicts that the spin-flip TME is approximately 16% of the non-spin-flip TME. It is important to note that the long wavelength approximation is not justified at 170 MeV. As such, we use this calculation as an indicator that spin-flip E1 strength is likely to be present in non-negligible amounts, but we do not claim the calculation to have any finer predictive power.

### 6.3 Direct Capture Calculations

Direct capture calculations have been performed using the computer code RADCAP [Cot72]. This code has the ability to calculate transition amplitudes for electric multipole radiation. After applying the Wigner-Eckert theorem (Eqs. 6.18 and 6.20), the code evaluates the remaining radial integral which contains the operator expanded in terms of spherical bessel functions (Eqs. 6.19 and 6.21). The evaluation of the radial integral is performed numerically, allowing the radius to vary from 0 to 20 fermi. The resulting reduced matrix elements are then transformed from RADCAP’s $j-j$ coupling scheme to the $l-s$ coupling scheme via the program CROSST [Aug85]. The outputs of this code were then adjusted according to the choice of D-state admixture following Eq. 6.16 and the spin-flip amplitude was calculated according to Eq. 6.22. The final values of the TME’s were used to obtain values for the angular distribution of the cross section using the formalism of Seyler and Weller [Sey79]. Additionally, values for the analyzing power $A(\theta)$ for the $^4$He($\gamma$, $dd$) reaction were calculated from the same matrix elements according to the formalism presented in Weller et al. [Wel92].

At very low center of mass energies, direct capture is expected to be the dominant mechanism in this reaction. For deuteron energies as high as 50 MeV, the DC model is able to predict with reasonable success both the cross section and the analyzing power data observed in experiments [Whi93]. However, as the deuteron or $\gamma$-ray energy increases, the
usefulness of the direct capture model becomes limited. For example, in the work of Pitts et al. [Pit63] at a deuteron energy of 95 MeV, the direct capture model failed to predict even the correct sign for the tensor analyzing power $A_{yy}$.

Keeping in mind that the model is useful primarily from an heuristic point of view, we have performed several direct capture calculations using the full Bessel function forms of the electric multipole operators (see the previous section). The calculations were performed using E2 transitions to the $S$- and $D$-states of $^4$He ($^1d_2$, $^5s_2$, $^5d_2$, $^5g_2$) and the spin-flip E1 transition ($^3p_1$). In all cases, the ground state of $^4$He was constructed by solving the Schrödinger equation with a real potential as described in Eq. 6.15. The specific parameters used were those of Whitton [Whi93], who determined the parameters for the $S$- and $D$-states of $^4$He (described in Table 6.1) by varying the potential well depths $V_S$ and $V_D$ in order to reproduce the observed binding energy. As mentioned above, a $\rho^2$ parameter of 4% was used in all calculations. Although this $D$-state strength may appear small, it should be remembered that this represents only the $L=2$ probability for the $D$-state in $^4$He, not the total $D$-state strength [Whi93].

A variety of potentials was used to construct the continuum wave functions. In one set of calculations, the optical model potential of Whitton [Whi93] was used. This potential was obtained from fits to elastic scattering data from the $^2\text{H}(d, \gamma)^2\text{H}$ reaction at $E_d=30$ MeV and $E_d=50$ MeV. A second calculation was performed using the same potential as the bound state for the scattering state. Finally, a plane wave calculation was performed, i.e. no (nuclear) scattering potential was used. These continuum state potential parameters are summarized in Table 6.2.

We have performed calculations from $E_d=10$ MeV to 452 MeV, corresponding to $E_\gamma=29$ to 250 MeV. The absolute total cross section results for the various calculations are presented in Fig. 6.2 along with a selection of the world data and the Legendre polynomial results for the present work from Sec. 5.4. For $E_\gamma$ below 70 MeV, the Optical calculation does a reasonably good job of accounting for the energy response function. At higher
Table 6.1: Bound state potential parameters for the calculation of the ground state wave function.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_S$</td>
<td>61.37 MeV</td>
</tr>
<tr>
<td>$r_S$</td>
<td>1.6 fm</td>
</tr>
<tr>
<td>$a_S$</td>
<td>0.5 fm</td>
</tr>
<tr>
<td>$V_D$</td>
<td>162.74 MeV</td>
</tr>
<tr>
<td>$r_D$</td>
<td>1.6 fm</td>
</tr>
<tr>
<td>$a_D$</td>
<td>0.5 fm</td>
</tr>
<tr>
<td>$V_z$</td>
<td>1.2 fm</td>
</tr>
</tbody>
</table>

energies, however, the optical potential overpredicts the observed total cross sections of both Arends [Are76] and the present result by approximately two orders of magnitude. The bound state potential does not agree well with the response function below 75 MeV, but at higher energies is lower than the prediction of the optical model by a factor of five. The Plane wave calculation does the worst job of approximating the shape or amplitude of the energy response of all three calculations and its results are not useful.

In addition to the total cross section the direct capture calculations provide information about the detailed distribution of strength among the contributing TME's. Table 6.3 plots the strength of the TME's as a fraction of the total cross section $\sigma_{TOT}$ versus $E_\gamma$. Concentrating on the results from the Optical and Bound calculations, the first feature to note is the distribution of capture strength to the $S$-state versus the $D$-state of $^4$He. The Optical calculation places approximately 90% of $\sigma_{TOT}$ into capture to the $D$-state for $E_\gamma$ above 132 MeV. The Bound calculation places approximately equal strength into capture to the $S$- and $D$-states for $\gamma$-ray energies above 132 MeV.

Looking at trends among the individual amplitudes, we see that both sets find a steadily increasing contribution due to $g$-wave capture to the $D$-state, reaching 90% for the Optical calculations with $E_\gamma$ above 132 MeV. At the same time, both calculations predict a
Table 6.2: Continuum state potential parameters for the Optical, Bound, and Plane calculations of the continuum state wave function.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optical</th>
<th>Bound</th>
<th>Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0$</td>
<td>70.63 MeV</td>
<td>61.37 MeV (S)</td>
<td>0.01 MeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>162.74 MeV (D)</td>
<td></td>
</tr>
<tr>
<td>$r_0$</td>
<td>1.6 fm</td>
<td>1.6 fm</td>
<td>1.6 fm</td>
</tr>
<tr>
<td>$a_0$</td>
<td>0.592 fm</td>
<td>0.5 fm</td>
<td>0.5 fm</td>
</tr>
<tr>
<td>$V_d$</td>
<td>2.7 MeV</td>
<td>0.01 MeV</td>
<td>0.01</td>
</tr>
<tr>
<td>$r_d$</td>
<td>1.6 fm</td>
<td>1.6 fm</td>
<td>1.6 fm</td>
</tr>
<tr>
<td>$a_d$</td>
<td>0.75 fm</td>
<td>0.5 fm</td>
<td>0.5 fm</td>
</tr>
<tr>
<td>$V_c$</td>
<td>1.2 fm</td>
<td>1.2 fm</td>
<td>1.2 fm</td>
</tr>
</tbody>
</table>

steadily decreasing contribution from $d$-wave capture to the $S$-state of $^4$He, the amplitude observed to dominate this cross section at lower energies [Whi93, Pit63]. The spin-flip E1 amplitude is predicted to be small by the Optical calculation (1.5% of the $\sigma_{TOT}$ at $E_\gamma=174$ MeV), but plays a more significant role in the bound calculation, contributing between 8.6% and 14.6% of $\sigma_{TOT}$ between $E_\gamma$ of 132 MeV and 259 MeV. $s$- and $d$-wave capture to the $D$-state play a minor role at all energies in both calculations, although both strengths steadily increase for $E_\gamma$ above 132 MeV.

Next, we investigate the predictions of the various calculations for the differential cross section ($\sigma(\theta)$) and analyzing power ($A(\theta)$) for incident linearly polarized photons. Fig. 6.3 shows the results for $\sigma(\theta)$ and $A(\theta)$ from the three calculations for a $\gamma$-ray energy of 174 MeV. The angular distributions of the cross section are all similar in nature, with a minimum at 90° and maxima near 45° and 135°. All of these calculations fail to predict the peaking behavior at 90° observed in the present work. Furthermore, the calculations predict the wrong sign for the analyzing power $A(\theta)$.

Clearly, the calculations presented above do not reproduce the experimental results observed in the present work. Trends in the calculations for the total cross section, however,
<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>$\frac{3p_1}{1d_2}$</th>
<th>$\frac{5s_2}{5d_2}$</th>
<th>$\frac{5g_2}{5d_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.0</td>
<td>0.012</td>
<td>0.962</td>
<td>0.009</td>
</tr>
<tr>
<td>40.3</td>
<td>0.009</td>
<td>0.961</td>
<td>0.004</td>
</tr>
<tr>
<td>50.4</td>
<td>0.015</td>
<td>0.894</td>
<td>0.007</td>
</tr>
<tr>
<td>70.7</td>
<td>0.020</td>
<td>0.511</td>
<td>0.006</td>
</tr>
<tr>
<td>91.2</td>
<td>0.020</td>
<td>0.268</td>
<td>0.002</td>
</tr>
<tr>
<td>132.0</td>
<td>0.017</td>
<td>0.115</td>
<td>0.000</td>
</tr>
<tr>
<td>174.0</td>
<td>0.015</td>
<td>0.067</td>
<td>0.002</td>
</tr>
<tr>
<td>216.0</td>
<td>0.016</td>
<td>0.052</td>
<td>0.006</td>
</tr>
<tr>
<td>259.0</td>
<td>0.016</td>
<td>0.039</td>
<td>0.011</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>$\frac{3p_1}{1d_2}$</th>
<th>$\frac{5s_2}{5d_2}$</th>
<th>$\frac{5g_2}{5d_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.0</td>
<td>0.083</td>
<td>0.907</td>
<td>0.005</td>
</tr>
<tr>
<td>40.3</td>
<td>0.011</td>
<td>0.979</td>
<td>0.001</td>
</tr>
<tr>
<td>50.4</td>
<td>0.017</td>
<td>0.904</td>
<td>0.002</td>
</tr>
<tr>
<td>70.7</td>
<td>0.023</td>
<td>0.601</td>
<td>0.004</td>
</tr>
<tr>
<td>91.2</td>
<td>0.040</td>
<td>0.579</td>
<td>0.008</td>
</tr>
<tr>
<td>132.0</td>
<td>0.086</td>
<td>0.479</td>
<td>0.016</td>
</tr>
<tr>
<td>174.0</td>
<td>0.123</td>
<td>0.392</td>
<td>0.022</td>
</tr>
<tr>
<td>216.0</td>
<td>0.137</td>
<td>0.335</td>
<td>0.028</td>
</tr>
<tr>
<td>259.0</td>
<td>0.143</td>
<td>0.270</td>
<td>0.033</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>$\frac{3p_1}{1d_2}$</th>
<th>$\frac{5s_2}{5d_2}$</th>
<th>$\frac{5g_2}{5d_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.0</td>
<td>0.482</td>
<td>0.453</td>
<td>0.058</td>
</tr>
<tr>
<td>40.3</td>
<td>0.347</td>
<td>0.636</td>
<td>0.003</td>
</tr>
<tr>
<td>50.4</td>
<td>0.309</td>
<td>0.671</td>
<td>0.000</td>
</tr>
<tr>
<td>70.7</td>
<td>0.275</td>
<td>0.687</td>
<td>0.001</td>
</tr>
<tr>
<td>91.2</td>
<td>0.255</td>
<td>0.682</td>
<td>0.003</td>
</tr>
<tr>
<td>132.0</td>
<td>0.236</td>
<td>0.636</td>
<td>0.004</td>
</tr>
<tr>
<td>174.0</td>
<td>0.234</td>
<td>0.564</td>
<td>0.003</td>
</tr>
<tr>
<td>216.0</td>
<td>0.246</td>
<td>0.488</td>
<td>0.001</td>
</tr>
<tr>
<td>259.0</td>
<td>0.270</td>
<td>0.415</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Figure 6.2: Results for the total cross section $\sigma_{TOT}$ from direct capture calculations. The data are those from Fig. 1.3 with the addition of the Legendre polynomial analysis results of the present work from Sec. 5.4 (uncertainties are purely statistical). The curves are results from the Optical (solid), Bound (dashed), and Plane wave (dot-dashed) calculations.

Indicate that as the scattering potential well depth is increased, the total cross section is reduced. Since the optical well depth was chosen to reproduce elastic scattering data at deuteron energies below 50 MeV, it is not surprising that the calculation fails to predict the total cross section at higher energies. Although the lack of elastic scattering data at the current experimental energies precludes an independent determination of the well depth, we have studied the effect of varying the (real) well depth upon the total cross section. Well depths for scattering from the $S$- and the $D$-states were varied independently. These well depths are labeled $V_0(S)$ and $V_0(D)$, respectively.

The results of this study are plotted in Fig. 6.4. All calculations were performed for a $\gamma$-ray energy of 174 MeV. In three cases, values of $V_0(S)$ were chosen (85 MeV, 90 MeV, and 100 MeV) while $V_0(D)$ was permitted to vary from 70 MeV to 340 MeV. Additionally,
Figure 6.3: Results for the cross section $\sigma(\theta)$ and analyzing power $A(\theta)$ from direct capture calculations for $E_\gamma=174$ MeV. The curves are results from the Optical (solid), Bound (dashed), and Plane wave (dot-dashed) calculations. The cross section data are the 150-190 MeV results from the SAL experiment.
Figure 6.4: $\sigma_{TOT}$ versus well depth $V_0(D)$ from direct capture calculations with $E_\gamma=174$ MeV. The horizontal lines represent experimental limits (including systematic uncertainties) obtained in the present work for the energy bin $E_\gamma=150-190$ MeV.

Another curve was generated by setting the two well depths to be equal and varying this quantity from 70 to 340 MeV. The figure shows that at a well depth $V_0(D)$ between 210 and 240 MeV, the calculated value of $\sigma_{TOT}$ approaches the experimentally observed value $(6.85 \pm 0.25 \pm 0.49$ nb/sr) for the present work in the energy bin $E_\gamma=150-190$ MeV.

One effect of allowing the well depths to vary independently was the ability to "dial up" the amount of capture strength to the $S$-state or $D$-state. Table 6.4 shows the distribution of strength among the amplitudes for those calculations giving total cross sections in agreement with the present experiment. For the most part, the calculations shown in this table show large—often greater than 50%—contributions from the $D$-state. Aside from changes in the total cross section, however, the effect of shifting strength from the $S$-state to the $D$-state was small. In particular, cross section angular distributions from the various calculations have nearly identical shapes. $\sigma(\theta)$ data from the $V_0(S)=V_0(D)=230$ MeV and from the $V_0(S)=85$ MeV, $V_0(D)=225$ MeV calculations are shown in Fig. 6.5 along with the present data from the energy bin $E_\gamma=150-190$ MeV. Furthermore, although total
Table 6.4: $\sigma_{TOT}$ Fractions for various well depths.

<table>
<thead>
<tr>
<th>$V_0(S)$ (MeV)</th>
<th>$V_0(D)$ (MeV)</th>
<th>$\sigma_{TOT}$ (nb/sr)</th>
<th>$^3p_1$</th>
<th>$^1d_2$</th>
<th>$^5s_2$</th>
<th>$^5d_2$</th>
<th>$^5g_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>85.00</td>
<td>210.00</td>
<td>12.05</td>
<td>0.028</td>
<td>0.222</td>
<td>0.046</td>
<td>0.110</td>
<td>0.593</td>
</tr>
<tr>
<td>85.00</td>
<td>225.00</td>
<td>6.767</td>
<td>0.051</td>
<td>0.396</td>
<td>0.043</td>
<td>0.094</td>
<td>0.416</td>
</tr>
<tr>
<td>85.00</td>
<td>240.00</td>
<td>4.116</td>
<td>0.083</td>
<td>0.651</td>
<td>0.029</td>
<td>0.058</td>
<td>0.179</td>
</tr>
<tr>
<td>90.00</td>
<td>210.00</td>
<td>9.572</td>
<td>0.002</td>
<td>0.055</td>
<td>0.058</td>
<td>0.138</td>
<td>0.747</td>
</tr>
<tr>
<td>90.00</td>
<td>225.00</td>
<td>4.486</td>
<td>0.004</td>
<td>0.122</td>
<td>0.068</td>
<td>0.149</td>
<td>0.657</td>
</tr>
<tr>
<td>100.00</td>
<td>210.00</td>
<td>9.843</td>
<td>0.030</td>
<td>0.052</td>
<td>0.057</td>
<td>0.134</td>
<td>0.726</td>
</tr>
<tr>
<td>100.00</td>
<td>225.00</td>
<td>4.555</td>
<td>0.065</td>
<td>0.113</td>
<td>0.064</td>
<td>0.140</td>
<td>0.618</td>
</tr>
<tr>
<td>210.00</td>
<td>210.00</td>
<td>10.78</td>
<td>0.077</td>
<td>0.085</td>
<td>0.052</td>
<td>0.123</td>
<td>0.663</td>
</tr>
<tr>
<td>220.00</td>
<td>220.00</td>
<td>8.738</td>
<td>0.149</td>
<td>0.260</td>
<td>0.042</td>
<td>0.042</td>
<td>0.453</td>
</tr>
<tr>
<td>230.00</td>
<td>230.00</td>
<td>8.405</td>
<td>0.211</td>
<td>0.477</td>
<td>0.026</td>
<td>0.057</td>
<td>0.228</td>
</tr>
<tr>
<td>240.00</td>
<td>240.00</td>
<td>9.183</td>
<td>0.237</td>
<td>0.643</td>
<td>0.013</td>
<td>0.026</td>
<td>0.080</td>
</tr>
</tbody>
</table>

$S$- and $D$-state capture strength was accessible, the distribution of capture strength among the three $D$-state TME's or the two $S$-state TME's was largely unaffected by variation in the well depths (or well radius or diffuseness, which were also investigated).

6.3.1 Discussion

Reviewing the set of direct capture calculations discussed above we can make a few remarks. First, the direct capture model can be made to produce total cross sections in reasonable agreement with the present measurement. This was accomplished by adjusting the depth of the real well used to generate the continuum wave function. Unfortunately, the lack of elastic scattering data at the energies of the present work preclude an independent check of the physical significance of parameters obtained in this fashion, and therefore do not serve to corroborate the present measurement.

One can, however, make cautious statements about the likely distribution of strength between transitions to the $S$- and $D$-states in general. The importance of the $D$-state is strongly indicated by the majority of the calculations, which show that the $D$-state accounts
Figure 6.5: Angular distributions from two Direct Capture calculations for $E_\gamma = 170$ MeV. The calculations exhibit a minimum in the cross section at $90^\circ$ and maxima near $45^\circ$ and $135^\circ$.

for 50% or more of the total cross section, although a few calculations predict only a 10-30% contribution.

More detailed statements about the contributing amplitudes cannot be made, however, as the calculations predict roughly the same relative strengths (among transitions to the same state of $^4$He) regardless of the value of the potential parameters. In particular, all of the calculations tend to place the majority of capture strength to the $D$-state into the $^5g_2$ amplitude. This is in sharp contrast with the results of the TME analysis presented in Sec. 5.5, which found that the angular distribution data could be explained by constructive interference of $s$- and $d$-wave capture to the $D$-state. The result is that the shape of the angular distribution predicted by these calculations remained roughly steady—minimum at $90^\circ$ and maximum near $45^\circ$ and $135^\circ$—at odds with the maximum at $90^\circ$ observed in the present experiment.

Given the limitations of the direct capture model, it is not surprising that the predictions it gives at these energies do not agree with the measured data. In the next
section we will discuss several techniques that treat the wave functions and the interactions in a more sophisticated manner. Although these techniques have not yet been applied to the current system at the present energies, the promise of the techniques merits some discussion.

6.4 Other Calculations

The theoretical treatment of the the photodisintegration of $^4$He began in 1950 when Flowers and Mandl [Flo51] calculated the "inverse" Direct Capture matrix elements for the $(\gamma,d)d$, $(\gamma,p)^3$H, and $(\gamma,n)^3$He channels. They assumed a central nuclear force and noted that, due to the symmetry conditions described in Sec. 1.5, the $dd$ channel would be dominated by E2 transitions. This early calculation used gaussians for both the bound state wave function and the continuum wave functions. The non-orthogonality of these wave functions introduced some slight error into the calculations.

Two decades later, Meyerhof et al. [Mey69] investigated the $^3$H$(d,\gamma)^4$He reaction at deuteron energies between 6 and 19 MeV in search of a $2^+ \ T=0$ resonance. His study showed that the reaction did not exhibit a resonance structure, but was consistent with a predominantly E2 direct reaction mechanism.

In 1984, Weller et al. [Wel84] measured the tensor analyzing power $T_{20}(\theta)$ for the radiative capture reaction at $E_d=9.7$ MeV and found it to be isotropic and negative. This result, they argued, indicated the importance of the $D$-state admixture in the ground state of $^4$He. Using an E2 direct capture model they predicted that a $D$-state admixture of 4.8% could account for the observed value of $T_{20}$. Soon thereafter, however, Mellema et al. [Mel86] measured a complete set of polarization observables for the radiative capture reaction at $E_d=10$ MeV. They performed a transition-matrix element analysis that included E1, M1, E2, and M2 multipoles and concluded that, while their data provided evidence for tensor force effects at the level of 15%, determination of the $D$-state admixture was difficult in the absence of simplifying assumptions (such as pure E2 radiation). They argued that an accurate determination of the $D$-state strength would require inclusion of other effects.
such as the deuteron $D$-state strength and angular momentum mixing between the two deuterons in the incident channel.

A detailed investigation of the dependence of direct capture calculations upon potential parameters was then performed by Blüge et al. These calculations were limited to E2 radiative transitions, but nevertheless showed that the cross section varied strongly with only minor changes in the potential parameters. These authors suggested that this dependence could indicate the importance of the $p^{-3}\text{H}$ and $n^{-3}\text{He}$ channels in this reaction.

An attempt to include the effects of the deuteron $D$-state was made by Piekarewicz and Koonin [Pie87]. This study probed the effect of the deuteron $D$-state within the context of a simple phenomenological model by explicitly including the internal coordinates of the nucleons in the deuteron. They constructed scattering state wave functions from products of the internal deuteron wave functions, and generated the bound state wave functions using Woods-Saxon potentials similar to those described in the previous section. Their results showed that the extracted $D$-state probability for $^4\text{He}$ increases substantially if the deuteron $D$-state is included. The dependence of their results on the details of the nuclear interior, however, precluded any stronger conclusions.

A more sophisticated treatment of the system was performed by Hofmann et al. [Wac88, Kel89, Kra93]. They performed a microscopic coupled-channels resonating group model (MCCRGM) calculation for this reaction. In the resonating group model, the system is expanded in terms of cluster wave functions. These wave functions in turn contain information about the substructure of the clusters, giving this model access to the microscopic structure of the system. Within this framework, the $^4\text{He}$ system was treated as a superposition of the $p^{-3}\text{H}$, $n^{-3}\text{He}$, and $d^{-d}$ clusters. The bound and continuum wave functions were treated on an equal footing and generated using the same potentials. Both a semi-realistic nucleon-nucleon potential and a realistic $N-N$ potential were used. The calculations were limited to relative orbital angular momenta between clusters of two or less, and only E1, M1, E2, and M2 radiative transitions (in the long wavelength limit) were
considered.

The first potential set used was a semi-realistic $N-N$ potential [Wac88] that include central, Coulomb, spin-orbit and tensor components. This potential predicted a deuteron $D$-state of 6.2% and a $^4\text{He}$ $D$-state of 2.2% for the $L=2$ component arising from the $d+d$ configuration. The second potential set used the one-boson-exchange full Bonn potential with a Gaussian parameterization [Kel89]. This calculation predicted a deuteron $D$-state probability of 4.8%, a lower (and, in the opinion of the authors, more realistic) value than the semi-realistic potential result. The calculation predicted a $^4\text{He}$ $D$-state probability of 12-13%.

Predictions for TME's using both potential parameterizations were used to generate polarization observables for the $^2\text{H}(d,\gamma)^4\text{He}$ reaction at $E_d=80-0$ keV. These results were compared with data taken by Kramer et al. [Kra93] at the same energies. It is interesting to note that the experimental data in that paper, as in the current work, exhibited a peak in the differential cross section at 90°. Neither calculation predicted the observed angular distribution. Results from the semi-realistic potential were in reasonable agreement with the vector and tensor analyzing data reported in the paper but, surprisingly, the realistic potential failed to reproduce the data. Kramer [Kra92] suggested that the failure of the realistic potential calculations to predict the data could be a consequence of the treatment of the tensor-force in the Bonn potential.

Predictions from the semi-realistic potential at deuteron energies between 0.8 and 15 MeV [Wac88, Lan88, Lan90] were also compared with experimental data. In general, the agreement with cross section and polarization observables was quite reasonable. A comparison of the calculated TME's with the results of TME fits, however, showed that the details of the calculations were not supported by the data. The resonating group model nonetheless constitutes one of the best calculational techniques available for this system. Hofmann and collaborators are presently working on extending their calculational techniques to energies near those used in the present measurement [Hof96].

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In recent years, a variety of exact or nearly-exact methods for solving the nuclear ground state have emerged. A recent review by Carlson and Schiavilla [Car97] enumerates the coordinate space and momentum space Faddeev methods, the correlated hyperspherical harmonics variational method, and the variational and Green's function Monte Carlo techniques. All of these techniques have met with a high degree of success at reproducing the wealth of experimental data for observables concerning light nuclei, including the A=4 system.

The same review article discusses the advancement of the treatment of the scattering state, describing the development of the Argonne, Bonn, and Nijmegen $N-N$ potentials. Very recently these potentials have been fit to an experimental database and adjusted separately to the $np$ and $pp$ data sets. In addition, the authors describe the emergence of three nucleon potentials and relativistic corrections. Explicit inclusion of degrees-of-freedom internal to the nucleon has also been attempted as efforts to find precise theories have increased.

Finally, treatments of the nuclear electroweak current operator have likewise advanced. One- and two-body (and many-body) currents have been included in modern treatments of the light nuclear systems. In addition to the standard meson-exchange terms, $\Delta$-isobar, $\rho \pi \gamma$, and $\omega \pi \gamma$ terms have begun to appear in the most sophisticated calculations.

Taken as a whole, the prospect for a (nearly) exact treatment of the four body system and its associated electroweak reactions in the not-too-distant future is good. The first such treatment, with certain simplifying assumptions, was a variational Monte Carlo calculation of the $^2\text{H}(d,\gamma)^4\text{He}$ reaction performed by Arriaga, Pandharipande, and Schiavilla [Arr91]. They studied the reaction at $E_{d,\text{cm}} \leq 500$ keV using the Argonne AV14 two-nucleon and Urbana-VII three nucleon interactions and limited themselves to E2 transitions. Comparisons of the results with low energy cross section data, however, showed sizable discrepancies. The authors were not surprised, however, and considered this first attempt of the variational method to show great promise.
As bound state, scattering state, and electroweak operator treatments continue to advance, prospects for improved treatments of the $^4\text{He}(\gamma, dd)$ reaction seem brighter than ever. With luck, an updated resonating group model calculation will emerge shortly. Nagornyi et al. [Nag97] are also currently at work on an integro-differential equation approach to the problem above pion threshold. Hopefully, the experimental result presented in this dissertation will lead theorists to develop the formalism and techniques necessary for an exact theoretical treatment which contains our present knowledge of nuclear physics. Once this is achieved, any discrepancies which remain will indicate the presence of new physics.
Chapter 7

Summary and Conclusions

In this thesis we have reported cross section data from the $^4\text{He}(\gamma, dd)$ reaction with $E_\gamma=150-250$ MeV. The data were divided into two bins with $E_\gamma=150-190$ MeV and $E_\gamma=190-250$ MeV. The mid-energy bin data represent the first measurement of the cross section in this energy range. The angular distribution for this bin is shown in Fig. 7.1. The angular distribution is peaked at $90^\circ$ in the center-of-mass frame. The total cross section for this bin was extracted using a Legendre polynomial fit including $P_0$, $P_2$, and $P_4$, and was found to be $6.85 \pm 0.25 \pm 0.49$ nb. The first error is purely statistical while the second represents an 7.1% systematic uncertainty.

The high-energy bin data are shown in Fig. 7.2. Also shown are the world data obtained at energies near $E_\gamma=220$ MeV. The results for the high-energy bin are in very good agreement with the Silverman data [Sil84] and are generally above the Arends data [Are76]. The angular distribution is peaked at $90^\circ$ in the center-of-mass, in agreement with the results of both Arends and Silverman, but in disagreement with O'Rielly [O’R97]. The total cross section for this bin was extracted using a Legendre polynomial fit including $P_0$, $P_2$, and $P_4$, and was found to be $3.68 \pm 0.19 \pm 0.52$ nb. The first error is purely statistical while the second represents a 13% systematic uncertainty. The total cross section data from both energy bins are presented in Fig. 7.3 along with a selection of world data for $E_\gamma$ above
Figure 7.1: SAL differential cross section for $E_\gamma = 150$ to $190$ MeV. Exploiting the symmetry of the system, measured data (circles) have been reflected about $\theta_{c.m.}=90^\circ$ and plotted (squares). The uncertainties shown are purely statistical and do not include an 7.1% systematic uncertainty.

30 MeV.

We have also measured the analyzing power $A(\theta)$ using linearly polarized $\gamma$ rays of energy $E_\gamma=185$-237 MeV. These are the first polarization observable data for this reaction at these energies. The results are shown in Fig. 7.4. The poor quality of the data is a consequence of insufficient statistics. The large statistical error, coupled with an unknown but likely sizable contamination from the npd channel, makes conclusions about the angular distribution difficult. The only firm conclusion that can be drawn is that the analyzing power is negative at all angles.

A transition matrix element analysis of the data (both cross section and analyzing power) including E1, M1, E2, and M2 multipole transitions was performed. This analysis found that between 60% and 100% of the cross section arises from capture to the $D$-state.
of $^4$He. The dominant contribution to this comes from $s$-wave capture to the $D$-state. Furthermore, it was found that the maximum in the cross section angular distribution at 90° is a consequence of E2-E2, E1-M2, and E2-M2 constructive interference.

A set of direct capture calculations was performed using a variety of scattering state potentials. Results using an optical model potential obtained from elastic scattering data at lower energies indicated that about 90% of the cross section arose from capture to the $D$-state of $^4$He. This calculation, however, failed to predict either the magnitude or the shape of the angular distribution. Since the calculation placed almost all of the capture to the $D$-state into $g$-waves, the resulting angular distribution was minimum at 90° and maximum near 45° and 135°. Varying the real well depth of this optical potential it was
Figure 7.3: World data compared with the results of the present measurements. Uncertainties quoted for the present work are purely statistical and do not include systematic uncertainty (7.1% for the mid-energy bin and 13% for the high-energy bin).

It was possible to obtain total cross sections in agreement with the present results, but the shape of the cross section always remained minimum at $90^\circ$, and the capture to the $D$-state was always dominated by $g$-waves. Additionally, the direct capture calculations predicted the wrong sign for the analyzing power.

The inability of the direct capture model to predict the observed behavior for this reaction underscores the need for a more sophisticated theoretical treatment of this system. One such treatment is the Multiple Coupled-Channels Resonating Group Model (MCCRMG). At the present time, however, no MCCRMG calculations have been performed for this system at these energies. Hofmann et al. are currently working on this calculation and...
Figure 7.4: dd (circles) and reflected (squares) $A(\theta)$ data from the LEGS experiment. Errors are purely statistical.

hope to have results in the near future.

In the absence of a sound theory, we can nevertheless draw some final conclusions from the present work. First, the absolute total cross section for $^4\text{He}(\gamma, dd)$ for $E_\gamma$ near 220 MeV favors the lower values of those published during the last 35 years. We feel that the cross section is now known to within $\sim 30\%$—as opposed to within a factor of 100 or 1000.

Second, the angular distribution was found in this work to be maximum at 90°, in agreement with the Arends [Are76] and Silverman [Sil84] measurements. The first observation of this sparked debate because such an angular distribution is normally associated with E1 radiation [Sil84]. For reasons discussed in detail in Sec. 1.5, E2 transitions are expected to dominate this reaction. Such angular distributions typically exhibit a $\sin^2 2\theta$ shape which is minimum at 90° and maximum near 45° and 135°.

This inconsistency caused Silverman [Sil84] to suggest that the shape of the angular
distribution arose from E1 radiation coming from meson-exchange currents. The isoscalar nature of both the deuteron and $^4$He, however, makes such exchange currents unlikely. In this work we have shown that it is, in fact, possible to create an angular distribution that is peaked at $90^\circ$ using E2 s-wave capture to the $D$-state interfering constructively with $d$-wave E2 capture to the $D$-state or with M2 radiation. M1-E2 constructive interference can also contribute to this shape. It is not necessary to resort to meson-exchange currents to explain the observed angular distribution.

These observations indicate the vital importance of the tensor force in the present system. The possibility that it plays a dominant role at such high energies is quite intriguing. We hope that this interesting result will motivate the four-body theorists to investigate this physics-rich reaction at these energies in the near future.
Appendix A

Various Computer Codes

A.1 Bremsstrahlung Code

Description:

The code used to integrate the bremsstrahlung spectrum for the various energy bins was written by Norm Kolb. It implements the Schiff thin-radiator formula [Sch51]. I called this routine using bin sizes equal to the tagger bite, 150-190 MeV, and 190-250 MeV to obtain a cross normalization of fluxes between the tagged and untagged runs.

Program:

```
program test_schiff
implicit none
real e, k, z, dummy, schiff_dk, midbin, tagflux
midbin = 0.
tagflux = 0.
z = 13.0
e = 273.0
```
do k = 1., 300., 1.0
    if (k .ge. e) then
        dummy = 0.
    else
        dummy = schiff_dk(e,k,z)
    endif
    if (k .ge. 150 .and. k .le. 290) then
        midbin = midbin + dummy
    endif
    if (k .ge. 171 .and. k .le. 212) then
        tagflux = tagflux + dummy
    endif
    write (*,*) k,dummy*(1.0E+24)
enddo
write(*,*) midbin, tagflux, tagflux/midbin
end

FUNCTION schiff_dk( Eo, k, Z )

  c Bremsstrahlung cross section of Schiff differential in
  c and photon energy (k).
  c L. I. Schiff, Phys. Rev. 83 (1951) 252.

  c INPUTS
  c Eo Electron beam energy
  c k Photon energy
  c Z Charge of radiator
  c
  c 91/02/25 Norm Kolb

DATA Re / 2.818E-13 /,!Electron radius (cm)
1 Me / 0.511 /,!Electron mass (MeV)
1 C / 111. /

real Me, Mx, k

E = Eo - k !Scattered electron energy

x = 0.
Mx = ( Me*k/( 2*Eo*E ) )**2 + ( Z**(1./3.)/( C*(x*x+1) ) )**2
Mx = 1./Mx

b = ( 2*Eo*E*Z**(1./3. ) )/( C*Me*k )

schiff_dk = ( (Eo*Eo+E*E)/(Eo*Eo) - 2*E/(3*Eo) )*
\begin{verbatim}
  ( LOG(Mx) + 1 - 2*ATAN(b)/b ) +
  (E/Eo)*( 2*LOG(1+b*b)/(b*b) +
  4*(2-b*b)/(3*b**3)*ATAN(b) -
  8./(3*b*b) + 2./9. )

  schiff_dk = ( 2.*Z*Z*Re*Re/137. ) * schiff_dk * ( 1./k )

  RETURN
  END
\end{verbatim}

### A.2 Kinematics Codes

**Description:**

The kinematics codes used for the two body reaction are based on the relativistic energy and momentum relationships. The actual code used was modified from one originally written for the $^3\text{He}(\gamma, dp)$ reaction by Norm Kolb. Switching it to handle $^4\text{He}(\gamma, dd)$ was a simple matter of changing some masses.

Transformation from the lab to center-of-mass frame for purposes of obtaining $\theta_{c.m.}$ and the transformation Jacobians was done using the code RKin. A copy of this code is available upon request (ricetunl.duke.edu).

**Program:**

```fortran
subroutine calc_dd_gama(thetad1,Td1,Eg,thetad2,Td2)
  c-----------------------------------------------
  C.
  c g + 4He -> d + d
  c Helium-4 2-body photo-disintegration
  C.
  c theta angle of the proton
  c Tp proton kinetic energy
```

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C. Norm Kolb 90/09/20
C modified from D(g,p)n routine. 92/02/19
C Bryan Rice
C modified from D(g,p)d routine. 96/09/18
C.
C----------------------------------------
C.
    real Td1, thetad1, Eg
    real Td2, thetad2
    real Pd1, Pd2, tmp
real Md1, Md2, M4, K
DATA Md1 / 1875.628 /,
1 Md2 / 1875.628 /,
1 M4 / 3727.409 /
C.
Td2 = 0
thetad2 = 0
Eg = 0
C.
K = M4 - Td1 - Md1
Ed1 = Td1 + Md1
Pd1 = SQRT( Ed1*Ed1 - Md1*Md1 )
tmp = ( 2.*( K + Pd1*COSD(thetad1) ) )
IF( tmp.ne.0 ) THEN
    Eg = ( Pd1*Pd1 + Md2*Md2 - K*K )/tmp
END IF
C.
IF( Eg.gt.0 ) THEN
    Ed2 = Eg + M4 - ( Ed1 )
    Td2 = Ed2 - Md2
    tmp = ( Ed2*Ed2 - Md2*Md2 )
    IF( tmp.gt.0 ) THEN
        Pd2 = SQRT( tmp )
    END IF
    thetad2 = ATAN2D( Pd1*SIND(thetad1), Eg-Pd1*COSD(thetad1) )
END IF
C.
RETURN
END
A.3 Energy Loss Codes

The size of the energy loss routines prohibits my including them here. The majority of the code was written by Grant O'Rielly and Rob Pywell, with some help from Norm Kolb and myself. For those interested in the details and for an exhaustive listing of the codes (several thousand lines of lucid, C, and Fortran code), please contact me at ricetunl.duke.edu.

Essentially, these routines used range-energy tables to estimate the integrated energy loss of particles traveling through known a thickness of material. These tables were generated using the corrected Bethe-Bloch energy loss equation described in Sec. 3.3.2 for a variety of materials, including scintillator, liquid helium, sodium iodide, mylar, and atmosphere. The tables were generated for bombarding energies from 0.1 MeV to 350 MeV, with the first 1 MeV subdivided into 0.1 MeV sections, and 1 to 350 MeV subdivided into 1 MeV sections.

The target geometry was specified in a simple layered fashion. Each layer's type and thickness were entered into an array. Target thicknesses were corrected for path length changes based on the angle of the detector that fired. The energy loss code could be directed to reconstruct a vertex energy (assuming the center of the target) from a detector energy, or it could take a specified vertex energy and generate the energy that would be deposited in a detector at a given angle.

In addition, the code was able to apply light output corrections for a variety of particle types. The light output for protons, deuterons, and tritons (among others) with energy between 0.1 and 350 MeV was computed according to the method of O'Rielly [O'R96]. These values were stored in tables and used to go from observed light output to actual energy, or vice-versa.
A.4 *dd* Extraction Code

**Description:**

This appendix presents the fitting routine used to perform the $\chi^2$ minimization of the $E_{\text{diff}}$ spectra. Competing channel $E_{\text{diff}}$ shapes were input from files. A rebin feature was implemented to bin the data by groups of channels. This allowed sparse data sets to be fit as well. A feature to allow the various background shapes to shift was also implemented.

**Program:**

```fortran
options /extend_source
subroutine FCN(npar, g, f, x, iflag)
    C In the user section of the MINUIT data file there
    C are several lines of input:
    C
    C   detector, numchannels, rebinfactor, numbackgrounds
    C   detector_name_1
    C   detector_name_2
    C   ...
    C   detector_name_(numbackgrounds+1)
    C
detector - an integer from 0 to 6, specifies the last
digit of the file names generated from lucid
    histograms--corresponds to detector number
    C
    C   numchannels - number of channels in the histogram files
    C
    C   rebinfactor - an integer from 0 to 8, this means
    C   that the output files will be generated with
    C   numpoints/2**rebinfactor bins of
    C   2**rebinfactor channels each
    C
    C   detector_name_x - character string of the form
    C   "Data.recon_xy_diff_ang_mid.",
    C   where x and y are {p|d|t}
    C
```
implicit none

C Various PARAMETERS
integer max_channels, max_curves, mni, max_ressz
PARAMETER (max_channels = 1024, max_curves = 10, mni = 50, max_ressz = 65)

C FCN parameters declared
double precision g(mni), f, x(mni)
integer npar, iflag

C Internal FCN variables declared
integer detector, numchannels, rebinfactor, numbackgrounds
character data_filenames(max_curves)*79
integer datay(max_curves, max_channels)
double precision datax(max_channels)
double precision background, signal
integer binsize, numbins
integer i, j, ressz, center
real smresp(max_ressz), respns(max_channels), ans(2*max_channels)
real smdata(max_channels)

C Declare functions to be called...
double precision gaussian, chisqr

C MINUIT common blocks required by FCN
double precision ERP(MNI), ERN(MNI), WERR(MNI), GLOBCC(MNI)
common /MN7ERR/ ERP, ERN, WERR, GLOBCC

C This serves as a case statement and branches execution to
C the various subportions of the user function.
IF (iflag .EQ. 1) THEN

C-----------------------------------------------
C Initialize

C Read in first line of user area of MINUIT input file
read(5,*) detector, numchannels, rebinfactor, numbackgrounds
write(*,*) detector, numchannels, rebinfactor, numbackgrounds

C Do some range checking on the parameters
if (detector .lt. 0 .or. detector .gt.6) then
   write(*,*)'Detector parameter out of range: ', detector
   stop
else if (numchannels .lt. 0 .or. numchannels .gt. max_channels) then
   write(*,*)'Number of channels parameter out of range: ',numchannels
   stop
else if (rebinfactor .lt. 0 .or. rebinfactor .gt. 8) then
   write(*,*)'Rebin factor parameter out of range: ',rebinfactor
   stop
else if (numbackgrounds .lt. 0 .or. 
numberbackgrounds .gt. max_curves-1) then
   write(*,*)'Number of backgrounds parameter out of range: ',
   numberbackgrounds
   stop
endif

C Read in the names of the data files to be read and included in the fit
   do i=1,numbackgrounds+1
      read(5,*) data_filenames(i)
   enddo

C Figure the binsize and number of bins
   binsize = int(2**rebinfactor)
   numbins = numchannels/binsize
   write (*,*) binsize, numbins

   call read_data(detector,numchannels,numbackgrounds,data_filenames,
                 datax,datay)
   call rebin_data(numchannels,binsize,numbins,numbackgrounds,datax,datay)

ELSE IF (iflag .EQ. 3) THEN

C Final call to FCN. Output results and exit.

C open(20,file='bf'//char(ichar('0')+detector) // '.out',status='new')

c report the fit results
   do i=1,numbackgrounds + 3
      write(20,*) x(i),'+/- ',werr(i)
   enddo

c ready a Savitsky-Golay smoothing filter for improving look of data
   ressz = max(1,int(2**(10-rebinfactor-5)))
   if (ressz .ne. 1) then
      ressz = ressz + 1
   endif
   call savgol(smresp,ressz,(ressz-1)/2,(ressz-1)/2,0,4)

   do j = 1, numbackgrounds + 1
      do i = 1, numbins
         if (i.le.ressz) then
            respns(i) = smresp(i)
         endif
         sndata(i) = real(datay(j,i))
      end do
   end do

   call convlv(sndata,numbins,respns,ressz,1,ans)
do i = 1, numbins
    datay(j,i) = int(ans(i))
end do
end do

write(20,*) 'Chisqr=', chisqr(x,numbackgrounds,datax,datay,numbins)

open(21,file='backg '// char(ichar('0')+detector) '// '.out',status='new')
open(22,file='bsignal '// char(ichar('0')+detector)
> '// '.out',status='new')
open(24,file='bdd '// char(ichar('0')+detector) '// '.out',status='new')
do j = 1, numbackgrounds
    open(24 + j,file='bg' '// char(ichar('0')+j) //
> char(ichar('0')+detector) '// '.out',status='new')
end do
do i = 1, numbins

  ready background and signal arrays
  background = 0.0
  do j = 1, numbackgrounds
    center = nint(x(3 + j + numbackgrounds)) + i
    if (center .ge. 1 .and. center .le. numbins) then
      background = background + x(3 + j)*datay(j + 1,center)
    endif
  end do

  signal = gaussian(datay(i),x(1),x(2),x(3))
  if (signal .lt. .001) then
    signal = 0.
  endif

  write things to output files
  write(21,*) datax(i)-x(2), background
  write(22,*) datax(i)-x(2), signal
  write(23,*) datax(i), background + signal
  write(23,*) datax(i)-x(2), datay(1,i) - background
  write(24,*) datax(i)-x(2), datay(1,i)
  do j = 1, numbackgrounds
    write(24+j,*), datax(i), datay(j+1,i)
  end do
enddo
close(21)
close(22)
close(23)
close(24)
do i=1,numbackgrounds
close(24+i)
end do

close(20)

ELSE IF (IFLAG .EQ. 4) THEN

C-- This is where the subroutine calculates the value of the function
to be minimized

f = chisqr(x,numbackgrounds,datax,datay,numbins)

ELSE

C-- Not used by this fitting routine

ENDIF

return

END

subroutine read_data(detector,numchannels,numbackgrounds,
data_filenames,datax,datay)

implicit none

C Various PARAMETERS
integer max_channels, max_curves, mni
PARAMETER (max_channels = 1024, max_curves = 10, mni = 50)

integer detector, numchannels, numbackgrounds
character data_filenames(max_curves)*79
double precision datax(max_channels)
integer datay(max_curves,max_channels)

character filename*79, tmp_filename*79
integer i

C Declare functions to be called
integer lnblnk

do i = 1, numbackgrounds+1
  tmp_filename = data_filenames(i)
  filename = tmp_filename(1:lnblnk(tmp_filename))
  // char(ichar('0')+detector)
write(*,*) filename
open(1,file=filename, status='old', err = 17)
call read_1024(i,numchannels,daxay,datay)
close(1)
end

goto do

goto 20

17 write(6,*)'read_data(): Cannot open file', filename(1:lnblnk(filename))
stop

20 return
END

subroutine read_1024(index,numchannels,daxay,datay)

implicit none

C Various PARAMETERS
integer max_channels, max_curves, mni
PARAMETER (max_channels = 1024, max_curves = 10, mni = 50)

integer index, numchannels
double precision daxay(max_channels)
integer datay(max_curves,max_channels)

integer i
character dummy*80

C Read in the header and ignore
100 format(a79)
do i = 1, 3
   read(1,100, err=18, end=18) dummy
enddo

do i = 1,numchannels
   read(1,* , err=18, end=18) daxay(i),datay(index,i)
enddo

goto 20

18 write(6,* )'read_1024(): Error reading data file.'
stop

20 return
END
subroutine rebin_data(numchannels, binsize, numbins,  
>       numbbackgrounds, datax, datay)

implicit none

C Various PARAMETERS
integer max_channels, max_curves, mni
PARAMETER (max_channels = 1024, max_curves = 10, mni = 50)

integer numchannels, binsize, numbins, numbbackgrounds
integer datay(max_curves, max_channels)
double precision datax(max_channels)

integer tempy(max_curves, max_channels)

integer i, j, k

do i = 1, numbins
   do k = 1, numbbackgrounds+1
      tempy(k, i) = 0
      do j = 1, binsize
         tempy(k, i) = tempy(k, i) + datay(k, (i-1)*binsize + 1)
      end do
      datay(k, i) = tempy(k, i)
   end do
   if (i .lt. numbins) then
      datax(i) = datax((i-1)*binsize + 1) +  
      +     binsize * ((datax((i-1)*binsize + 2) -  
      +     datax((i-1)*binsize + 1))) / 2.
   else
      datax(i) = datax((i-1)*binsize + 1) +  
      +     binsize * ((datax((i-1)*binsize + 1) -  
      +     datax((i-1)*binsize + 0))) / 2.
   endif
end do

return
end

function gaussian(x, amplitude, mean, sigma)
implicit none

double precision x, amplitude, mean, sigma
double precision gaussian

gaussian = amplitude * 0.39894228 / sigma *
+ exp(-((x-mean)/(1.4142136*sigma))**2)

return
end

function chisqr(x,numbbackgrounds,datax,datay,numpoints)

implicit none

C Various PARAMETERS
integer max_channels, max_curves, mni
PARAMETER (max_channels = 1024, max_curves = 10, mni = 50)

double precision x(mni), datax(max_channels)
integer numbackgrounds, datay(max_curves,max_channels), numpoints

double precision chisqr, sum, temp
integer i, j, nu, center

C Declare functions to be called
double precision gaussian

C array x is sig amp, mean, sigma, back #1 amp, amp #2, etc
sum = 0
nu = 0
do i = 1, numpoints
   nu = nu + 1
   temp = 0.
do j = 1, numbackgrounds
      center = nint(x(j+3+numbackgrounds)) + i
      if (center .ge. 1 .and. center .le. numpoints) then
         temp = temp + x(3 + j)*datay(j + 1,center)
      endif
endo
dtemp = temp + gaussian(datax(i),x(1),x(2),x(3))
sum = sum + (temp - datay(1,i))**2
endo
chisqr = sum/nu
return
END

Sample Input File:

DD fitting for Egam = 150 - 190 MeV
A.5 Transition-matrix Element Analysis Code

Description:

This appendix section describes the transition-matrix element analysis routine used to perform the $\chi^2$ minimization of the cross section and analyzing power data. The routine is called by a main program which is linked with the MINUIT library. Formalism is from Ref. [Wel92].

The code itself is patterned after TMEDFIT, a program written by the Radiative
Capture group that has evolved over the past decade and more. The code is available upon request from ricetunl.duke.edu, but is a little too long to be included here. In this incarnation I removed all references to tensor analyzing powers. In addition, I used the angular momentum coupling coefficients from Ref. [Wel92] for linearly polarized $\gamma$ rays. I then altered the cross section and analyzing power expressions to be consistent with the definitions in Ref. [Wel92].

Sample input and output files are given below. Care should be exercised when using the Legendre polynomial coefficients that this code generates. The B coefficients correspond to the $B_{2q}^{ab}$ coefficients in Ref. [Wel92]. The expression for the analyzing power, however, includes the A coefficients, which correspond to the $B_{0q}^{ab}$ coefficients from Ref. [Wel92].

Sample Input File:

```
Egamm = 200MeV, Spin-flip E1 & normal E2 Fit
1 'A1D5'  0.01  0.01  0.0  3.0
2 'A1D5pha'  0.0  0.01  -360.0  360.0
3 'A5S5'  0.40  0.01  0.0  3.0
4 'A5S5pha'  0.0  0.01  -360.0  360.0
5 'A5D5'  0.27  0.01  0.0  3.0
6 'A5D5pha'  0.0  0.01  -360.0  360.0
7 'A5G5'  0.01  0.01  0.0  3.0
8 'A5G5pha'  0.0  0.01  -360.0  360.0
9 'A3P3'  0.1  0.01  0.0  1.0
10 'A3P3pha'  0.0  0.01  -360.0  360.0
11 'A5D3'  0.1  0.01  0.0  1.0
12 'A5D3pha'  0.0  0.01  -360.0  360.0
13 'A3P5'  0.1  0.01  0.0  1.0
14 'A3P5pha'  0.0  0.01  -360.0  360.0
15 'A3F5'  0.1  0.01  0.0  1.0
16 'A3F5pha'  0.0  0.01  -360.0  360.0
8
0 2 2 1 2
2 0 2 1 2
2 2 2 1 2
2 4 2 1 2
1 1 1 1 1
2 2 1 2 1
```
Sample Output File:

E_{gam} = 200 MeV, Spin-flip E1, M1, E2, M2 3-Feb-98

Sigma Chi-squared = 5.928
A Chi-squared = 16.739
Total chi-squared = 22.667
Number of Data Points = 12
Number of Varied Parameters = 15
Number of Degrees of Freedom = -3

Matrix Elements: (notation S,L,J represents 2S+1, 2L+1, 2J+1)

Amplitude Phase S L J MULT
0.2654E-03 +/- 0.2379E+01 -172.59 +/- 172.59 0 2 2 E2
0.4921E+00 +/- 0.2575E-01 *F* 0.00 +/- 0.01 2 0 2 E2
0.8165E-01 +/- 0.3402E-01 0.00 +/- 76.76 2 2 2 E2
*L* 0.1542E-08 +/- 0.8417E-02 0.00 +/- 537.80 2 4 2 E2
0.3044E+00 +/- 0.4764E-01 0.00 +/- 31.86 1 1 1 E1
*L* 0.1783E-08 +/- 0.3072E-01 0.00 +/- 537.80 2 2 1 M1
0.2193E+00 +/- 0.4447E-01 0.00 +/- 38.14 1 1 2 M2
0.1791E+00 +/- 0.5446E-01 0.00 +/- 43.33 1 3 2 M2

Cross Section Fractions: (notation is 2S+1, 2L+1, 2J+1, multipolarity)

Fraction ( 0 2 2 E2 ) = 0.000 +/- 0.0033
Fraction ( 2 0 2 E2 ) = 0.630 +/- 0.0659
Fraction ( 2 2 2 E2 ) = 0.017 +/- 0.0144
Fraction ( 2 4 2 E2 ) = 0.000 +/- 0.0000
Fraction ( 1 1 1 E1 ) = 0.145 +/- 0.0452
Fraction ( 2 2 1 M1 ) = 0.000 +/- 0.0000
Fraction ( 1 1 2 M2 ) = 0.125 +/- 0.0507
Fraction ( 1 3 2 M2 ) = 0.083 +/- 0.0507

Q0 = 1.0000  Q1 = 0.9850  Q2 = 0.9556  Q3 = 0.9125  Q4 = 0.8573

Legendre coefficients:
A0 = 0.144E+01 +/- 0.156E+00
A1 = 0.000E+00 +/- 0.000E+00  a1 = 0.000E+00 +/- 0.000E+00
A2 = -0.457E+00 +/- 0.142E+00  a2 = -0.317E+00 +/- 0.104E+00
A3 = 0.000E+00 +/- 0.000E+00  a3 = 0.000E+00 +/- 0.000E+00
A4 = 0.331E+00 +/- 0.118E+00  a4 = 0.230E+00 +/- 0.853E-01
B1 = 0.000E+00 +/- 0.000E+00  b1 = 0.000E+00 +/- 0.000E+00
B2 = 0.279E+00 +/- 0.465E-01  b2 = 0.193E+00 +/- 0.384E-01
B3 = 0.000E+00 +/- 0.000E+00  b3 = 0.000E+00 +/- 0.000E+00
B4 = -0.297E-01 +/- 0.980E-02  b4 = -0.206E-01 +/- 0.715E-02
Bibliography


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Biography

Bryan Joseph Rice

Personal

• Born in Hamilton, Ohio, 3 January 1969

Education

• B.S. Physics, Georgia Institute of Technology, Atlanta, Georgia, 1991
• M.S. Computer Science, Georgia Institute of Technology, Atlanta, Georgia, 1991
• A.M. Physics, Duke University, Durham, North Carolina, 1994

Research and Teaching Positions

• Undergraduate Research Assistant, Georgia Tech, 1990-1991
• Teaching Assistant, Duke University, 1992-1994
• Research Assistant, Duke University, 1994-1998

Honors and Awards

• Georgia Tech Sigma Xi Best Research Paper Award (1995)
• Georgia Tech Scholarship for French Language Study in France
• Georgia Tech President’s Scholarship (1987-1991)
• IBM Thomas J. Watson Scholarship (1987-1991)
• National Merit Scholar

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Memberships

- American Physical Society
- Division of Nuclear Physics
- Phi Kappa Phi

Journal Publications


3. B. J. Rice and H. R. Weller. *A determination of the asymptotic D- to S-state ratio for ^3He from the reaction p(\bar{d},\gamma)^3He at E_{d,lab}=80-0 keV* Physical Review C 55, 2700 (1997).


Oral Presentations

1. *Some investigations of ^3He and ^4He.* Given at MIT, Cambridge, MA (October 16, 1997) and at Intel Corporation, Hillsboro, OR (October 30, 1997).

2. *Photodisintegration of ^4He into dd at E_\gamma=150-250 MeV.* Given at the DNP Meeting, Whistler, BC, Canada (October 6, 1997).

3. *Continuing study of the \(^1H(\bar{d},\gamma)^3He Reaction at E_d = 80-0 keV.* Given at the APS meeting, Washington, D.C. (April 1997).

4. *The \(^1H(\bar{d},\gamma)^3He Reaction at E_d = 80-0 keV.* Given at the DNP meeting, Bloomington, IN (October 1995).