The $^7\text{Li}(p,\gamma)^8\text{Be}$ Reaction Below 80 keV and the Astrophysical $S$-Factor.

by

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Date: November 5, 1996

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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

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Mark Allen Godwin
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ABSTRACT
(Physics – Nuclear)

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ABSTRACT

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The \(^7\)Li\((p,\gamma)^8\)Be reaction has been studied in the energy range \(E_{p,\text{lab}}=80-0\) keV. Capture reactions to the ground, first, and third excited states have been examined. In particular the vector analyzing power, \(A_v(\theta)\), has been measured for each of the transitions and the angular distribution of the cross section, \(\frac{d\sigma}{d\Omega}(\theta)\), has been measured for proton capture to the third excited state. Additionally, the absolute cross section, \(\sigma_T(E)\), and (equivalently) the astrophysical \(S\)-factor, \(S(E)\), has been measured for capture to the third excited state.

The primary motivations for studying these reactions are the following: To study the \(^7\)Li\((p,\gamma_0)^8\)Be reaction and to quantify how the observed M1 radiation affects the extraction of the astrophysical \(S\)-factor. To determine what role M1 radiation (\(p\)-wave capture) plays in the \(^7\)Li\((p,\gamma_3)^8\)Be reaction. Based on the analysis of the above, to draw conclusions regarding the likelihood of \(p\)-wave effects in the \(^7\)Be\((p,\gamma)^8\)B reaction, and to estimate their possible impact on the \(S\)-factor for this reaction.

A model-independent transition matrix element (TME) analysis shows the presence of substantial (40–90\%) M1 radiation in the ground state transition. The first and third excited states do not show the same behavior, and a TME analysis of the latter predicts either a pure E1 or pure M1 solution. Extensive direct capture plus M1 resonances calculations have been performed for all three transitions. While they predict the behavior of the first and third excited state, they do not reproduce quantitatively the M1 strength seen in the ground state. The astrophysical \(S\)-factor determined for capture to the third excited
state is in fair agreement (within a factor of 2) with the direct capture calculations.

The direct capture plus M1 resonances calculations have been extended to the \( ^7\text{Be}(p,\gamma)^8\text{B} \) system. This calculation predicts no M1 strength below 80 keV. We therefore conclude that the extrapolation of the astrophysical S-factor for the \( ^7\text{Be}(p,\gamma)^8\text{B} \) reaction, which has been performed previously by assuming pure E1 capture, is valid with regard to the neglect of any significant p-wave capture strength, and that the presence of low-energy p-wave capture in this reaction does not offer any insight into the solar neutrino problem.
Acknowledgements

There are many people I would like to thank for their assistance with this project. First and foremost is Henry Weller, who’s guidance, enthusiasm, and encouragement have been a tremendous help. His expertise in both experimental and theoretical nuclear physics are vast, and have been of great value. Ron Tilley and Dick Prior’s participation and interest in all my experiments is greatly appreciated. I am indebted to the members of the Radiative Capture group who have helped acquire the data (and lift the lead bricks). I’d especially like to thank Bob Chasteler, Chip Laymon, Bryan Rice, and Greg Schmid for their countless hours of work and numerous discussions.

A special thanks goes to my parents, Mary and Richard Godwin, who have supported me in all my endeavors. They have always shown an interest in and placed a high value on my education.

I would like to thank Marla Tuchinsky for all her love, friendship, and encouragement, but that would require many more pages and this dissertation is already too long. Thanks —la!

"We’ve done it, haven’t we?" he said.
In payment for every effort, for every sleepless night, for every silent thrust against despair, this moment was all he wanted.
"Yes. We have."

—A.R.
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Chapter 1

Introduction

1.1 Overview

In 1930 Wolfgang Pauli postulated an uncharged, spin $\frac{1}{2}$ particle of small or zero mass is emitted during beta decay. Prior to this, experiments had shown that certain nuclei would undergo spontaneous conversion, where a neutron converts to a proton and an electron:

\[ n \rightarrow p + e^- . \]  \hspace{1cm} (1.1)

The problem is that this reaction violates conservation of energy, conservation of momentum, and conservation of angular momentum. This mysterious particle proposed by Pauli (later christened the neutrino, or "little neutral one", by Enrico Fermi) possesses the properties necessary to solve the problems listed above. The neutrino (symbol $\nu$) and antineutrino (symbol $\bar{\nu}$) participate in beta decay reactions in the following manner:

\[ n \rightarrow p + e^- + \bar{\nu} \]
\[ p \rightarrow n + e^+ + \nu. \]  \hspace{1cm} (1.2)

The interaction of these particles with matter will certainly be very weak, since they lack charge and mass and are not influenced by the electromagnetic force. In fact, the cross
sections for these weak force interactions are about 20 orders of magnitude smaller than a
typical nuclear reaction [Rol38]. Now the experimenter is left with the challenge of detecting
these particles in order to better understand them.

The sun produces vast quantities of neutrinos as it burns hydrogen in the $p$-$p$ chain
(see section 1.2.1). Billions of these “solar neutrinos” arrive at the Earth’s surface every
second and there are many experiments that aim to measure this flux. The first of these
has been performed in the Homestake gold mine, in South Dakota. Davis [Dav68] and his
colleagues have measured this flux to be $2.1 \pm 0.3$ SNU (Solar Neutrino Unit, defined as
$10^{-36}$ reactions per target atom per second). Theoretical calculations based on the standard
solar model [Bah82] predict a value of $5.8 \pm 2.2$ SNU. This huge discrepancy is the Solar
Neutrino Problem.

As will be explained later in this chapter, the key reaction producing the neutrinos
detected in the Homestake experiment is $^7\text{Be}(p,\gamma)^8\text{B}$. Any knowledge of the mechanisms for
this reaction would be most useful in unraveling this puzzle. Direct measurements of this
reaction are very difficult for several reasons which will be discussed in Chapter 5. However,
the reaction $^7\text{Li}(p,\gamma)^8\text{Be}^*$ is quite similar (see section 1.5 for an explanation). Therefore
we have undertaken an extensive study of this reaction, the details of which are presented
in this dissertation.

1.2 Nuclear Astrophysics

The field of nuclear astrophysics has received considerable attention by the physics
community recently. One reason for this is the unexplained solar neutrino problem, men-
tioned at the beginning of this chapter and to be discussed in more detail below. If the solar
neutrino problem is confirmed in future experiments, new neutrino physics is implied and
perhaps an alteration to the accepted model of the sun. In order to study these astrophysi-
cal questions, nuclear astrophysicist use the techniques of nuclear physics. One central part
of this is to measure the rates (or cross sections) for the reactions occurring in the stars.
CHAPTER 1. INTRODUCTION

<table>
<thead>
<tr>
<th>The p-p Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>p + p → d + e^+ + ν (99.75%)</td>
</tr>
<tr>
<td>p + p + e^- → d + ν (0.25%)</td>
</tr>
<tr>
<td>p + d → ^3He + γ</td>
</tr>
<tr>
<td>^3He + ^3He → ^4He + 2p (86%)</td>
</tr>
<tr>
<td>^3He + ^4He → ^7Be + γ (14%)</td>
</tr>
<tr>
<td>^7Be + e^- → ^7Li + ν (99.89%)</td>
</tr>
<tr>
<td>p + ^7Li → ^4He + ^4He</td>
</tr>
<tr>
<td>^7Be + p → ^8B + γ (0.11%)</td>
</tr>
<tr>
<td>^8B → ^8Be + e^+ + ν</td>
</tr>
<tr>
<td>^8Be → ^4He + ^4He</td>
</tr>
</tbody>
</table>

Table 1.1: Nuclear fusion reactions in the sun (up to ^8B). The branching ratios have been calculated using the standard solar model [Bah90].

1.2.1 The P-P Chain

All the main-sequence stars in the Universe are believed to produce energy by nuclear fusion. These stars undergo hydrogen burning, where four protons are used to create a ^4He nucleus and a release of energy:

\[ 4p \rightarrow ^4He + 2e^+ + 2\nu + 26.73 \text{ MeV}. \] (1.3)

This is a very simplified version of what occurs. The entire process is known as the p-p chain and is thought to provide more than 98 percent of the sun’s energy [Bah90]. The reactions are displayed in Table 1.1. These reactions are of great interest and much work has been performed from both the theoretical and experimental side towards understanding them.
1.2.2 Appropriate Energy Regime

It is important to examine what the appropriate energy regime is for the reactions which fuel the stars. Let us first consider the fusion of two protons in a typical star: the sun. From a classical point of view, the two protons would require a relative kinetic energy of 550 keV to overcome the Coulomb barrier. If we consider the sun to be a sphere of hot gas (mostly hydrogen), where the particles obey simple thermodynamical properties (i.e. the Maxwell-Boltzmann distribution), we would expect the energy distribution to be characterized by the temperature \( T \) and to peak at \( E = kT \). The energy listed above would imply a stellar temperature \( (E = kT) \) of 6 billion Kelvin. However, from surface studies of the sun the core temperature is known to be about 15 million Kelvin. Obviously nuclear fusion in the sun is classically impossible.

This conundrum is solved with knowledge of quantum physics. Gamow [Gam28] and independently Gurney and Condon [Gur29] showed that it is possible for a particle to penetrate a potential barrier greater than its kinetic energy. In our case, the proton must tunnel through the Coulomb barrier. The probability for this is derived by solving the Schrödinger equation for the Coulomb potential, and is [Rol88]:

\[
P = \exp(-2\pi \eta) \]

\[
E \ll E_{\text{Coul}}, \quad l = 0
\]  \hspace{1cm} (1.4)

where \( \eta \) is the Sommerfeld parameter, defined as

\[
\eta = \frac{Z_1 Z_2 e^2}{\hbar v}.
\]  \hspace{1cm} (1.5)

Here \( Z_1 \) and \( Z_2 \) are the charges of the interacting particles and \( v \) is their relative velocity. It is convenient to note that \( \eta \) may be written in terms of the reduced mass \( \mu \) (in amu) and the center of mass energy \( E_{\text{cm}} \) (in keV) as follows:

\[
\eta = \frac{1}{2\pi} (31.29) Z_1 Z_2 \sqrt{\frac{\mu}{E_{\text{cm}}}}.
\]  \hspace{1cm} (1.6)
Figure 1.1: The dominant energy dependent functions for a charged particle nuclear reaction are shown. These are the Maxwell-Boltzmann distribution and the quantum mechanical tunneling through the Coulomb barrier. Each one is small in their mutual overlap region, however when both are accounted for, the result is a peak at $E_0$, the Gamow Energy.

Convoluting this tunneling probability with the Maxwell-Boltzmann distribution (discussed above) shifts this statistical energy distribution of gases to an energy somewhat greater than $kT$, referred to as the Gamow peak. Numerically this peak is

$$E_0 = 1.22(Z_1^2 Z_2^2 \mu T_0^3)^{1/3} \text{ keV},$$

where $T_0$ is measured in millions of degrees Kelvin. Figure 1.1 displays the dominant energy-dependent functions and the Gamow peak for a general charged particle nuclear reaction. A more detailed discussion of this may be found in [Rol88].

Listed below are the values of this effective mean temperature of nuclear fusion for
various reactions:

\[ p + p : \quad E_0 = 5.9 \text{ keV} \]
\[ p + ^7\text{Li} : \quad E_0 = 14.8 \text{ keV} \]
\[ p + ^7\text{Be} : \quad E_0 = 17.9 \text{ keV} \]

As you can see, the energies of interest are quite low. Because of the rapidly decreasing cross sections, it is experimentally impossible to perform measurements at these energies. For example, the total cross section for the \(^7\text{Be}(p,\gamma)^8\text{B}\) reaction at 18 keV [Fil83b] is expected to be approximately 1 femto-barn. Under the experimental conditions presented in Chapter 2, a crude measurement (observation of 100 \(\gamma\) rays) would require taking data for 2000 years! Therefore, the general technique employed is to use data from multiple energies (the lower the better) and then extrapolate to zero energy. For a more reliable extrapolation, a quantity that accounts for only the strictly nuclear effects is introduced.

1.2.3 The Astrophysical \(S\)-Factor

To perform these extrapolations we rewrite the cross section in a form that takes out all the known non-nuclear energy dependences. We have already discussed the low energy Coulomb tunneling probability in equation 1.4. We can also argue that the cross section will depend upon the classical "geometrical area", \(\pi(r_1 + r_2)^2\). In quantum mechanics this would be \(\sigma \propto \pi \lambda^2\), where \(\lambda\) is the de Broglie wavelength. Since \(E \propto 1/\lambda^2\), we expect the cross section to vary as \(E^{-1}\). Thus we write:

\[
\sigma(E_{\text{cm}}) = \frac{S(E_{\text{cm}}) e^{-2\pi\eta}}{E_{\text{cm}}},
\]

(1.8)

where \(S\) is defined as the astrophysical \(S\)-factor. We would now expect the astrophysical \(S\)-factor to vary much more slowly with energy than the cross section, perhaps even linearly, at least in the absence of any resonant structure. In fact, for a capture reaction which proceeds only by "s-wave" capture, the value of \(S(E)\) would be a constant. In the following
Neutrino Fluxes

<table>
<thead>
<tr>
<th>Source Reaction</th>
<th>Energy (MeV)</th>
<th>Flux at Earth (cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + p \rightarrow d + e^+ + \nu$</td>
<td>$\leq 0.42$</td>
<td>$6.1 \times 10^{10}$</td>
</tr>
<tr>
<td>$p + p + e^- \rightarrow d + \nu$</td>
<td>$1.44$</td>
<td>$1.5 \times 10^{8}$</td>
</tr>
<tr>
<td>$^7$Be + e$^-$ → $^7$Li + $\nu$</td>
<td>$0.86$ (90%)</td>
<td>$3.9 \times 10^{9}$</td>
</tr>
<tr>
<td>$^8$B → $^8$Be + $e^+$ + $\nu$</td>
<td>$0.38$ (10%)</td>
<td>$4.0 \times 10^{8}$</td>
</tr>
<tr>
<td>$^8$B → $^8$Be + $e^+$ + $\nu$</td>
<td>$\leq 14.1$</td>
<td>$5.6 \times 10^{6}$</td>
</tr>
</tbody>
</table>

Table 1.2: Solar neutrino sources, energies, and fluxes from the $p$-$p$ chain

Chapters we will discuss the cross section and astrophysical $S$-factor for various reactions. Note that measuring the cross section (at a particular energy) is equivalent to measuring the astrophysical $S$-factor at that energy, and so quite often the terms are used interchangeably.

1.3 The Solar Neutrino Problem

Since the remnants from the thermonuclear reactions occurring in the sun (see the $p$-$p$ chain in Table 1.1) are all trapped inside except for the neutrinos, our only direct knowledge of the sun's core will come from the measurement of these neutrinos. They are produced by a number of weak interactions ($\beta$-decays and electron capture). The expected fluxes and energies of these have been calculated [Bah82, Rol88] and are shown in Table 1.2.

The first experimental observation of the neutrino was performed in the 1950's by Reines and Cowan [Rei60] by monitoring a tank of cadmium chloride with scintillating liquid placed near a nuclear reactor. Reines was awarded the Nobel Prize in 1955 partly for this groundbreaking work. Since 1965, a large scale effort has been underway to measure the flux of neutrinos produced in the sun. Ray Davis and collaborators have constructed a large vessel containing 100,000 gallons of percloroethylene. It is placed deep down in the Homestake Gold Mine in South Dakota in order to shield it from cosmic radiation. This
neutrino observatory works by monitoring the reaction:

\[ {^{37}}Cl + \nu \rightarrow {^{37}}Ar + e^- \] \hspace{1cm} (1.9)

Unfortunately, this reaction is only sensitive to the higher energy neutrinos and can not detect the more plentiful p+p neutrinos. Most of the neutrinos detected will have been created by the decay of \(^{8}\)B nuclei which were in turn created by the \(^7\)Be\((p,\gamma)^{8}\)B reaction.

According to calculations using the Standard Solar Model [Bah82, Bah90], a rate of 5.8\(\pm\)2.2 SNU (recall that SNU stands for Solar Neutrino Unit and was defined in section 1.1) is expected for the number of solar neutrino events measured using the detector described above. The group led by Davis has observed an average of 1 event every 3 days. After careful subtraction of background events this equates to 2.1 \(\pm\) 0.3 SNU, a factor of 3 lower than the number predicted! This discrepancy is the Solar Neutrino Problem.

This anomaly has stirred up an interest in measuring solar neutrinos. Many new experiments are underway, including SAGE, GALLEX, Super Kamiokande, SNO and more. These projects involve large numbers of physicists from many countries and constitute an entirely new branch of physics: neutrino physics. Of greatest importance is to detect solar neutrinos, in hopes of better understanding the conditions inside the sun and testing current astrophysical theories, including ones which explain the solar neutrino problem. One of many such theories [Mik85, Wol78], referred to as neutrino oscillations or the MSW (Mikheyev-Smirnov-Wolfenstein) effect, suggests that during their 8 minute flight from the sun, the electron neutrinos transform into mu and tau neutrinos. On the other side of the coin, a better understanding of the reactions occurring in the p-p chain (and specifically the \(^7\)Be\((p,\gamma)^{8}\)B reaction) might shed some light on this problem. It is this approach that our group has pursued.
CHAPTER 1. INTRODUCTION

1.4 Low Energy Nuclear Physics

Many significant advances in Nuclear Physics have come from the study of low energy (below a few hundred keV) capture reactions [Wel96b]. Despite this fact, there is very little data available to test the models of these reactions at energies close to those relevant to astrophysics. Some of the available work include studies performed by Griffiths [Gri63], Zahnow [Zah95a, Zah95b], and Cecil [Cec92]. One major assumption in the latter work is that reactions at these energies will proceed by s-wave capture only. In addition, a simple s-wave only, direct capture model has been used to extrapolate astrophysical S-factors from a few hundred keV down to zero keV.

Recent advances in experimental and theoretical techniques have led to more detailed studies of low energy reactions [Wel96b]. On the experimental front, advances in ion sources have given the experimentalist very intense beams. Also, it is now possible to obtain large Germanium detectors which are very efficient and have excellent energy resolution. Some of the recently published work in this field includes the research of Kramer [Kra93] and of Schmid [Sch95a]. The former study shows evidence for p-wave capture in the $^2\text{H}(d,\gamma)^4\text{He}$ reaction while the latter has led to a significant reduction in the $^2\text{H}(p,\gamma)^3\text{He}$ astrophysical S-factor.

One of the most important and surprising finding comes from the work of Chasteler et al. [Cha94]. In this work the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction was studied using polarized protons. Large analyzing powers ($\approx 40\%$) and an anisotropic cross section ($\approx 30\%$) were reported. The authors note that this implies significant p-wave capture strength, of 18% to 95%, and could imply a reduction in the astrophysical S-factor by 7% to 38%. Besides these startling results, the most important result of this paper is the possible implication on the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. As Chasteler points out, since the ground state of $^8\text{B}$ is largely a $p_{3/2}$ proton single particle (as is the ground state of $^8\text{Be}$), p-wave capture strength might be expected in this reaction as well. However, it would be most intriguing to study proton capture to the third and fourth excited states of $^8\text{Be}$ since these states have spin-parity of
2\(^+\) as does the ground state of \(^8\)B. To understand the similarities of these two reactions in more detail, let us examine the A=8 isobar diagram.

1.5 The A=8 Isobar Diagram

Figure 1.2 shows a portion of the A=8 isobar diagram, taken from [AS88]. As the figure shows, the third and fourth excited states of \(^8\)Be are at 16.626 and 16.922 MeV and the Q value for the \(^7\)Li\((p,\gamma)\)\(^8\)Be reaction is 17.254 MeV. Recall that in our experiments, we use a polarized proton beam with an energy of 80 keV. Therefore the \(\gamma\) rays corresponding to capture to the third and fourth excited states of \(^8\)Be (at \(\theta = 90^\circ\)) will have energies of 698 and 402 keV, respectively. These states have been previously studied [Mar66], and are determined to be completely isospin-mixed (\(T=0+1\)). The 16.6 MeV state is essentially a pure proton single particle whereas the 16.9 MeV state is a neutron single particle:

\[
\begin{align*}
\ ^8\text{Be}^*(16.62) & : \ ^7\text{Li}(g.s.) + p, \ J^\pi = 2^+, \ T = 0 + 1 \\
\ ^8\text{Be}^*(16.92) & : \ ^7\text{Li}(g.s.) + n, \ J^\pi = 2^+, \ T = 0 + 1.
\end{align*}
\] (1.10)

Thus it is expected (and indeed confirmed in this dissertation) that the 16.6 MeV state will be much more dominant than the 16.9 MeV state in proton capture reactions.

As Figure 1.2 shows, both the third and fourth excited states of \(^8\)Be have spin-parity equal to 2\(^+\), as does the ground state of \(^8\)B. In fact, the T=1 component of these states is collectively the isospin analog of the \(^8\)B ground state and must have the same space-spin wave function. Additionally, the energies of the \(\gamma\) rays from the \(^7\)Li\((p,\gamma)\)\(^8\)Be and \(^7\)Be\((p,\gamma)\)\(^8\)B reactions are quite similar (approximately 700 and 200 keV, respectively, for a proton beam of energy \(E_p=80\) keV), much more so than the \(^7\)Li\((p,\gamma)\)\(^8\)Be reaction (which yields 17.3 MeV \(\gamma\) rays). Because of these reasons, we expect the \(^7\)Li\((p,\gamma)\)\(^8\)Be and \(^7\)Be\((p,\gamma)\)\(^8\)B reactions to be rather closely related. Of course the isospin mixing, isospin selection rules, and Coulomb forces will complicate any comparisons.
Figure 1.2: A portion of the A=8 isobar diagram taken from [AS88] displaying the p + ^7Li entrance channel and the states of interest in this study.
1.6 Literature Review and Recent Relevant Work

Some of the theoretical and experimental studies related to the work presented in this dissertation have been discussed, but it is convenient to review all of them here. For a more thorough evaluation the reader is referred to the data compilation work of Fay Ajzenberg-Selove [AS88], and it is noted that many of the $^8\text{Be}$ properties are taken from this reference.

1.6.1 The ground state and first excited state

The $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction has received considerable attention from experimentalist and theorists alike. In 1960 Mainsbridge [Mai60] published angular distributions for capture to the (resolved) ground state and (unresolved) first excited state over the energy range $E_p=200$–1100 keV. In addition Mainsbridge identifies two $1^+$ resonances at proton energies of 441 and 1030 keV. Using polarized protons, Ulbricht et al. [Ulb77] have studied the analyzing power for capture to the ground state of $^8\text{Be}$. A more recent low-energy study has been performed [Cec92], using $\gamma$-ray to charged-particle branching ratios. Proton bombarding energies between 40 and 180 keV were used to evaluate the angular distribution and absolute cross section for both the ground and first excited state. In Cecil's paper a determination of the astrophysical $S$-factor (at zero energy) was made by extrapolation assuming a pure E1, s-wave direct capture mechanism. We will see shortly that recent evidence suggests otherwise.

1.6.2 The third and fourth excited states

As shown in Figure 1.2 both the third and fourth excited states have spin-parity of $2^+$ and are at 16.62 and 16.92 MeV respectively. The work of Marion and Wilson [Mar66] established the single-particle nature of these states and showed that this fact precludes their description as eigenstates of total isobaric spin. Continuing this study, Marion [Mar67] reports the widths of these isospin mixed states, and Sweeney and Marion [Swe69] report
cross sections for proton capture to these states over the energy range $E_p=0.441-2.45$ MeV. They conclude that the best representation of the third and fourth excited state is

$$
\begin{align*}
|16.63\rangle &= 0.772 \ |T = 0\rangle + 0.636 \ |T = 1\rangle, \\
|16.92\rangle &= 0.636 \ |T = 0\rangle - 0.772 \ |T = 1\rangle.
\end{align*}
$$

Therefore the third excited state wave function consists of 59% $T = 0$ and 41% $T = 1$, and just the opposite for the fourth excited state.

1.6.3 Recent work

In section 1.4 a recent study by Chasteler et al. [Cha94] of the $^7\text{Li}(\vec{p},\gamma)^8\text{Be}$ reaction at $E_p=80-0$ keV is mentioned. The authors of that work reported large analyzing powers ($\approx 40\%$) at $90^\circ$ and an anisotropic cross section ($\approx 30\%$). This data suggests the presence of $p$-wave capture (a strength of 18–95%) at low energies, contrary to the findings of Cecil et al. [Cha94], who assumed a pure $s$-wave direct capture mechanism. These authors argued that the presence of $p$-waves in the $^7\text{Li}(\vec{p},\gamma)^8\text{Be}$ reaction could imply the same in the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, and thereby bringing into question the extrapolation of the astrophysical $S$-factor to zero energy based on pure $s$-wave direct capture model. This paper has spurred a series of reports: (see [Rol94], [Wei95], [Bar95], [Zah95a], [God96], [Hah96], [Bar96], [Cso96], and [Bla96]). Note that the data are not under suspicion since the anisotropic cross section has been confirmed by Hahn et al. [Hah96], and the analyzing powers by Godwin et al. [God96].

In the work of Chasteler et al. an unconstrained fit to the data produced four distinct solutions. When all $s$-wave $E1$ and $p$-wave $M1$ transitions are allowed, the fit with the smallest amount of $M1$ strength which was able to fit the data amounted to about 50% of the cross section. If only the $p_{1/2}$ capture term is used, a solution is found which consists of 29% $M1$. Rolfs and Kavanagh [Rol94] argue that the low-energy tail of the $M1$ resonance at 441 keV (proton energy) provides sufficient strength to account for the asymmetry of the
CHAPTER 1. INTRODUCTION

cross section data presented in [Cha94]. However, Weller and Chasteler [We95] point out that this conclusion does not consider the analyzing power data. When these data and the cross section data are both accounted for, the 2% p-wave contribution reported by [Rol94] is shown to be at least an order of magnitude too low.

Fred Barker [Bar95] has performed detailed R-Matrix fits to the data presented in [Cha94]. In this work he considers the tails of the two 1+ resonances at 441 and 1030 keV to be the sole source of p-wave strength at low energies. The best fit to the data contained 9.2% M1 strength, although this result requires that the two levels constructively interfere at 80 keV, which was achieved by reversing the sign of the 1030 keV resonance with respect to the 441 keV resonance. Both the shell model and fits to higher energy data imply otherwise. This paper also criticizes the conclusions of [Cha94] in regards to the relationship between the \(^7\text{Li}(p,\gamma_0)^8\text{Be}\) reaction and the \(^7\text{Be}(p,\gamma)^8\text{B}\) reaction, since the former leads to a \(J^\pi=0^+\), \(T=0\) state and the latter a \(J^\pi=2^+\), \(T=1\) state and because of the vastly different \(\gamma\)-ray energies (17.3 MeV and 140 keV, respectively).

At about the same time a new set of data was published by Zahnow et al. [Zah95a]. Data for proton capture to the ground state and (unresolved) ground plus first excited state of \(^8\text{Be}\) are presented for the energy range \(E_p=100\text{–}1500\) keV. Astrophysical S-factor values and forward-backward anisotropies are given. These authors used a direct capture model and added the two well known 1+ resonances. The data were fit quite well, and the data for the angular distribution of the cross section from [Cha94] also agrees with their calculations. However, no attempt to account for the analyzing power is made.

Continuing the study of the \(^7\text{Li}(p,\gamma)^8\text{Be}\) reaction Godwin et al. [God96] have examined capture to the ground state. Much of those results are presented in this dissertation. Here the authors present a chi-squared plot as a function of M1%, which shows a broad minimum at 50% and 2 local minima above 80%. In addition, capture to the third excited state of \(^8\text{Be}\) is studied. This reaction is much more closely related to the \(^7\text{Be}(p,\gamma)^8\text{B}\) reaction than is the \(^7\text{Li}(p,\gamma_0)^8\text{Be}\) reaction as explained previously (section 1.5). An isotropic
cross section and analyzing powers consistent with zero have led the authors to conclude that this reaction proceeds by essentially pure s-wave (E1) or pure p-wave (M1) capture.

In a recently submitted paper [Bar96] Barker attempts to account for the data of Zahnow et al. [Zah95a] and Chasteler et al. [Cha94] simultaneously. The M1 strength is taken to arise from the two 1+ levels (mentioned previously). The E1 strength is assumed to come from either s-wave direct capture, or (in the R-matrix two-level approximation) from the tails of two 1− states. One of these states is the giant dipole resonance and the other “represents an actual 1−, T = 1 level, or an isospin mixed T = 0 level, or more generally some background contribution” [Bar96]. Contrary to his earlier work [Bar95], these recent fits (using an R-matrix approach and an E1 direct capture calculation) have signs in agreement with shell model calculations (constructive interference between the two levels at 80 keV). Here the level parameters are the fitting parameters, rather than the transition matrix element. However, even these solutions appear to have some problems. The R-matrix fit does agree with the 80 keV analyzing power data, but under-predicts the cross section at and below 200 keV, at least as measured by [Zah95a]. On the other hand, the direct capture calculation, although fitting the low-energy cross section data, under-predicts the analyzing power. In fact, the b1 analyzing power coefficient (see section 4.3 for a detailed discussion of these coefficients) at 80 keV is almost a factor of 2 lower than the experimentally measured value of Chasteler et al. [Cha94].

A discussion of these results will be presented in Chapter 6, where the conclusions concerning the data obtained for this dissertation are drawn.

1.7 Scope and Goals of this Experiment

This experiment will examine polarized and unpolarized proton radiative capture to the ground, first, and third excited state of 8Be. We will study the analyzing power and cross section as a function of angle for these transitions at energies of E_p = 80–0 keV. The main goals of this experiment are as follows:
1. To study the $^7\text{Li}(p,\gamma_0)^8\text{Be}$ reaction and quantify how the observed M1 radiation affects the astrophysical $S$-factor and to extract a more reliable value for the $S$-factor of this reaction.

2. To determine what role M1 radiation (i.e. $p$-wave capture) plays in the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ reaction.

3. Based on the analysis of the above, to attempt to draw conclusions regarding the likelihood of $p$-wave effects in the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, and to estimate their possible impact on the $S$-factor for this reaction.

A detailed Transition Matrix Element (TME) analysis will be used to unravel the contributing multipole components. Direct Capture (DC) calculations will be presented and used to predict the measured observables. Also, a determination of the astrophysical $S$-factor will be performed.

The following chapters will present and thoroughly explain all aspects of the $^7\text{Li}(p,\gamma)^8\text{Be}$ experiment. In Chapter 2 the details of the experimental set-up, detectors, electronics, and computer algorithms used will be explained. Following this we will demonstrate how the data were analyzed (Chapter 3) and then present the experimental results (Chapter 4). Chapter 4 will also include an explanation of a transition matrix element (TME) analysis and the results of this analysis. Extensive direct capture plus M1 resonances calculations are described, displayed and discussed in Chapter 5. Lastly, in Chapter 6 the results are tied together. Here we will summarize the conclusions drawn from our study of the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction and discuss the implications of these results for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction.
Chapter 2

Experimental Techniques and Equipment

2.1 Introduction

The data presented in this dissertation were obtained at the Triangle Universities Nuclear Laboratory (TUNL) on the campus of Duke University in Durham, North Carolina. We have used the Atomic Beam Polarized Ion Source (ABPIS) to produce a beam of positively charged hydrogen ions with the nuclear spins polarized. In this chapter, the experimental equipment and techniques will be presented. Included will be a description of the polarization procedures and formalism (section 2.2), the necessary equipment and targets (section 2.3), the various detectors used for obtaining data (section 2.4), and the data acquisition procedures (section 2.5).

2.2 Polarization

The nucleus of an atom is known to have an intrinsic angular momentum, called spin. Under normal conditions the spin is oriented in a random direction. However, using
a collection of particles (a beam or a target) whose spins are polarized can prove to be quite advantageous when performing nuclear physics experiments. The reason for this is that the observables measured using a "polarized" beam or target are very sensitive to interference effects. The general convention for indicating a polarized beam or target is the use of an arrow or vector placed over the particle. For example, a reaction of the form \( A(\vec{p}, \gamma) D \) indicates the use of a polarized beam of protons. Much of the data presented in this dissertation were obtained using polarized proton beams.

### 2.2.1 Formalism

The discussion and description of polarized beams requires a defined coordinate system. In this work we follow the system known as the Madison convention [Bar71] where the positive \( z \) axis is defined by \( \vec{k}_{\text{in}} \), and the positive \( y \) axis is given by \( \vec{k}_{\text{in}} \times \vec{k}_{\text{out}} \). In this system the \( z \) axis will be the beam direction and the \( xz \) plane will contain the target and the detector. Thus the polarization vector \( \zeta \) can be described by the angles \( \beta \) and \( \phi \). This is clearly shown in Figure 2.1.

In this work, we will be discussing polarized protons, which are spin \( 1/2 \) particles. In this case, the spin is represented by a rank 1 tensor, in either spherical or Cartesian coordinates. In the latter system, we have

\[
p_i = \langle S_i \rangle, \tag{2.1}
\]

where \( i = x, y, z \). Here \( \langle S_i \rangle \) are the expectation values of the spin operators and \( p_i \) is referred to as the vector polarization.

To define the axis of symmetry \( \zeta \) for a polarized beam, a uniform magnetic field is applied. For the ABPIS used in these experiments (see section 2.2.3) this is the \( +z \) axis. The polarization state of a beam of particles is then described by an incoherent sum of particles whose spins are parallel and antiparallel to this axis, representing protons with magnetic substates \( m_j = +1 \) and \( m_j = -1 \), respectively. Defining \( f_+ \) and \( f_- \) be the fraction

\[
f_+ + f_- = 1
\]
of particles with $m_j = +1$ and $m_j = -1$, the beam moment $p_z$ can be written as:

$$p_z = (f_+) - (f_-)$$

where $(f_+) + (f_-) = 1$. \hfill (2.2)

### 2.2.2 Polarized Cross Sections and Analyzing Powers

Some of the observables that may be measured with these beams are the analyzing power and the polarized cross section. The polarized cross section is defined in terms of the unpolarized cross section by the formula

$$\sigma_p(\theta) = \sigma_u(\theta)[1 + \bar{P}_z \cdot \bar{A}(\theta)], \hfill (2.3)$$

where $\bar{P}_z$ is the beam polarization and $\bar{A}(\theta)$ is the analyzing power. For the experiments performed with polarized beams, the polarization quantization axis was rotated to the $y$
axis. Therefore, the vector beam moment is \( p_y \) and we have

\[
\sigma_p(\theta) = \sigma_v(\theta)[1 + p_y A_y(\theta)].
\]  

(2.4)

The analyzing power describes how sensitive the reaction's cross section is to the polarization and is defined as

\[
A_y(\theta) = \frac{1}{p_y} \frac{\sigma^+(\theta) - \sigma^-(\theta)}{\sigma^+(\theta) + \sigma^-(\theta)},
\]  

(2.5)

where \( \sigma^+(\theta) \) and \( \sigma^-(\theta) \) indicate the cross section measured for spins oriented "up" and "down" (\( \pm \gamma \)), respectively.

### 2.2.3 Polarized Beams and the ABPIS

The beams of polarized protons were produced using the ABPIS of TUNL. Figure 2.2 shows a schematic drawing of the source. A brief description of the procedure follows, but the reader is referred to the papers of Clegg et al. [Cle90, Cle95a, Cle95b, Din95] for a more thorough discussion.

By using hydrogen or deuterium gas the ABPIS can produce beams of vector polarized protons or beams of vector and tensor polarized deuterons. The procedure is quite similar, but let us consider polarized proton beams. Pure hydrogen gas (H\(_2\)) is introduced
into the dissociator chamber where an RF discharge breaks the hydrogen molecular bonds. The atomic hydrogen next diffuses into a high vacuum chamber through a copper cold nozzle, cryogenically cooled to 35K to retard recombination of the atoms. Additionally, nitrogen gas is allowed to flow continuously through the "cold head" to reduce molecular recombination.

Next the atomic hydrogen beam enters the polarization region. Here two Stern-Gerlach type sextupole magnets are used to create a magnetic field. This separates the substates of atomic hydrogen into four different energy levels, shown in Figure 2.3. The sextupole magnets defocus two of these states (those with \( m_j = -\frac{1}{2} \)), focus the other two (\( m_j = +\frac{1}{2} \)) and thus creates a polarized atomic beam. Nuclear polarization is achieved by selecting one of the two rf transition units, SF2 and MF2, which cause a transition from state 2 to 4 and 1 to 3, respectively. The end result is a beam of protons with nuclear spin oriented in the \( m_I = +\frac{1}{2} \) or \(-\frac{1}{2} \) (SF2 or MF2) direction.

Following the polarization, the electrons of the beam are stripped off; that is, the beam is ionized. The ABPIS uses an electron-cyclotron-resonance (ECR) ionizer cavity to accomplish this task. We are left with a beam of positively charged polarized protons, whose polarization is given by

\[
p_x = \frac{N^+ - N^-}{N^+ + N^-},
\]

where \( N^+ \) (\( N^- \)) indicates the fraction of protons with spins \( m_I = +\frac{1}{2} \) (\( m_I = -\frac{1}{2} \)). After the ionizer, a series of electrostatic lenses are used to focus the beam. If desired, the beam can be negatively charged by allowing it to pass through the cesium oven, where the beam will pick up electrons via charge exchange collisions with cesium vapor. This procedure is necessary in order to accelerate the beam through the tandem Van de Graaff accelerator, and will be discussed further in section 2.2.4.

The final step is to orient the polarized beam such that it arrives at the target with its spin pointing in the desired direction (\( \pm \vec{y} \) for this experiment). The Wien Filter spin precessor accomplishes this task by applying a magnetic field (to rotate the spin) and a
Figure 2.3: Energy level diagram for the hydrogen atom showing the hyperfine splitting as a function of the applied magnetic field.

crossed electric field (to compensate for the deflection of the beam). In order to determine the magnetic field setting and orientation (so called mechanical angle) for the Wien Filter, the fortran codes PRECESS_LE and PRECESS_HE were used. These codes determine the appropriate settings necessary in order for a beam of protons or deuterons to arrive at a specific target area in the laboratory in a user specified orientation by accounting for the precession of the particle’s spin as it passes through the various bending magnets. In general, different setting are needed for beams at low (80 keV) and high (6.18 MeV) energies. Since the polarization can be measured at both energies (see section 2.2.4 and references [Pri95] and [Wil93]) the settings for the Wien Filter may be verified. In this experiment, proton spins oriented in the \( \pm \vec{y} \) direction were desired. Note that the bending magnets do not have any effect here since the magnetic moment and magnetic field vectors (\( \vec{\mu} \) and \( \vec{B} \)) are
parallel and thus the torque \((\vec{\mu} \times \vec{B})\) will be zero.

Last, a series of acceleration sections before and after the Wien Filter accelerates the beam to an operator set value (up to a maximum energy of 80 keV). All of the experiments presented in this dissertation used an 80 keV proton beam.

2.2.4 Accelerating the Beam and Measuring Polarization

At the beginning of an experiment the beam polarization needs to be maximized. The most accurate way to achieve this requires accelerating the beam to higher energies. Therefore we changed the beam from a positive to a negative ion state and accelerated it through the TUNL FN tandem Van de Graaff accelerator to an energy of 6.18 MeV. This accelerator operates by applying a large, positive potential to the central terminal. The negative beam is accelerated toward the center where it encounters a thin carbon foil, which strips the electrons off the atom. The beam is now positively charged and accelerated again (thus the name “tandem”).

The beam is then focused into the proton polarimeter [Wil93] which is used to measure the beam polarization. This polarimeter consists of a thin carbon target \((\approx 5\mu g/cm^2)\) and two surface barrier detectors placed symmetrically about the beam axis at ±40°. To measure the polarization, we use the \(^{12}\text{C}(\vec{p},\vec{p})^{12}\text{C}\) reaction and determine the left-right asymmetry of the elastically scattered protons, where

\[
asym = \frac{N_L - N_R}{N_L + N_R}.
\]  

(2.7)

In this equation \(N_L(N_R)\) refer to the number of particles detected in the left (right) detectors. The electronics used for this task are shown in Figure 2.4. Since the analyzing powers are large and well known for a variety of energies and scattering angles [Mos65, Ter68], we may determine the polarization. This is given as:

\[
p = \frac{\asym}{A_y}.
\]  

(2.8)
Figure 2.4: Schematic diagram displaying the electronics used for the proton polarimeter.

When on target, the beam's polarization could be tuned (by changing the magnetic field settings in the transition units) and measured within a few minutes. Typical values for the polarization were \( \approx 60-70\% \), with errors of \( \approx 2\% \). After this was accomplished the ion source would be switched back to positive beam and the beam directed toward the LE CAL target chamber. We monitored the polarization during the experiment by using the established analyzing power values for the \( ^7\text{Li}(p,\gamma)^8\text{Be} \) reaction [Cha94, Pri95]. Occasionally during a run, and always at the end of an experiment, we would remeasure the polarization using the high energy method described above.

## 2.3 Experimental Equipment

### 2.3.1 Acceleration and Transport

The positive ion beam produced from the ABPIS was accelerated through an 80 kV potential difference. It was then deflected by 60° into the LE CAL beam line. This beam line
and the important components are shown in Figure 2.5. The various dipole and quadrupole magnets were used to steer and focus the beam into the chamber and onto our targets. Typically, beams of \( \approx 20 - 25 \mu \text{A} \) on target were obtained.

### 2.3.2 Lithium Target

The \(^7\text{Li} \) targets used in this experiment were produced by evaporating lithium metal. The metal used was isotopically enriched to 99.99%. Although the target thickness was not determined, it is estimated to be \( \approx 500 \mu \text{g/cm}^2 \). This is thick enough to stop protons with an energy much greater than 80 keV. Thus it is noted that the data presented in this dissertation represents integrated \( \gamma \)-ray yields from proton energies of 80 to 0 keV! The data presented for the analyzing power and angular distribution of the cross section required lithium to be evaporated onto a very thin (0.00005 inches) Ni foil purchased from Chromium Corporation. For the absolute cross section data, lithium was evaporated onto a homemade aluminum disc of thickness 0.0625 inches. In both cases the targets were transferred from evaporator to target chamber in an Argon atmosphere.

### 2.3.3 Target Chamber

A schematic diagram of the target chamber used in the analyzing power and angular distribution of the cross section experiments is shown in Figure 2.6 and Figure 2.7. Figure 2.6 shows the experimental set-up with the High Purity Germanium (HPGe) \( \gamma \)-ray detector (to be discussed in section 2.4) at 90°, and Figure 2.7 is a close up side-view of the target chamber. Shown here is our evaporated lithium target clamped between two copper square frames and a plastic scintillator placed directly in back of the target. As will be shown in Chapter 3, measuring the ground state and first excited state \( \gamma \) rays was straightforward. However, the third excited state was a bit more subtle. The low energy of this \( \gamma \) ray (\( \approx 700 \) keV) implies a large background and, along with the large width of the state (\( \approx 110 \) keV), proves too difficult for a “singles” measurement. After capture to
Figure 2.5: The low energy capture (LECAL) beam transport facility.
the third excited state of $^8$Be, the nucleus decays essentially 100% of the time by forming two energetic alpha particles, each with over 8 MeV of kinetic energy. If we can detect one of these alpha particles, then a coincidence between it and a $\gamma$ ray might provide a clean signal.

To accomplish this coincidence measurement a plastic scintillator was used in back of the target to detect alpha particles. It was wrapped with aluminized mylar to keep out background light, since a beam of 25$\mu$A striking the target causes it to fluoresce. The scintillator was manufactured by Bicron (Newbury, Ohio), from BC-412 plastic and cut to be 2" wide, 2.75" long, and 0.125" thick. The incident protons are stopped in the target. The two alpha particles will be traveling in opposite directions (exactly 180° in the center.
Figure 2.7: A close up view of the target chamber used for the $^7$Li($p$,γ)$^8$Be experiment. Notice that the plastic scintillator (used for detecting alpha particles) is placed directly in back of a very thin Ni foil, which has lithium metal evaporated onto it.
of mass frame, approximately 180° in the lab frame), and so one will be directed towards the plastic scintillator. It will lose energy in the target, Ni foil, and aluminized mylar and then be detected in the plastic. Alphas which are emitted perpendicular to the plane of the target lose approximately 1.5 MeV. Those which emerge at ±70° with respect to the normal to the target will lose about 6.5 MeV. We detect recoils in this angular range, thus covering ~75% of the possible decays. Note that the distribution of alpha particles has been studied previously [Swe69] and is isotropic at the energies.

The beam current was measured by integrating the charge from the electrically isolated target/target rod system. It was biased to a voltage of +90 volts in order to suppress secondary electrons. Additionally, the collimator and slits were also biased to +90 V. The target current was fed into the control room and measured by means of a model 1000 Brookhaven Instruments Corporation current integrator, which is known to be accurate to within 1%.

It should be mentioned that the attenuation of 700 keV (17.3 MeV) γ rays emitted from the target and detected in the HPGe detector was approximately 5.5% (1%) for this experimental set-up. Also note that the condition of the target was monitored by the use of a surface barrier detector, which will be discussed in section 2.4.4.

2.3.4 Absolute Cross Section Experimental Setup

During the course of performing the experiments described above, it was determined that an accurate evaluation of the absolute cross section could not be obtained from these measurements. The reasons for this will be discussed in section 3.5.1. In order to measure the absolute cross section, a new technique was developed; the details of this procedure are described below. Note that this measurement did not require the use of polarized beams and one week of unpolarized beam time was devoted to this project.

In order to extract information about the third excited state we must perform a coincidence experiment, detecting one of the two alpha particles from the decay of 8Be.
Obviously, one alpha will be directed towards the target backing while the other will emerge from the front face of the target. The first improvement to be made was to change the physical nature of the target. The new targets were made by the evaporation of lithium metal not onto a thin Ni foil but rather onto a $\frac{1}{16}$" thick Al disc. This is the same procedure employed in other experiments performed by our group [Cha94, Lay96] and has proven to be quite successful. We used prefabricated plastic scintillators from Bicron, but placed them in front of the target. Figure 2.8 shows a conceptual diagram of this and Figure 2.9 is a top view. Since the alpha distribution is relatively isotropic at these energies [Cec92, Swe69] we need to cover as much of $2\pi$ steradians as possible, yet still keep the design fairly simple. The plan shown in these figures was easy to implement, inexpensive, and yet still covered approximately 60% of the alpha decays! This measurement will be discussed further in section 4.5.5. An additional and equally important benefit of this technique is that the energy distribution of the coincident alpha particles is not “smeared out” from 8.5 to 0 MeV, but rather is a Gaussian-like distribution and so an energy cut off can be established and reproduced.

The rest of the experimental apparatuses used were the same as those used in the analyzing power measurements described previously. Also, the detectors, electronics, and data analysis procedures were quite similar.

2.4 Detectors

In this section the various detectors used for data collection are described. Included will be a brief discussion about the HPGe, the NaI shield, the plastic scintillator, and the monitor detector. Figure 2.6 (see page 27) shows all of these in a typical experimental run.

2.4.1 The High Purity Germanium Detector

The primary goal in performing a radiative capture experiment is to detect $\gamma$ rays. To accomplish this task, we have used a p-type High Purity Germanium (HPGe) detector
Figure 2.8: Conceptual diagram of the absolute cross section measurement target chamber.
purchased from EG&G Ortec (Oak Ridge, TN). A γ-ray which enters the crystal can interact with matter primarily via three processes: photoelectric absorption, Compton scattering, and pair production (if E > 2m_e c^2, or 1.022 MeV). How often these occur depends on the γ-ray energy and is described elsewhere [Kra88]. The germanium detector itself is a large p-n junction (between the contact pin and the crystal). Thus a large depletion region is created. When radiation enters the crystal it can create electron-hole pairs where the holes flow one way and the electrons the other. The result is an electronic pulse proportional to the energy deposited. Ideally we would like to detect the full energy of every γ-ray of interest.

This is certainly not the case. Unfortunately, the γ-ray may not deposit its full energy in the crystal. A Compton scattered γ-ray produces a secondary (scattered) γ-ray which might escape the detector without being detected. This results in a continuous
distribution of Compton scattered events, ranging in energy from the Compton edge (i.e. the theoretical maximum energy imparted to an electron from a scattered $\gamma$ ray) to zero energy. It is also possible for a $\gamma$ ray which undergoes pair production not to deposit its entire energy in the crystal. The positron created will annihilate and produce two 511 keV $\gamma$ rays, either of which (or both) may escape the crystal without being detected. Of course the response function (accounting for the resolution and efficiency) of the detector will also affect the observed $\gamma$-ray spectra.

The HPGe detector used for this experiment was run at +3000 volts, and was operated at 77$^\circ$ K by means of a copper thermal contact to a 30 liter dewar of liquid nitrogen. This reduces the thermal excitation of electrons across the energy gap and thus results in a substantial reduction in the background noise. The detector is cylindrical in shape with a diameter and length of approximately 8.25 cm and 10.9 cm, respectively. There is a gold plated copper contact pin in the center (creating a cylindrical hollow center) and so the detector has an active volume of 576 cm$^3$. These features are depicted in Figure 2.10. Detectors of this type are known to have excellent resolution, but somewhat poor efficiency. For a 1.33 MeV $\gamma$ ray (from $^{60}$Co) the present detector has an efficiency of 128% (compared to a 3$''\times$3$''$ NaI crystal) and a full-width, half-maximum (FWHM) resolution of 2 keV.

During the course of these experiments a second large HPGe was obtained from Ortec. We used this detector for two analyzing power measurements. Its operation is quite similar to the detector described above. Physically, it is 8.96 cm in diameter and 9.3 cm long, and has an active volume of 582 cm$^3$. The quoted efficiency is 145% for the 1.33 MeV $\gamma$ rays from $^{60}$Co.

### 2.4.2 NaI Shield

In these experiments we surrounded the HPGe detector with a NaI shield which was actively run in anticoincidence; that is, it rejected events that deposited energy in both detectors at the same time. This resulted in a reduction of the well known escape and double-
CHAPTER 2. EXPERIMENTAL TECHNIQUES AND EQUIPMENT

Figure 2.10: Cross sectional view of the HPGe detector showing some of the important features. More details are given in the text and a complete description may be found in the detector owner’s manual [EG 93].
escape peaks, the Compton scattered events, and the cosmic-ray background. The effects of this are clearly seen when comparing spectra taken with and without the anticoincidence condition. For example, Figure 2.11 displays the detector response from proton capture to the ground state of $^8\text{Be}$ (producing a 17.3 MeV $\gamma$ ray) with and without rejection.

The basic procedure for how the NaI detects $\gamma$ radiation is as follows. Gamma rays that enter the crystal interact via the three processes described above (photoelectric absorption, Compton scattering, and pair production). The result is that the energy of the photon is converted into energetic electrons (from photoabsorption and Compton scattering), the secondary electrons are stopped rapidly in the crystal and low-energy light is produced. A dopant is added to shift the absorbed $\gamma$-ray energy into the visible region, to which the detector is transparent. This light eventually finds its way to the back of the detector, where a photosensitive device is placed, and can cause an electron emission.
Figure 2.12: Front view of the HPGe detector and the NaI annular shield used for the $^7$Li($p,\gamma$)$^8$Be experiments.

(the photoelectric effect). These secondary electrons are then multiplied (by a factor of 10 million or more!) by a photomultiplier tube (PMT), collected, and read as an electronic pulse. This signal may then be processed by our electronics.

Figure 2.12 shows a front view of the HPGe and NaI shield detectors used for these experiments. The detector is an annulus, approximately 9" in diameter and 8.25" long, with a 4.375" diameter cylindrical hole cut out from the center. Additionally, it is physically separated into four quadrants, but for the purposes of these experiments the linear signals from each section were gain matched, summed together, and read as one.
2.4.3 The Plastic Scintillator

As discussed earlier, it was necessary to detect the alpha particles emitted that correspond to capture to the third excited state of $^8$Be. A typical way to accomplish this would be to use a silicon surface barrier detector. However, the angular acceptance of such a detector would imply a very low counting rate. A very inexpensive and readily available option is to use plastic scintillators. These work in a manner very similar to that of the NaI detector described above.

In both the polarized and the unpolarized experiments we used precut thin plastic scintillator sheets (BC-412) from Bicron Corporation. These sheets were then optically cemented to a light pipe which was in turn connected to a photomultiplier tube (PMT). The PMT used for these experiments was manufactured by Hamamatsu (type R329). The PMT signals were processed by a high-current, transistorized, Bicron base (model P-21-X). This setup is shown in Figure 2.7. Of course care must be taken to maximize the internal reflection and prevent background light from entering the system. This was accomplished by using 0.25 mil (1 mil = $\frac{1}{1000}$ inch) aluminized mylar and special reflective sheets obtained from Bicron. For the polarized experiments, one BC-412 plastic scintillator ($2'' \times 2.75'' \times 0.125''$) was placed in back of the target. For the unpolarized experiments, we used four pieces (5'' long, 0.0625'' thick, and 1-2'' wide) which were positioned as shown in Figure 2.9.

These plastic scintillators provided us with superb timing signals—the rise time is on the order of 5 nanoseconds or better! The raw signal from the PMT was processed by the electronics and stored in the computer, as described below in section 2.5, and provided both energy and timing information.

2.4.4 Monitor Detector

The large beam currents ($\approx 25\mu$A) which were used in these experiments had the potential of causing significant target deterioration. Therefore, we monitored the condition of the lithium target during the course of the experiments using a silicon surface barrier
detector. By examining the alpha particles from the $^7\text{Li}(p,\alpha)^4\text{He}$ reaction we could estimate the target condition. Besides elastic scattering this is the most prevalent reaction occurring, and has been studied in much detail [Rol86].

The solid state, silicon surface barrier detector was purchased from EG&G Ortec. This type of detector works in a manner quite similar to the HPGe detector. When an external bias is applied, the depletion region will contain an electric field. Free charge carriers are created in this region when ionizing radiation enters the detector. The electric field separates these charge carriers, this current is integrated, and a charge is produced which is proportional to the energy of the ionizing radiation. A more thorough description is given elsewhere [Gou74].

The detectors used had an active area of 450 mm$^2$, were 300–1000 μm thick, and have quoted FWHM resolutions of $\approx 20\%$ for 5.486 MeV alpha particles from $^{241}\text{Am}$. They were placed at $\theta_{\text{lab}} = 120^\circ$ to the left of the beam (the HPGe was on the right side). Each detector was covered with 0.25 mil thick aluminized mylar in order to protect it from elastically scattered protons, and lithium that was baked off the target. It was found that running beam currents around or under 22 μA usually would not deteriorate the target significantly. However, if the beam was not evenly distributed about the target (if there were “hot spots”) even small currents could rapidly deplete the target. The only way to combat this problem was to view the target with beam on and if “hot spots” were observed, search for a different tune. In any event it should be noted that this will not affect our analyzing power measurements because of the fast spin flip technique, described below.

It should also be noted that similar detectors were used in the high energy proton polarimeter described in section 2.2.4. These types of detectors are excellent for measuring charged particles emitted from a nuclear reaction and are essentially 100% efficient.
2.5 Electronics and Data Acquisition

The purpose of this experiment was to study the $\gamma$ rays from proton capture on $^7\text{Li}$. Data from this experiment was electronically processed and collected by Computer Automated Measurements and Control (CAMAC) modules. The MBD-11 (Microprogrammed Branch Driver) then sends the data to a computer, which supervises the experiment and controls the data acquisition, storage, and on-line manipulation. We used a Digital Equipment Corporation (DEC) Micro VAX 3200 computer and the TUNL XSYS [Set95] data acquisition and analysis packages. The codes for controlling this were developed before, and modified during the course of the experiments.

2.5.1 Electronics

In the preceding sections the operation of all the detectors used during the experiment have been discussed. The end result of each detector is to produce an electronic pulse proportional to the energy deposited in it. Additionally, the signal should vary linearly with the energy, although this is critical only for the HPGe detector. These "linear" signals were then sent into the control room to be processed and stored.

The basics of the electronics set-up employed are shown in Figure 2.13. The goals of this are as follows:

1. To process linear signals for the HPGe detector. Note that this required splitting the signal and amplification by two Spectrum Amplifiers, one for the low energy ($\approx 700$ keV) $\gamma$ rays and one for the high energy ($\approx 17$ MeV) $\gamma$ rays. These parameters are labeled as LE and HE in the Figure 2.13.

2. To process linear signals for the NaI shield, plastic scintillator, and monitor detectors, labeled NaI, Scint, and Mon, respectively.

3. To establish whether a coincidence occurred between the NaI and the HPGe and between the Scintillator and the HPGe using two Time to Amplitude Converters
(TACs). These are labeled TAC-N and TAC-S.

4. To process scaler information for all of the above and to determine the spin state (up or down) during the event. (Also see Figure 2.14)

5. To prepare the signals for storage into the Analog to Digital Converters (ADCs).

6. To use the information recorded by the ADCs to create energy and timing histograms.

7. To record the data in such a way that we may reanalyze the data off-line (referred to as "sorting" or "replay").

As mentioned earlier, an event was defined as an interaction occurring in our germanium detector. Within the detector's canister, the signal was sent through a preamplifier and then fanned out into two signals. One of these two signals was used for timing purposes. The raw timing signal was sent through a Timing Filter Amplifier (TFA) and then to a constant fraction discriminator, which sets an energy cut off (usually set at 200–300 keV). That signal was used as the start for both TACs, as a scaler to count the number of triggers, and to gate the ADCs. The other HPGe signal was used as an energy signal. For this experiment we divided this signal into two, and amplified each separately. This was done so that we could examine the high energy (17.3 MeV) γ rays coming from the ground state transition at the same time as the low energy (698 keV) γ rays coming from the transition to the third excited state, where a larger gain was desired in order to see the details of the spectrum. Using a spectrum consisting of 4096 channels implies that our resolution was approximately 5 and 0.25 keV per channel for the high and low energy spectra, respectively. In both cases the raw signal was sent through an Ortec 672 Spectrum Amplifier to be shaped and amplified before going to the ADC.

The plastic scintillator sends a very quick pulse when a charged particle hits it. This signal was brought into the control room over a low-loss RG-8 52Ω cable, fanned out, amplified and sent to a leading edge discriminator. The timing signal was used to stop the
Figure 2.13: Schematic diagram of the electronics used for the experiment.
HPGe/Scint coincidence TAC and to update a scaler counter. In addition, linear energy signals were sent to the ADC (which was gated by the HPGe detector). Also, one fanned out signal was sent to an independent ADC and run as a separate, so-called singles, event. In this mode the plastic scintillator was used to create the gate for the ADC.

The HPGe detector was surrounded by a NaI annulus, which acted as an anticoincidence shield for cosmic-ray rejection. The signal from it was fanned out such that we would have both a linear and a timing signal. The linear signal was sent through a spectrum amplifier and then sent to the ADC, which was triggered by the HPGe detector. The timing signal was used as the stop signal for the HPGe/NaI coincidence TAC and as a scaler counter. This coincidence could be caused by an event which deposited energy in both detectors (possibly a cosmic ray or events which do not deposit their full energy in the HPGe, such as Compton scattered events, first and second escape peaks, etc.) or by two unrelated events. The former represents the real events we are interested in vetoing, while the latter will cause an accidental rejection of an event. By examining the off TAC background we can account for this. As it turns out, the accidental rate was practically negligible because of the low counting rate of the real events. This is quantitatively shown in section 4.5.1.

Lastly, we used a silicon surface barrier detector to examine the $^7\text{Li}(p,\alpha)^4\text{He}$ reaction. This was run as a separate process, using a different ADC to process the energy signal. After passing through a preamplifier, the signal was sent into the control room where it was shaped and amplified. The detector's raw signal was also used to create a gate to trigger the ADC.

2.5.2 NIM Electronics Used

The electronic modules that were used in this experiment were from Ortec, Phillips Scientific, Lecroy, Northern, and Kinetic Systems. The primary ADCs used were two Ortec 413A CAMAC quad 13 bit ADCs. All four inputs are strobed by a single gate, generated by the HPGe detector discriminator and fanned out to both ADCs. Various ADCs
manufactured by Northern (model numbers TN1212A and NS621) were used for the polarimeter, monitor, and scintillator singles signals. These ADCs accept linear, 0-10 volt signals, operate at 50 or 100 MHz, and were used to generate spectra 1024 channels wide.

2.5.3 Fast Spin Flip

A polarized beam was used for the analyzing power and angular distribution of the cross section measurements. The polarization axis was either up or down, depending on which source transitions were used. In order to eliminate small instrumental asymmetries we changed the spin direction at the rate of 10 Hz. This was controlled by a homemade NIM spin state controller (SSC). This module operates on an eight step sequence (+ − + − + + − −) in order to cancel linear and quadratic drifts in time. See [Huf95] for a thorough discussion of this. Each step runs for 100 ms, with a 7 ms dead-time between steps. The electronics used for this procedure are displayed in Figure 2.14.

In order for the computer to know which spin state the ABP1S was in when an event occurred, we used a 12-bit input register manufactured by Bi Ra Systems (Albuquerque, NM). The FSF electronics controlled the spin state of the ABP1S (SF2 or MF2) and sent a logic signal to the input register which was stored as a specific bit. A strobe was sent to it every time the HPGe discriminator fired, and the bits were read by the computer. In this way we could sort the data coming from reactions into spectra with proton spin up and spin down, and so measure the analyzing power.

It should be noted that the measurement of the absolute cross section does not require this procedure and it was not employed during those measurements. In that case an unpolarized beam was used and these electronics were disconnected. Also, the angular distribution of the cross section measurements need not use these electronics, however, since these cross section data were taken at the same time as the analyzing power data (using a polarized proton beam), the FSF electronics were used.
Figure 2.14: Schematic diagram of the Fast Spin Flip (FSF) electronics.
2.5.4 Computer Interface

The data taken were digitized by the CAMAC ADCs and scaler units. Once these CAMAC modules digitize a pulse they send out a LAM ("Look At Me") signal to the crate controller which in turn notifies the MBD that data are ready. Next the data are passed to the MBD, which is flushed to the Micro VAX whenever the buffer is filled. These data consisted of 4 energy signals, 2 TACs, multiple scalers and the bit register. Additionally, data were taken in event storage mode, which allows the experimenter to adjust gate settings and sorting requirements off line. As the data was sent to the computer it was sorted and displayed using the TUNL XSYS [Set95] data acquisition algorithms. The display package allowed for this data to be plotted in histograms of counts versus ADC channel number as the experiment was performed.
Chapter 3

Data Analysis and Calculations

3.1 Introduction

The previous chapter described how the experiments were run and how data from the detectors were transferred to the computer. After the experiment was run this data needed to be analyzed in order to extract the necessary information to determine the quantities of interest. This chapter explains how this was accomplished. The observables measured in this experiment were the angular distributions of the vector analyzing power and the cross section, and the absolute cross section for the $^7\text{Li}(p,\gamma)^9\text{Be}$ reaction leading to the ground, first and third excited states. At the heart of this analysis is the determination of yields, that is, the number of specific $\gamma$ rays observed for a specific set of experimental parameters. It should be stressed that the proton beam is stopped in the target, and so the data presented represents integrated yields over the energy range $E_p=80-0$ keV. However, most of the yield (over 80%) arises from $E_p=80-60$ keV, and so the data can be thought of as arising from a mean proton energy of approximately 70 keV. Details of how this is known will be discussed below.
CHAPTER 3. DATA ANALYSIS AND CALCULATIONS

3.2 Replay of Event Mode Data

As the experiments were run data was continuously fed to the computer, creating 7 "raw" data areas. Guided by the event analysis (eval) codes, the computer then placed this data in various spectra, depending on the experimental conditions. For example, each time the ADCs were read, a determination was made as to which ABPIS spin state was on, and the data obtained in the HPGe were sorted accordingly. In practice, the eval codes consisted of many options dependent on numerous conditions and gate settings. If the data rate was fast enough it would have been possible to run the experiment and adjust these gates online. This was not the case here.

Instead, the computer kept track of all the data in an event (.EVN) file. At a later time the experimenter could make more accurate gate settings and literally rerun the experiment. In fact, the eval code could be altered to include new spectra, change spectra sizes, add gates and other conditions, and thus check multiple TAC gate settings and the results on the TAC-gated energy spectra. The most important benefit was that this allowed the experimenter to adjust the TAC gates in such a way as to set a tight window of acceptance on the data for capture to the third excited state.

3.3 Energy Spectra and Calibration

A raw energy spectrum obtained by the HPGe detector is shown in Figure 3.1. The background is significantly reduced when the anticoincidence shield condition is turned on, as shown by the second pulse-height spectra in this figure. There are three $\gamma$ rays that we wish to observe. The energies of these are approximately 17.3, 14.3, and 0.698 MeV and their widths are 0.0068, 1500, and 108.1 keV, respectively [AS88]. Again note that these will be spread out due to the stopping of the beam in the target although, in fact, this will only have a major effect on the ground state and a slight effect on the third excited state response. In the next three sections we will examine each transition individually.
Figure 3.1 displays many interesting features and deserves some attention. First, the full-energy ground state is prominently displayed in both spectra. The very narrow spike near channel 3250 in both curves is the $\gamma$ ray representing proton capture to the ground state of $^8$Be. The first escape peak is also present in both spectra (channel 3150). Although it is not obvious from this figure, an examination of Figure 2.11 on page 35 will show that the ratio of these peaks is significantly altered when the anticoincidence condition is required. The second escape peak is seen (around channel 3050) in the raw spectrum, labeled “without shield”, but has all but vanished in the spectrum labeled “with shield”. The broad peak around channel 2600 corresponds to capture to the first excited state. Notice the large Compton background between channels 2900–3250 and the cosmic-ray background above the full-energy peak. Both of these are greatly reduced with the anticoincidence shield.
CHAPTER 3. DATA ANALYSIS AND CALCULATIONS

The HPGe is the detector used in these experiments for γ-ray spectroscopy, and so great care was taken to ensure an accurate energy calibration. The detector was calibrated by using various radioactive sources. Three sources that were used are $^{137}$Cs (661.7 keV), $^{60}$Co (1173. and 1330. keV), and the "QCD-1" source [Ame94], produced by Amersham International, which emits 11 different energy γ rays from 9 radionuclides. These provide a very accurate measure of the energy calibration at low energies. Assuming a linear fit, the calibration can be extrapolated out to higher energies as well, although the calibration could easily be slightly inaccurate at the high energies. However, by using the known energy for the full-energy peak corresponding to the ground state transition and the associated escape peaks allowed us to make corrections. These corrections were found to be ≤200 keV in most cases. Present in all the raw germanium spectra are the two background lines at 1460 keV (due to the decay of $^{40}$K) and 2614 keV (Radio-thorium). During all experiments we continuously observed these background lines in order to monitor for gain shift effects. If gain shifts were observed, subsequent spectra could be corrected for these before being added to previous ones.

3.3.1 The Ground State Transition

Figure 3.2 displays the high energy region of the HPGe spectrum. Notice that the full-energy and first escape peaks for γ₀ (at 17.3 and 16.789 MeV) stand out prominently. To extract the number of counts (yield) is quite simple and requires just a summation over the peak and a background subtraction. The number of background counts was assumed to be linear over this small energy range and was computed by examining the number of background γ-rays detected in the region above the peak, approximately 17.5–19.5 MeV. The statistical error involved in a measurement of this type is simply [Bev69]

\[
\text{error} = \sqrt{\text{Yield}}
\]

\[
\text{error} = (\text{Peak Yield} + \text{Background Yield})^{\frac{1}{2}}.
\]  (3.1)
Figure 3.2: Typical HPGe spectrum examining the $\gamma_0$ region, with the shield anticoincidence requirement applied. The full-energy peak and the first escape peak are seen. Also notice that there is very little cosmic-ray background.

Note that the contributions to the errors from the background are quite small, and were typically below 1%. The yields and errors for $\gamma_0$ could then be used for analyzing power and cross section calculations.

Note that this peak is approximately 70 keV wide, resulting from the natural state width, the resolution of the detector, and the energy spread associated with the beam stopping in the target. The $\gamma$ rays observed represent reactions occurring from 80 to 0 keV (in the lab frame). Using the known stopping powers [And77] for this reaction we can
calculate the distribution of $\gamma$ rays over energy. The number observed is rapidly decreasing as the beam energy decreases due to the Coulomb barrier. Indeed we find that 50% of the reactions occur in the first 8.3 keV and 95% in the first 30 keV. These results are graphically shown in Figure 3.3 and listed in Table 3.1. In the figure the accumulated yield (as a percentage of the total yield) arising from protons of energies 80 keV to $E_p$ is plotted. In equation form this is:

$$Y(\%) = \frac{\int_{E_p}^{E_0} y dE}{\int_{80}^{E_0} y dE},$$  \hspace{1cm} (3.2)

where $y$ is the yield per unit energy and is defined later in equation 3.16.

The full-energy peak information could be used to calculate the vector analyzing power as well. However, a closer examination of Figure 3.2 reveals the first and second
### Table 3.1: Results of the thick target yield calculation as a function of proton beam energy for the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction. The calculation was performed by considering layers of $^7\text{Li}$ target 2µg/cm$^2$ thick. The $\gamma$-ray yield for each step and the accumulated yield are given, expressed as a percentage of the total yield.

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<th>Yield (% of Total)</th>
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escape peaks and a significant portion of the Compton scattered events. These all come from a transition to the ground state and can be utilized as such, with appropriate background subtraction. Both methods were pursued (using the full-energy peak and using the full-energy peak, escape peaks, and the high energy portion of the Compton background to calculate the analyzing powers) and gave agreeing results, but of course the full summation technique provided much better statistics. The results will be presented in Chapter 4.

3.3.2 The First Excited State

Figure 3.4 displays the anticoincidence energy spectrum above 8 MeV. The large, broad peak present here arises from capture to the first excited state of $^8\text{Be}$. Capture to this state will yield 14.3 MeV $\gamma$ rays, with a width of 1500 keV [AS88]. In order to extract the yield, the background must be determined. Here we notice two sources of background.
First, the Compton scattered events from capture to the ground state. Second, the constant cosmic-ray background. Subtracting these events was achieved by using the XSYS [Set95] background subtraction procedures. The solid line in Figure 3.4 displays this background.

The gate labeled $\gamma_1$ represents one width up and two widths down from the centroid energy. The extracted yield is then taken as the number of counts in this peak minus the background curve.

### 3.3.3 The Third Excited State

Gamma rays leading to the third excited state of $^8$Be will have an energy of approximately 700 keV, and a width of at least 108 keV (the intrinsic width of the third excited state of $^8$Be, located at 16.626 MeV). Figure 3.5a displays one particular low energy, anticoincidence $\gamma$-ray spectrum obtained by running the HPGe detector in anticoincidence with the NaI annulus which surrounded it. There is no clear signal of this transition in the spectrum. However, as explained in Chapter 2, a plastic scintillator was used to detect the energetic alpha particles that are emitted from the decay of this state. When this coincidence requirement is applied the result is Figure 3.5b. Notice the dramatic difference in the scale and the "bump" indicating capture to the third excited state. The TAC spectrum for this coincidence is shown in Figure 3.6 along with the final gate setting for accepted $\gamma$-ray events. Background gates were set above and below so that properly normalized off-TAC counts could be subtracted.

Figure 3.7 shows the same data as presented in Figure 3.5, except with the horizontal scale compressed (by a factor of 4), the vertical scale suppressed, and the data smoothed (over 3 channels). Here we clearly see the 700 keV capture $\gamma$ ray superimposed on a continuous background. In order to calculate the yield, a simultaneous fit to the spectrum was performed by assuming a Breit-Wigner shaped peak and a background continuum approximated by a quadratic exponential function. Thus, the functional form used in the
Figure 3.5: (a) Typical low-energy $\gamma$-ray spectrum obtained in the HPGe detector. (b) Same as (a) but in coincidence with an event in the scintillator.
Figure 3.6: TAC spectrum for coincidences between the HPGe and the scintillator. Also shown is the final timing gate used.

The fitting procedure was:

\[
\text{Yield} = \text{Background} + \text{Breit-Wigner} \\
\text{Background} = \exp(A + BE_\gamma + CE_\gamma^2) \\
\text{Breit-Wigner} = \frac{D}{E_\gamma (E_\gamma - E_c)^2 + \left(\frac{\Gamma}{2}\right)^2},
\]

where \(E_\gamma\) is the \(\gamma\)-ray energy, \(E_c\) is the centroid of the peak, \(\Gamma\) is the peak's width, and \(A\), \(B\), \(C\), and \(D\) are parameters of the fit. \(E_c\) was let to vary, so as to account for small errors in the energy calibration. In theory the response of the germanium detector would also need to be considered (see, for example, the work of Kramer [Kra93]) and convoluted into this function. But since the resolution of the detector is only a few keV (and quite negligible when compared to the width of the state) this was not pursued. The width is fixed by the
user and is calculated by the following equation:

$$\Gamma^2 = (\text{natural state width})^2 + (\text{detector width})^2 + (\text{width due to beam stopping in target})^2.$$  \hspace{1cm} (3.4)

The center of mass width of the state is 108.1 keV [AS88], the detector's width is \(\approx 3\) keV, and the beam width was taken as 20 keV since over 80\% of the \(\gamma\) rays are produced within this energy region.

This parameterized function was then used to fit the pulse-height distribution. The program SGASS.FCN was written to utilize the MINUIT [Jam77] subroutines and perform a chi-squared minimization to the data. This code is presented in Appendix A. The width
was constrained as described above, and all other parameters \((A, B, C, D, E_c)\) were free. The fitting range was selected by the user. It was found that the quality of the fits depended on this choice. Especially critical was the lower bound. A choice too high would cut off some of the peak, resulting in erroneous yields, but a choice too low might extend into the threshold setting, resulting in a poor representation of the background. Therefore many different fitting regions were attempted, and the best fit chosen. Because of the poor statistics involved, it was found that the best procedure was to fit the total data (not sorted by spin state) and constrain the background function to have the same functional form for each spin state while allowing the normalization to vary. Also, the omnipresent \(511 \text{ keV}\) peak was not included in the fitting procedure. Figure 3.8 shows a typical pulse-height spectrum (both spin states) and the fit to it represented by the solid curve. The background and Breit-Wigner components are shown separately as a dashed and dotted curve, respectively.

By following this procedure, quality fits to each spin state were calculated, with reduced chi-squared values near 1.15. To extract the yields, the backgrounds were subtracted from the spectrum and the resulting spectrum summed. This summing region was taken to be from \((E_c - \Gamma)\) to \((E_c + \Gamma)\) where \(E_c\) is determined by the fit and \(\Gamma\) (the width) is the known width from equation 3.4, as previously discussed. In Figure 3.9 the pulse-height-minus-background spectrum is shown, along with the best fit curve and the summing region.

The statistical error contributions to these sums are twofold. Both the uncertainty in the yield and the uncertainty in the background were included. These errors were multiplied by the reduced chi-squared value for the fit, according to Bevington [Bev69]. Specifically,

\[
\text{Statistical Error} = \chi^2_v \times \sigma_A. \tag{3.5}
\]
3.4 Analyzing Power Measurements

The vector analyzing power has been measured for the three transitions discussed above at several angles. At this point we have only discussed extracting yields from the data. However this (and knowledge of the polarization) is all the data necessary to determine the vector analyzing power. Recall that the polarized cross section can be related to the unpolarized cross section as [Sey79]

\[
\sigma_p(\theta) = \sigma_u(\theta)\left[1 + \vec{P}_\zeta \cdot \vec{A}(\theta)\right],
\]  

\[(3.6)\]
Figure 3.9: A typical pulse-height-minus-background spectrum and the fit obtained along with the summing gate. Note that the 511 keV peak has been suppressed.

where $\vec{P}_\gamma$ is the polarization vector and $A$ is the analyzing power. In this experiment the proton spin was either parallel or anti-parallel to the y axis, and the spin states are referred to as “up” and “down”. Substituting into equation 3.6 for spin up ($p_+$) and spin down ($p_-$) and solving for $A_\gamma$ gives

$$A_\gamma(\theta) = \frac{\sigma^+(\theta) - \sigma^-(\theta)}{p_-\sigma^+(\theta) + p_+\sigma^-(\theta)}. \quad (3.7)$$

Note that this equation depends only on the ratio of cross sections. Since we are considering one detector at a time items such as efficiency, solid angle, etc. can be divided out of the equation. Also recall that the data obtained for the analyzing power used the fast spin flip technique described in section 2.5.3. Therefore any time dependent changes (such as target
CHAPTER 3. DATA ANALYSIS AND CALCULATIONS

thickness, computer dead-time, accidental corrections, etc.) are of no concern; they will be represented equally in both spin states and will divide out of equation 3.7. Thus we can substitute the detector yield \( Y \) in place of the cross section \( \sigma \) and we are left with

\[
A_v(\theta) = \frac{Y^+(\theta) - Y^-(\theta)}{p_-Y^+(\theta) + p_+Y^-(\theta)}.
\]  

(3.8)

The associated error may be derived using the the expression for the error of a function [Bev89]. Assuming the errors for the measured quantities present in equation 3.8 are uncorrelated, we find that the error in the measured analyzing power is

\[
dx_A = \frac{\left\{ (Y^+ - Y^-)^2 \left[ (Y^-dP_+)^2 + (Y^+dP_-)^2 \right] + (p_+ + p_-)^2 \left[ (Y^-dY^+)^2 + (Y^+dY^-)^2 \right] \right\}^{\frac{1}{2}}}{[p_+Y^+ + p_-Y^-]^2}
\]  

(3.9)

Here \( dp \) is the error associated with the polarization measurement (for each spin state) and \( dY \) is the statistical error in the detector yield (again, for each spin state). The analyzing power and its error are thus simple to calculate for each transition. The numerical values obtained will be presented in Chapter 4.

3.4.1 Analyzing Power as a Function of Energy

As explained earlier, we are using an 80 keV beam that stops in our target, and thus produces \( \gamma \) rays over an energy range. Because of the excellent energy resolution of the HPGe detector it is theoretically possible to extract the energy dependence of the measured observables, provided certain conditions exist. First, there must be no significant contribution to the width of the energy peak due to any factors other than the detector’s response. Second, no detector gain shifts may be present. Third, the number of counts in any energy region must be sufficient in order to make the results statistically significant. As you can see, the first and third excited states are obviously not suitable for this analysis because of the natural widths of the state. But the ground state transition might be a candidate! Let us pursue this.
A detailed analysis of the D(\bar{p},\gamma)\(^3\)He reaction has been performed by Greg Schmid [Sch95a]. In this work the author examines the vector analyzing power and cross section's energy dependence. Two methods are attempted. In the first, a detailed deconvolution analysis is performed, where the yield and detector response are separated. In the second, a simple binning of the full-energy peak (into 7 energy "slices") is done. Both methods gave similar results.

We would like to apply these procedures to the data obtained for ground state capture. Three factors conspire against us. In the aforementioned reaction the \(\gamma\) ray observed has an energy of 5.5 MeV. For the \(^7\)Li(p,\gamma)\(^8\)Be reaction, the energy is more than 3 times this amount, and so the peak's width (in ADC channels) will be that much smaller. Second, the coulomb force is much greater in the \(^7\)Li(p,\gamma)\(^8\)Be reaction, as so the yield will drop off much faster than for the \(^2\)H(p,\gamma)\(^3\)He case. Third, the cross section is significantly lower and thus the number of counts is lower. Nevertheless, the binning analysis was attempted. Only two bins could be drawn, each accounting for approximately half the yield.

Some of the data could not be used because gain shifts in the detector worsened the resolution. In order to gauge the effects of detector gain shifts we monitored two background lines. These are at 1460 and 2614 keV and are far and away the most prevalent non-zero signals in our HPGe detector. If the centroid of these lines changed even slightly during a run this could produce large shifts at \(\gamma_0\) energies. Four different runs met all the criteria. These were analyzed and the results are presented in Chapter 4.

### 3.5 Cross Section Measurements

The cross section for a reaction at a specific energy can be related to the yield by the following expression:

\[
\frac{d\sigma}{d\Omega}(\theta, E) \equiv \sigma(\theta, E) = \frac{Y(\theta, E)}{\epsilon(n) \frac{Q}{2} \Delta \Omega},
\]  

(3.10)
where:

\[ Y(\theta, E) = \text{the yield measured at the angle } \theta \text{ and at a specific energy } E; \]
\[ \varepsilon = \text{the } \gamma\text{-ray detector's efficiency (for the full-energy peak)}; \]
\[ nt = \text{Avogadro's number times the areal density of the target (units of mg/cm}^2); \]
\[ Q/e = \text{the number of protons incident on the target during the experiment} \]
\[ \text{(total charge } Q \text{ incident on target divided by the charge of one proton);} \]
\[ \Delta \Omega = \text{the solid angle subtended by the detector.} \]

When performing a coincidence experiment (\( \gamma \alpha \)) this expression must be divided by the probability to detect the other particle (an \( \alpha \) particle in this case). This would be:

\[ 2\varepsilon_\alpha \frac{d\Omega}{4\pi}, \quad (3.11) \]

where \( \varepsilon_\alpha \) is the scintillator's efficiency, the 2 accounts for two identical particles, and the last term is the percent of \( 4\pi \) steradians that the detector covers. This will be discussed in section 4.5.5.

### 3.5.1 Angular Distribution of the Cross Section

Without the knowledge of the detector's efficiency it is still possible to measure the angular distribution of the cross section, \( \sigma(\theta)/A_0 \), where \( A_0 \) is the total cross section (for all space) divided by \( 4\pi \) (steradians). If the same experimental setup is used for various angles then the ratio of the cross section is simply the ratio of the yields obtained, normalized for the beam charge and changes in target thickness (\( Qt \)). Of particular interest is measuring this observable for the third excited state. No measurements of this observable exist at these low energies of this experiment.

The normalization factor (\( Qt \)) was successfully determined in previous experiments [Kra92, Cha94] by using a silicon surface barrier detector. This monitor detector (as described in Chapter 2) detects the direct production of 8.7 MeV alpha particles from the
\(^7\text{Li}(p,\alpha)^4\text{He}\) reaction. Since these particles are easily detected and counted, it was hoped that these yields could be used to normalize the HPGe yields and thus obtain relative cross section information.

Unfortunately, this was not the case. The angular distribution of the cross section for capture to the ground state has been previously measured by Chasteler et al. [Cha94]. Comparing our calculations to those results indicates that this procedure would not work in the present experiment.

Several possible explanations for the failure of this normalization procedure present themselves. First, target stability. Recall we had 20–25 \(\mu\text{A}\) of beam incident on a thin coating of lithium evaporated onto a 1/20 mil thick foil. This is certainly suspect. In fact, after a run the target sometimes appeared to have small holes in them (and burn marks on the scintillator) and/or areas where the lithium had been depleted. Second, carbon buildup. The beamline where we do these experiments must be evacuated by the use of high vacuum pumps. The types found at TUNL either use oil or are backed by mechanical pumps which use oil. This oil can backstream into the high vacuum line and thus deposit small amounts on the target. Even trace amounts will slow the 80 keV protons down, and therefore change the observed yield. Third, different angular acceptance by the scintillator. At first one would not suspect this to be a factor, since the scintillator is directly in back of the target foil. But if significantly different amounts of lithium were present on the foil, this would change the straggling of alpha particles through the target. It is possible that in one (week long) run alphas emitted at less than 70° made it through the target and were detected but in a different run alphas < 50° made it. Fourth, scintillator electronic acceptance. Since the coincident alpha particles that are detected by the scintillator possess energies from 8.5–0 MeV, it was necessary to accept all the counts in the scintillator spectrum. The discriminator used for the scintillator electronics (Lecroy 821) has a threshold potentiometer on it. Although care was taken to reproduce the same values, no direct experimental evidence could show this. Last, beam tuning. The optics of the ABPIS and low energy
beam lines necessitate a rather large beam spot. Because of the close geometry involved, a
tune slightly to one side could cause large effects. Additionally, during the time that these
experiments were run, many improvements were being made to the ABPIS. These changed
the optics within the source and, in turn, at our target.

In order to correct for these problems we attempted to normalize the $\gamma_3$ yield to a
known reaction. The angular distribution of the cross section for the $^7$Li$(p,\gamma_0)^{8}$Be reaction
has been previously measured at these energies and is reported in [Cha94]. Therefore, by
comparing the angular distribution of the $\gamma_0$ cross section in the present experiment to that
given previously, we could apply this normalization factor to the $\gamma_3$ yields and arrive at a
reliable relative cross section. Rather than leaving the cross section in arbitrary units, we
set the 90$^\circ$ cross section to unity. Thus:

$$\frac{\sigma(\theta)}{A_0} = \left( \frac{Y_{3}^{G}(\theta)}{Y_{3}^{G}(90^\circ)} \right) \cdot \left[ \frac{Y_{0}^{C}(\theta)/Y_{0}^{G}(90^\circ)}{Y_{0}^{G}(\theta)/Y_{0}^{G}(90^\circ)} \right], \quad (3.12)$$

where the subscripts 0 and 3 refer to the ground and third excited state, respectively, and
the superscripts G and C refer to the data gathered by Godwin et al. [God96] and Chasteler
et al. [Cha94]. These results will be presented in Chapter 4. Unfortunately, this procedure
will only eliminate some of the problems discussed above (the ones which affect both the $\gamma_3$
and $\gamma_0$ yield equally), and so not all the data could be used for the angular distribution of
the cross section. Note that the analyzing power measurements are, by design, not affected
by this analysis.

3.5.2 Absolute Cross Section

At the onset of this experiment, we had planned to measure the absolute cross
section. Because of the reasons listed in the previous section this was not possible with
the original experimental design. Therefore a new experiment was pursued in the hopes of
eliminating some of these problems. The design has been detailed in Chapter 2.3.4.

Of paramount importance to the design is placing the scintillators in front of the
target. Since, with this arrangement, the alpha particles need not straggle through the back
side of the target, any reasonable amount of lithium may be used by evaporating onto a thick Al disc. The range of an 80 keV proton beam in lithium is approximately 2.5 μm. The energetic alpha particles will lose only a few keV while traveling through the front of the target, even at the extreme angles. Therefore, the energy of the alphas will be uniform and well above zero, so a reproducible gate can be set in the scintillator spectrum. Figure 3.10 shows the scintillator spectrum obtained. The two peaks are formed from a gain shift in the scintillator energy during the course of the run. But note that it is still very easy to set a reproducible energy gate since the lowest setting is well above zero. Extra care was taken to obtain a quality, uniform beam tune. This was accomplished by placing a phosphorescent quartz in place of the target and viewing the beam spot prior to taking data. Then as the user experimented with various optics settings (quadrupoles, steerers, ABPIS lenses, etc.) the resulting beam on target could be examined. If the tune appeared to yield a uniform
distribution of charge at the target with no "hot spots" it was considered acceptable.

3.5.3 Energy-Integrated Yields and the Astrophysical S-Factor

In this experiment, we measured an energy-integrated yield. In this case the cross section may be expressed as:

\[ \sigma(\theta, E) = \frac{Y(\theta, E)}{(T)(\frac{Q}{e})(\epsilon \Delta \Omega)}, \]  

(3.13)

where \( T \) is the number of target atoms per cm\(^2\) that the beam encounters in the target (i.e. the areal density), \( \frac{Q}{e} \) is the number of protons incident on the target, and \( Y \) is the yield at a specific energy. Here \( T \) may be replaced with:

\[ T = \frac{dE_p}{STP(E_p)}, \]  

(3.14)

where STP is the stopping power for protons incident on \(^7\)Li. The stopping power as a function of energy is given in [And77] as

\[
STP = \begin{cases} 
A_1 \sqrt{E} & \text{if } E_p \leq 10 \text{ keV}, \\
((S_{\text{low}})^{-1} + (S_{\text{high}})^{-1})^{-1} & \text{if } E_p > 10 \text{ keV},
\end{cases}
\]  

(3.15)

where

\[ S_{\text{low}} = A_2 E^{0.45}, \]

\[ S_{\text{high}} = (A_3/E) \ln(1 + A_4/E + A_5 E). \]

If we define \( y \) as the yield per unit energy then the total measured yield is

\[ Y_T = \int_{80}^{0 \text{ keV}} y dE. \]  

(3.16)

Combining equations 3.13, 3.14, and 3.15 we have

\[ y dE = \frac{d\sigma}{d\Omega} \frac{Q}{e} \epsilon \Delta \Omega \frac{1}{STP(E)} dE. \]  

(3.17)

The result of integrating both sides of this equation is

\[ Y_T = \int_{80}^{3 \text{ keV}} \left( \frac{Q}{e} \right)(\epsilon \Delta \Omega)(\frac{d\sigma}{d\Omega})(\frac{1}{STP(E)}) dE. \]  

(3.18)
Lastly, using equation 1.8 and replacing the differential cross section by the expression for it in terms of the astrophysical $S$-factor gives the following equation:

$$Y_T = \int_{80}^{0 \, \text{keV}} \left( \frac{Q}{e} \right) (\varepsilon \Delta \Omega) \frac{S(E)}{E} \frac{e^{-2\tau_\gamma}}{STP(E)} \, dE. \quad (3.19)$$

This integral will be used in Chapter 4 to calculate the astrophysical $S$-factor, and therefore, the cross section.
Chapter 4

Results and Analysis

4.1 Introduction

The previous chapter thoroughly discussed the methods used to extract the various observables. This chapter presents these measured quantities. All of the values for the experimental observables displayed in the various plots are tabulated in Appendix B.

Recall that the measured values include: $A_y(\theta)$, $\sigma(\theta)/A_0$, $A_y(E)$, and $\sigma_{\text{total}}(E)$. While performing these experiments, $\gamma$-ray transitions to the ground, first, and third excited state were observed. Values for the vector analyzing power were measured for all three states. The angular distribution of the cross section (relative to the value at $90^\circ$) was measured for the $\gamma_3$ transition in the present work. Note that the angular distribution of the cross section for capture to the ground state and first excited state at the energies of the present experiments ($E_p=80-0$ keV) have been previously well determined by Chasteler et al. [Cha94] and have been used in some of the analyses. These values, along with the analyzing power measurements of Chasteler et al. [Cha94] are tabulated in Appendix B. Extraction of the energy dependence of the analyzing power, which is only possible for the ground state transition, has been performed. Lastly, the total (absolute) cross section has been measured for all three states and is discussed in this chapter.
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Energy Levels of $^8$Be

<table>
<thead>
<tr>
<th>$E_n$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ground state</td>
<td>$0^+; 0$</td>
<td>$6.8 \pm 1.7$ eV</td>
</tr>
<tr>
<td>$3.04 \pm 30$</td>
<td>$2^+; 0$</td>
<td>$1500 \pm 20$</td>
</tr>
<tr>
<td>$11.4 \pm 300$</td>
<td>$4^+; 0$</td>
<td>$\sim 3500$</td>
</tr>
<tr>
<td>$16.626 \pm 3$</td>
<td>$2^+; 0 + 1$</td>
<td>$108.1 \pm 0.5$</td>
</tr>
<tr>
<td>$16.922 \pm 3$</td>
<td>$2^+; 0 + 1$</td>
<td>$74.0 \pm 0.4$</td>
</tr>
<tr>
<td>$17.640 \pm 1$</td>
<td>$1^+; 1$</td>
<td>$10.7 \pm 0.5$</td>
</tr>
<tr>
<td>$18.150 \pm 4$</td>
<td>$1^+; 0$</td>
<td>$138 \pm 6$</td>
</tr>
</tbody>
</table>

Table 4.1: The low-lying energy levels of $^8$Be taken from [AS88].

4.2 Vector Analyzing Power and Relative Cross Section

The data presented in this section were obtained in approximately 6 weeks of beam time. During these runs the Fast Spin Flip technique (described in section 2.5.3) was used to control the ABPIS spin state (either “up” or “down”). Values for the polarization ranged from 0.546 to 0.805, and were typically about 0.7. Also, these data were taken with the original target/scintillator design, as discussed in Chapter 2.3.3

4.2.1 The Ground State

The ground state of $^8$Be is known to be a $J^\pi = 0^+; T = 0$ state which decays into two alpha particles, approximately 90 keV lower in energy. The width of the state is given as $\Gamma = 6.8 \pm 1.7$ eV. These properties [AS88] are summarized in Table 4.1, along with the same parameters for the first four excited states. Additionally we note that the ground state is considered a pure $p_{3/2}$ single particle with a spectroscopic factor of unity. These properties will be discussed in section 5.2.

Figure 4.1a displays the angular distribution of the cross section for proton cap
ture to the ground state of $^8$Be previously determined by Chasteler et al. [Cha94], while Figure 4.1b presents both the vector analyzing power values measured by Chasteler and measured in the present experiments (at 8 different angles). Notice that the analyzing powers are non-zero (and quite large at 90°) and that the cross section is anisotropic. The curves are the result of a Transition Matrix Element (TME) analysis of the data and will be discussed in section 4.3. Note that these data exhibit signatures of the presence of interfering multipolarity radiation, most likely E1 and M1.

4.2.2 The First Excited State

The first excited state of $^8$Be lies 3.04 MeV higher in energy than the ground state. It is a $J^\pi = 2^+$, $T = 0$ state, and decays into 2 alpha particles. The first excited state is considered a mixture of $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ single-particle states (see section 5.2 for a further discussion). As in the previous section, the (unpublished) data for the angular distribution of the cross section obtained by Chasteler et al. [Cha94] along with the analyzing power data obtained for proton capture to the first excited state of $^8$Be both by Chasteler et al. [Cha94] and in the recent work are plotted in Figure 4.2a and 4.2b. Notice that the cross section is isotropic within experimental error and the analyzing powers are consistent with zero, within error.

4.2.3 The Third Excited State

The main focus of this dissertation is to examine radiative capture to the third excited state of $^8$Be. This state is a $J^\pi = 2^+$ state and is completely isospin mixed with the fourth excited state such that ($T=0+1$). Together, the $T = 1$ component of these states is the isobaric analog to the ground state of $^8$B. The third excited state lies 16.626 MeV higher in energy than the ground state, and has a width of $\Gamma = 108.1 \pm 0.5$ keV [AS88]. This state is also considered a mixture of $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ single-particle states, but the latter component is far more dominant than the former.
Figure 4.1: The vector analyzing powers measured for the $^7$Li($p,\gamma_0$)$^8$Be reaction along with the angular distribution of the cross section from Chasteler et al. [Cha94]. The dashed curves represent a TME analysis of the data and are discussed in section 4.3.
Figure 4.2: The vector analyzing powers measured for the $^7\text{Li}(\vec{p},\gamma_1)^8\text{Be}$ reaction along with the angular distribution of the cross section from Chasteler et al. [Cha94].
CHAPTER 4. RESULTS AND ANALYSIS

The analyzing power and the angular distribution of the cross section as a function of $\gamma$-ray angle have been measured and are plotted in Figure 4.3. The curves represent the results of a TME analysis, which will be discussed in section 4.3. Note that unlike the $\gamma_0$ transition, the analyzing powers are consistent with zero and the cross section is isotropic.

4.3 Transition Matrix Element Analysis

4.3.1 Introduction

We have now examined the measured values for the angular distribution of the cross section and analyzing powers for the $^7\text{Li} (\vec{p}, \gamma)^8\text{Be}$ reaction. What we need to determine is the transitions that are involved in this nuclear reaction. To accomplish this a model independent transition matrix element (TME) analysis of the data is performed.

Recall that a reduced TME represents a transition from a specific initial state to a specific final state. For radiative capture reactions we write:

$$R = \langle \Psi | H_{\text{int}} | \Phi \rangle,$$

where $|\Phi\rangle$ is the continuum initial state, $|\Psi\rangle$ is the final bound state, and $H_{\text{int}}$ is the electromagnetic interaction Hamiltonian. Since $R$ is a complex number it is often expressed in terms of an amplitude and a phase: $R = |R|e^{i\phi}$. In the reactions studied for this dissertation, the final "bound" state is $^8\text{Be}$ or $^8\text{Be}^*$, which immediately decays into two alpha particles.

In the following discussion it will be shown that by using the formalism of Seyler and Weller [Sey79] the cross section and analyzing powers may be expressed in terms of the reduced transition matrix elements. In this way, one may directly fit the obtained data by varying the amplitudes and phases of the TMEs, while searching for a minimum in the chi-squared. It is of course possible to uncover multiple solutions to these equations, since this chi-squared minimization procedure involved is nonlinear in nature. The FORTRAN
Figure 4.3: The vector analyzing powers and angular distribution of the cross section measured for the $^7\text{Li}(\vec{p},\gamma_3)^8\text{Be}$ reaction. The dashed curves represent a TME analysis of the data and are discussed in section 4.3.
code TMEFIT, using the MINUIT [Jam77] minimization subroutines, was used to perform a TME analysis of the data, the results of which are presented in section 4.3.4.

4.3.2 Theory

In Chapter 2 the cross section for polarized capture was expressed as

\[ \sigma_{\rho}(\theta) = \sigma_u(\theta)[1 + \vec{P}_\rho \cdot \vec{A}(\theta)]. \]

Using the choice of axes prescribed by the Madison Convention (see section 2.2.1 for details) we may rewrite this equation as

\[ \sigma_{\rho}(\theta) = \sigma_u(\theta)[1 + p_y A_y(\theta)]. \quad (4.2) \]

Recall that \( p_y \) is the vector beam polarization and \( A_y(\theta) \) is the vector analyzing power. We can expand the cross section (of a point detector) in terms of Legendre and associated Legendre polynomials as

\[ \sigma_{\rho}(\theta) = \sum_k (A_k P_k + B_k P_k^1 p_y), \quad (4.3) \]

where \( P_k^m \) are the associated Legendre polynomials (see, for example, Arfken [Arf85] for a list and discussion), and \( A_k \) and \( B_k \) are the Legendre coefficients.

Comparing equations 4.2 and 4.3 shows that the analyzing power and unpolarized cross section may be expressed in terms of Legendre polynomials and coefficients. For the unpolarized cross section \( \sigma_u(\theta) \), and vector analyzing power \( A_y(\theta) \), we have

\[ \sigma_u(\theta) = \sum_k A_k P_k(\cos\theta), \quad (4.4) \]

\[ A_y \sigma_u(\theta) = \sum_k B_k P_k^1(\cos\theta). \quad (4.5) \]

The physical size of the detector can be accounted for by introducing the finite geometry correction factors \( Q_k \) [Ros53]. Also, the term \( A_0 \) may be explicitly represented in each
CHAPTER 4. RESULTS AND ANALYSIS

coefficients by simply defining \( A_k = A_0 a_k \) and \( B_k = A_0 b_k \). Thus, the final expressions are

\[
\sigma_u(\theta) = A_0 \left[ 1 + \sum_{k=1}^{\infty} Q_k a_k P_k(\cos \theta) \right],
\]

(4.6)

\[
A_y \sigma_u(\theta) = A_0 \sum_{k=1}^{\infty} b_k P_k^l(\cos \theta).
\]

(4.7)

The \( A_0 \) coefficient is then the absolute cross section normalization constant and is directly related to the total angle-integrated cross section. This may be shown by integrating the differential cross section in equation 4.6 over all angles. The result is

\[
\sigma_T = \int \int \sigma(\theta, \phi) \, d\Omega = 4\pi A_0.
\]

(4.8)

The Legendre coefficients may be expressed in terms of the complex reduced transition matrix elements, \( R \), by following the formalism found in [Sey79]. In that paper, polarized capture reactions, whose angular momentum are specified by

\[
e(\alpha, \lambda)c
\]

and \( l \) (the orbital angular momentum of the projectile) are considered. In equation 4.9 \( a, x, \) and \( c \) are the spins of the target, projectile (beam), and residual nucleus, respectively, and \( \lambda \) is the angular momentum associated with the photon released. Using the channel-spin representation, we may couple the spins in the following order:

\[
\vec{\alpha} + \vec{a} = \vec{\tau}, \quad \vec{t} + \vec{s} = \vec{\jmath}, \quad \text{and} \quad \vec{\lambda} + \vec{c} = \vec{\jmath}.
\]

(4.10)

We may also use the jj coupling scheme, where we have

\[
\vec{\alpha} + \vec{t} = \vec{\jmath}, \quad \vec{j} + \vec{a} = \vec{b}, \quad \text{and} \quad \vec{\lambda} + \vec{c} = \vec{b}.
\]

(4.11)

Note that in both coupling schemes we arrive at an intermediate state, who’s spin is expressed as \( \vec{\jmath} \) or \( \vec{b} \). The TMEs are labeled by their continuum state quantum numbers \((^{2s+1}I_J\) in the channel-spin representation, \(^{2b+1}I_J\) in the jj representation) and the multipolarity (\( E\lambda \) or \( M\lambda \)) of the outgoing \( \gamma \) ray. The generalized expressions are given in [Sey79], but it is
worthwhile to list the relevant (but abbreviated) expansions here:

\[
\begin{align*}
  a_0 &= \sum (2J + 1) |R|^2, \\
  a_k &= \sum (\cdots) Re[RR^*], \\
  b_k &= \sum (\cdots) Re[iRR^*].
\end{align*}
\] (4.12)

The sums are over the different possible combinations of matrix elements along with their associated quantum numbers, and the \((\cdots)\) symbols are defined in the formalism. It is interesting to note that the \(a_k\) coefficients will be proportional to \(\cos(\phi - \phi')\) and the \(b_k\) coefficients to \(\sin(\phi - \phi')\), and that \(R = R'\) terms appear in \(a_k\) but not in \(b_k\).

### 4.3.3 Allowed Transitions

In order to determine the appropriate TMEs to be considered for the \(^7\text{Li}(p,\gamma)^8\text{Be}\) reaction, we need to examine the angular momentum and parity of the constituent particles. The incident proton and \(^7\text{Li}\) target have spin-parities of \(\frac{1}{2}^+\) and \(\frac{3}{2}^-\), respectively. For ground state capture, the (short-lived) \(^8\text{Be}\) nucleus possesses \(J^\pi = 0^+\), and for capture to the first and third excited states, \(J^\pi = 2^+\). The \(\gamma\) ray will carry away a discrete quanta of angular momentum, which is specified by the multipolarity (\(\lambda\) or \(L\)). The parity associated with this \(\gamma\) ray is determined by the mode (E or M) and is \((-1)^L\) for electric transitions and \((-1)^{L+1}\) for magnetic transitions. Figure 4.4 displays the \(^7\text{Li}(p,\gamma)^8\text{Be}\) radiative capture reaction and the associated angular momenta.

In the TME fits that follow the jj coupling scheme was used. Let us now consider the possible contributing partial wave amplitudes. We first note that the coulomb barrier will suppress higher order partial waves. Since the energies of this experiment were quite low (\(E_p \leq 80\) keV), we have considered only \(l = 0\) and \(l = 1\) transitions. The justification is obvious when investigating the penetrability factors, which are approximately \(3 \times 10^{-4}, 1 \times 10^{-5}, 7 \times 10^{-6}\), and \(1 \times 10^{-10}\) for \(l = 0, 1, 2,\) and \(3\), respectively. The possible E1 and M1 contributing partial waves for all three transitions are listed in Table 4.2.
4.3.4 Results

The ground state

A previous study [Cha94] of the angular distribution of the cross section and analyzing power for the \(^7\text{Li}(p,\gamma)\)\(^8\text{Be}\) reaction has shown the presence of significant p-wave contributions. The analyzing power data obtained in the present experiment are significantly more accurate than those presented by Chasteler et al. [Cha94]. A TME analysis was performed using the previously determined cross section and the recently acquired analyzing power data for this transition. Under the constraints mentioned earlier (l=0,1) there are only 3 possible contributing partial waves. In the jj coupling scheme they are: \(^3s_\frac{1}{2}\), \(^3p_\frac{1}{2}\), and \(^3p_\frac{3}{2}\) (see Table 4.2). A transition matrix element analysis of the ground state data was performed using the computer code TMEFIT. Three solutions were found that fit the data very well. Figure 4.1 shows the data and the TME fits to this data. The amplitudes and
Contributing TMEs

<table>
<thead>
<tr>
<th></th>
<th>E1</th>
<th>M1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_0$</td>
<td>$^3s_{1/2}$</td>
<td>$^3p_{1/2}$</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>$^3s_{1/2}$</td>
<td>$^5s_{1/2}$</td>
</tr>
<tr>
<td>$\gamma_3$</td>
<td>$^3s_{1/2}$</td>
<td>$^5s_{1/2}$</td>
</tr>
</tbody>
</table>

Table 4.2: The possible E1 and M1 TMEs labeled according to the partial waves in the incident channel, and restricted to include only s-wave and p-wave ($l=0,1$) capture. The jj coupling scheme has been used with the label $^{2l+1}l_j$ specifying the quantum numbers of the incoming partial wave in the various TMEs.

phases are listed in Table 4.3. Here we find three solutions, which vary in total M1 strength from 40 to 90%.

**Chi-squared as a function of M1 strength**

The above analysis shows the presence of p-wave capture strength between 40 and 90%. The authors of [Cha94] reported four TME solutions varying in p-wave strength between 59 and 93%. They also explain that, if the energy dependence for E1 and M1 strength follow the direct capture model, the analysis would imply a reduction of the astrophysical S-factor by as much as 40%.

As explained in Chapter 1, there has been considerable interest in these results. Barker [Bar95] has attempted to fit the data (using an R-matrix formalism) by allowing the M1 strength to arise solely from the tails of the two $1^+$ levels in $^8$Be (at 441 keV and 1030 keV proton energy). Searching on the resonance amplitudes and their relative phase, Barker’s best fit gave 9.2% p-wave strength. This idea (the tails of the $1^+$ levels) is pursued in detail in Chapter 5.

In order to further study the p-wave strength in this reaction, the TME analysis has been extended. Allowing both s-wave E1 and p-wave M1 transitions, the E1 percentage was varied from 0 to 100% (and conversely the M1 percentage from 100 to 0%), and in each
Table 4.3: Results of the model independent transition matrix element analysis for proton capture to the ground state of $^8$Be. Three solutions have been found and are labeled FIT1, FIT2, and FIT3. The transition matrix elements are expressed as percent contribution to the total cross section strength. The phases are relative to the $s_{1/2}$ term which has been set arbitrarily to zero. The number of degrees of freedom is $\nu=(18$ data points $- 5$ parameters)$=13$. The fits are illustrated in Figure 4.1.

In order to perform a TME analysis of the third excited state data, 13 free parameters would have to be accounted for (7 amplitudes and 6 relative phases). To simplify the
procedure, some reasonable assumptions were made. First, as expected from the direct capture model, TMEs with the same $b$ value were set equal. Next, since the proton is capturing to a final state which is largely a $p_{\frac{3}{2}}$ shell, any continuum $p_{\frac{3}{2}}$ TMEs are neglected. Here M1 contributions would be expected to be negligibly small because of orthogonal states.

These constraints for the $\gamma_3$ transition yield three undetermined parameters: an $s$-wave, E1 amplitude (which shall be labeled $s$), a $p$-wave, M1 amplitude ($p$), and a relative phase ($\delta$). The equations listed in section 4.3.2 may be used to write the Legendre
CHAPTER 4. RESULTS AND ANALYSIS

Table 4.4: Results of the model independent transition matrix element analysis for proton capture to the third excited state of $^8\text{Be}$. Two solutions are found and are labeled FIT1 and FIT2. The transition matrix elements are expressed as percent contribution to the total cross section. The phases are relative to the $s_{1/2}$ term which has been set arbitrarily to zero. The number of degrees of freedom is $\nu=(13$ data points $- 3$ parameters)$=10$. The fits are illustrated in Figure 4.3.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Multipolarity</th>
<th>FIT 1</th>
<th>FIT 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strengths</td>
<td>Phases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(%)</td>
<td>(deg)</td>
</tr>
<tr>
<td>$^3s_{1/2}$</td>
<td>E1</td>
<td>100.0 ± 7.5</td>
<td>0</td>
</tr>
<tr>
<td>$^3p_{1/2}$</td>
<td>M1</td>
<td>0.0 ± 0.1</td>
<td>80.8 ± 185</td>
</tr>
<tr>
<td>$\chi^2_\nu$</td>
<td></td>
<td>0.288</td>
<td></td>
</tr>
</tbody>
</table>

The angular distribution of the cross section and analyzing power data for the $^7\text{Li}(\bar{p},\gamma_3)^8\text{Be}$ reaction have been presented in section 4.2.3. A TME analysis of this data has been performed and the results are shown as a dashed line in Figure 4.3. Because of the quadratic nature of equations 4.13, two solutions are found and are presented in Table 4.4. One consists of at most 0.1% M1 admixture, the other of 0.1% E1 admixture. These results are not surprising since the cross section data here are consistent with being isotropic and do not show any nonzero analyzing powers outside of statistical errors. Although two solutions are found, the traditional direct capture model predicts a dominant E1 (s-wave) amplitude. A definitive experimental proof requires showing that the s-wave, E1 capture solution, is indeed the physical one and can be done only by measuring the linear polarization of the

\[
A_0 = |s|^2 + |p|^2, \\
a_1 = -1.951 |s||p| \cos \delta, \\
b_2 = -1.951 |s||p| \sin \delta. \tag{4.13}
\]
emitted γ rays. An experiment which will use the new TUNL Compton Polarimeter [Gui96] to perform this measurement is being pursued vigorously.

4.4 Analyzing Power as a Function of Energy

Recall that the experiments being described involved stopping an 80 keV beam in a lithium target. Therefore the observables actually represent values measured over the proton energy range 80 to 0 keV. As explained in Chapter 3.4.1, it is possible to extract the energy dependence of measured observables under very specific conditions. The γ0 transition is the only possible candidate in this experiment and an attempt at extracting $A_\gamma(E)$ has been made.

There are two possible techniques that may be pursued. One involves a rigorous deconvolution of the detector response function and the energy dependence of the observable and the other is a simple binning of the full-energy peak. Both procedures produced similar results in a study of the $^2\text{H}(p,\gamma)^3\text{He}$ reaction [Sch95b]. However, because of the low statistics of the present experiment, only the binning method has been attempted.

The results are shown in Figure 4.6 for three different measurements that met the strict criteria listed previously in section 3.4.1. Here the full-energy peak was divided into two regions: 80–65 keV and 65–0 keV. Note that the when we sort the data into a 8192 channel spectrum (the maximum number of channels possible with the ADCs available at TUNL), each channel is approximately 3 keV wide and the uncertainty of the energy should be taken to be at least this large.

The first item noticed is that the full-energy peak (80–0 keV) analyzing power data have significant errors associated with them and that they are much greater than those originally depicted in Figure 4.1. This is because only the full-energy peak may be used. The data presented in section 4.2.1 were determined by using the full-energy peak and the two escape peaks and a portion of the Compton background. This gives yields approximately four to five times larger than using only the full-energy peak, and consequently much smaller
Figure 4.6: The vector analyzing powers for three separate measurements binned into two energy regions, along with the unbinned result (for the full-energy peak) and the total value (consisting of the full-energy peak, both escape peaks, and a portion of the Compton background).

errors. Second, the binned analyzing power pieces (80–65 and 65–0 keV) are equal to each other and the full-energy peak, at least within the statistical uncertainties present. Our conclusion is that in the energy region studied here, the $^7\text{Li}(p,\gamma_0)^8\text{Be}$ analyzing power data show no dependence on energy, at least not outside of the statistical errors associated with these data points.
4.5 Absolute Cross Section

Now we turn to the measurement of the absolute cross section for the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction. Recall that the experimental setup used for this has been detailed in section 2.3.4. The absolute cross section for any of the three transitions studied in this experiment can be calculated by solving equation 3.19 for $S$ and then using the relationship given in equation 1.8 to determine the cross section at the desired energy. These two equations are listed here:

$$Y_T = \int_{E_p=80}^{0 \text{ keV}} \frac{Q}{e} (\varepsilon \Delta \Omega) \frac{S(E)}{E STP(E)} e^{-2\pi \eta} dE,$$

and

$$S(E_{cm}) = \sigma(E_{cm}) E_{cm} e^{2\pi \eta}.$$

$Y_T$ is the total yield (number of counts) detected for capture to a specific state (over the entire proton energy range 80 to 0 keV). The measurement of this quantity has been discussed in section 3.3. Yet to be addressed, however, are the corrections that need to be applied to this yield, including losses due to instrumental and/or other data acquisition effects.

4.5.1 Corrections to Measured Yields

Accidentals

Recall that the HPGe detector was run in anticoincidence with a NaI shield. This procedure will veto cosmic rays (which deposit energy in the shield and in the HPGe detector), escape peaks, and Compton scattered events (which do not deposit their entire energy in the germanium crystal but do happen to interact with the NaI annulus). It is possible that a real event occurs at the same time as a (background) shield event. In such a case we will have accidentally rejected a good $\gamma$-ray event. Because the data rate is very low, this is not expected to be a big effect. Nonetheless, we have examined the TAC spectra (shown
Figure 4.7: The TAC spectrum generated for coincidences between the HPGe and the NaI shield. This was used to estimate the accidental rate (rejection of good events).

in Figure 4.7) between these two detectors in order to estimate this effect. By measuring the TAC and off-TAC events we calculate the accidental rate correction as

\[ \text{Accidental Correction (AC)} = \frac{1}{1 - \frac{\text{ACC}}{\text{COIN}}} \]  

(4.14)

The number of coincidences (COIN) is simply the number of events in the TAC peak and the number of accidentals (ACC) can be estimated by the number of events occurring outside the TAC peak region. The accidental rejection correction factor was calculated to be \( AC = 1.0058 \) during the absolute cross section experiment. The measured yields for each transition were then multiplied by this correction factor.

Computer dead-time

Another correction to be applied to the measured yield is the computer dead-time. Since the electronics require a finite time to process an event, it is possible that another
event occurred during this time period, and was therefore not counted. Obviously, higher count rates and multiple active processes will enlarge the effect. Although it is not expected to be a concern in the present experiment, we have measured this factor. Every time the HPGe detector fired, a signal was sent to a very fast scaler, which has essentially no dead time. We also measure the number of events that were actually processed, and record this information using a scaler. The dead-time correction is then calculated as:

\[
\text{Dead Time Correction (DTC)} = \frac{\text{number of events triggered}}{\text{number of events processed}}
\]  

(4.15)

This factor was \( DTC = 1.0067 \). The measured yields for each transition were then multiplied by this correction factor.

**Attenuation**

The \( \gamma \) rays emitted from the target must pass through a number of different objects before reaching the HPGe crystal. These include the following: the lithium target, the target backing, the target chamber, and the end cap of the detector. In doing so, some will interact and not be measured, resulting in an erroneously low yield. This attenuation factor is easily computed using the equation

\[
I(t) = I_0 e^{-\mu t},
\]

(4.16)

where \( I \) is the intensity (or number) of \( \gamma \) rays detected, \( I_0 \) is the number emanating from the target, \( \mu \) is the linear attenuation coefficient of a particular material, and \( t \) is the thickness of that material. The values for \( \mu/\rho \) used in these calculations have been tabulated by the National Bureau of Standards [Hub69]. These coefficients, along with the other variables needed to calculate the \( \gamma \)-ray attenuation, are given in Table 4.5.

In the absolute cross section measurement, the ratio \( I'/I_0 \) for a 698 keV, 14.3 MeV, and 17.3 MeV \( \gamma \) ray was 0.90865, 0.97146, and 0.97185, respectively. The corresponding measured yields have been corrected by dividing by these factors.
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Table 4.5: Parameters used in the attenuation factor calculation needed for the absolute cross section measurement. The values for the mass attenuation coefficient are taken from [Hub69]. Note that the only significant contributions come from the aluminum of the target backing, target chamber, and HPGe detector canister.

<table>
<thead>
<tr>
<th>quantity</th>
<th>symbol</th>
<th>$\gamma_0$</th>
<th>$\gamma_1$</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td>$-$</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
</tr>
<tr>
<td>thickness (cm)</td>
<td>$t$</td>
<td>0.486</td>
<td>0.486</td>
<td>0.486</td>
</tr>
<tr>
<td>coefficient (cm$^2$/g)</td>
<td>$\mu/\rho$</td>
<td>0.0218</td>
<td>0.0221</td>
<td>0.0730</td>
</tr>
<tr>
<td>density (g/cm$^3$)</td>
<td>$\rho$</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Attenuation (%)</td>
<td>$I/I_0$</td>
<td>97.185</td>
<td>97.146</td>
<td>90.865</td>
</tr>
</tbody>
</table>

4.5.2 Efficiency and Solid Angle

The efficiency for the HPGe/NaI shield detector system used at TUNL has been studied in great detail [Sch95a, Sch95b, Sch96]. In those works, the efficiency was determined using the known relative intensities for the $\gamma$-ray lines in $^{66}$Ga and an absolutely calibrated mixed radionuclide source placed 23 cm from the HPGe detector. An independent calibration measurement (performed by another experimental group at TUNL) using the $^{19}$F$(p,\alpha\gamma)^{16}$O reaction [Ma95] agreed with these results.

The photopeak efficiency of the HPGe detector was also investigated theoretically using an EGS4 [Nei85] Monte Carlo simulation. In this calculation, $\gamma$ rays were launched isotropically towards the detector from a point source 23 cm away. The program then determined the number of $\gamma$ rays that deposit their full energy in the detector and compared this to the total number of $\gamma$ rays that entered the front face of the detector. Thus the intrinsic efficiency of the HPGe detector can be determined by dividing by the solid angle, as defined in the following equation:

$$\Delta \Omega = 2\pi \left[ 1 - \cos \{ \arctan \left( \frac{D}{2R} \right) \} \right]. \quad (4.17)$$

Here $D$ is the detector's diameter and $R$ is the target to front face distance. Note that
this reduces to the well known approximation \( \frac{\pi D^2}{4R^2} \) as \( \frac{D}{R} \to 0 \). For all the absolute cross section measurements performed in this dissertation the value for \( \Delta \Omega \) was 0.515 sr. In a previous experiment [Sch95b] the high-energy (above \( \sim 2 \) MeV) results agreed quite well with the EGS4 Monte Carlo calculation. Although the efficiency calculation appears to be quite good at the energies of these previous studies (\( \sim 5.5 \) MeV), the efficiency is not well determined at the high energies (\( \sim 17 \) MeV) associated with the \( ^7\text{Li}(p,\gamma_0)^8\text{Be} \) reaction studied here. Therefore, for the ground state data, we choose to normalize our data to the absolute cross section value given by Cecil et al. [Cec92] at \( E_p=70 \) keV. This will be discussed in section 4.5.3. For the first excited state data, we will report the angle-integrated cross section relative to the ground state value, as is discussed in section 4.5.4.

Additionally, there is evidence that the EGS4 low-energy results are not accurate, possibly because of assumptions used in the calculation. One main simplification was the neglecting of thin absorbing materials and detector dead layers, which will have less of an effect on the high-energy \( \gamma \) rays but could be necessary for low-energy \( \gamma \) rays (see [Sch95b, Sch96] for a discussion). Therefore, an independent determination of the efficiency for capture to the third excited state was made and is discussed below.

The value \( \varepsilon \Delta \Omega \) for capture to the third excited state of \(^8\text{Be} \) was determined using a radioactive source. The QCD-1 radioactive source [Ame94] was placed in the exact target position used in the cross section measurement after the data had been accumulated. This source contains 9 radionuclides (producing 11 different \( \gamma \)-ray energies), and was calibrated by Amersham on 01 May, 1994. At the time of the experiment 4 calibration lines could be detected, at 661.7, 1173, 1333, and 1836 keV. Accounting for the half life of \(^{137}\text{Cs} \), \(^{60}\text{Co} \), and \(^{88}\text{Y} \) the number of \( \gamma \) rays emitted into all space (4\( \pi \) steradians) at the time of the experiment can be calculated. After corrections for the attenuation, computer dead-time, and accidental rejection of true events are applied, the quantity \( \varepsilon \Delta \Omega \) is determined for each \( \gamma \) ray. Figure 4.8 displays our findings and a smooth curve fit to the data following the
Figure 4.8: Plot of the detector efficiency times solid angle measurement. The errors associated with each data point arise from the statistical uncertainty in the measurement and the overall uncertainty of the source, as quoted by [Ame94]. The functional form of the fit is from [Kno88] and is given in equation 4.18.

\[ \varepsilon \Delta \Omega = [A + Be^{-CE_\gamma}]. \]  

(4.18)

Here \( \varepsilon \) is the intrinsic photopeak efficiency, \( \Delta \Omega \) is the solid angle subtended by the detector, \( E_\gamma \) is the \( \gamma \)-ray energy (in MeV), and A, B, and C are parameters of the fit. The error in the data is taken from the statistical error in the measurement and the overall uncertainty of the calibrated QCD-1 radioactive source, as quoted by [Ame94]. As Figure 4.8 shows, the fit is excellent in the low-energy regime (below \( \sim 2 \) MeV) and the value at a \( \gamma \)-ray energy
of 698 keV is $\varepsilon \Delta \Omega = 0.1084$.

4.5.3 Calculation of $S(E)$: The Ground State

In a previous study of proton capture to the ground state of $^8\text{Be}$ performed by Cecil et al. [Cec92] the astrophysical $S$-factor was assumed to be a constant. However, it is clear from the data presented here that a significant portion of the capture strength is due to M1 radiation, which implies that the $S$-factor will vary with energy. Previous experiments [Sch95a] have been able to use the excellent resolution of the HPGe detector to unravel the energy dependence of the cross section (or, equivalently, the $S$-factor) and it was hoped that this procedure could be used here. Unfortunately, this was not possible, largely because of the statistical limitations (see section 4.4 for a discussion). A direct experimental determination of the energy dependence of the $^{7}\text{Li}(p,\gamma)^{8}\text{Be}$ cross section below 100 keV is currently underway [Spr96].

Recall that a solution to equation 3.19 is not possible unless the astrophysical $S$-factor is either a constant or its energy dependence is known. Since a determination of this was not possible from the experimental data, the direct capture model was used to predict this function. In Chapter 5 an extensive set of direct capture plus M1 resonances calculations will be presented and discussed for the $^{7}\text{Li}(p,\gamma)^{8}\text{Be}$ reaction. For the present calculations, the E1 and M1 cross sections in the vicinity of the energy range of this study ($E_p=80-0$ keV) will be used. Shown in Figure 4.9 is the ratio of the predicted contributions to the total cross section for M1 radiation compared to E1 radiation. Also shown is a fit to the calculated points, assuming a functional form quadratic in energy:

$$r = A + BE_p + C E_p^2,$$

where $r$ is the ratio of the M1 to E1 cross section, $E_p$ is the proton energy in the laboratory frame, and $A$, $B$, and $C$ are constants. We may replace the $S(E)$ factor in equation 3.19
with an overall normalization constant times the functional form listed above:

\[ S(E) = S_{E1} + S_{M1} \]

\[ = E1 + M1 \]

\[ = E1(1 + \frac{M1}{E1}) \]

\[ = K(1 + [A + BE + CE^2]) \]

\[ = k(1 + aE + bE^2). \] (4.20)

Note that the direct capture calculations (see Chapter 5) predict that \( S_{E1} \) is constant in this energy regime (as expected). Also note that \( k \) is a normalization constant which will be adjusted. From the fit to the data shown in Figure 4.9 the constants \( a \) and \( b \) are calculated.
to be 0.0003561 keV$^{-1}$ and 3.4128 × 10$^{-6}$ keV$^{-2}$, respectively. It should be stressed that this extrapolation method may be applied to any measurement of the astrophysical S-factor. The limitations of this will be discussed in Chapter 5 when the direct capture calculations are presented.

Since it is not possible to analytically solve equation 3.19 a computer program was written which performs the necessary integration from $E_p=80$ to $E_p=0$ keV. The integration over this energy range is approximated by a summation of the yield function multiplied by an incremental energy step. The program used is named CALCXS and is displayed in Appendix C along with sample input and output files. The user specifies the reaction (mass and charge of the beam and target) and the experimental results (beam integrated charge, detector solid-angle, detector efficiency, and the corrected observed $\gamma$-ray yield). Then the user will input the functional form of the astrophysical S-factor and a guess at the normalization coefficient (see equation 4.20). The program numerically integrates over the energy range, compares the calculated yield to the user specified experimental yield, adjusts the S-factor normalization constant accordingly, and prints out the results.

To determine the $^7$Li$(p,\gamma_0)^8$Be S-factor the efficiency of the HPGe detector needs to be determined for a $\gamma$-ray energy of 17.3 MeV. The measured efficiency at low energies is quite excellent (see section 4.5.2) and previous work ([Sch95b]) shows that an EGS4 simulation can extend the efficiency measurement to energies of $\sim$ 5.5 MeV. However, the efficiency of the HPGe detector is not well known at the very high energies associated with the $^7$Li$(p,\gamma_0)^8$Be reaction. It was stressed earlier that calculating $S(E)$ using the quadratic energy dependence predicted by our direct capture plus M1 resonances calculations is subject to an overall normalization factor and could therefore be applied for any absolute cross section measurement. A much more accurate way of determining the absolute cross section would be to use an anticoincidence shielded NaI detector. These detectors are routinely used in capture experiments and their efficiencies up to and beyond 20 MeV are well known (see [Wel81], for example). Note that an investigation of the $^7$Li$(p,\gamma_0)^8$Be absolute cross
section below 100 keV using NaI detectors is currently underway [Spr96]. For the present analysis we shall use the value given by Cecil et al. [Cec92] at $E_p=70$ keV and compare our method of extrapolating the astrophysical $S$-factor to zero energy with previous methods. Recall that in section 3.3.1 we explain that our measurements (which are energy-integrated observables) may be thought of as arising from a mono-energetic 70 keV proton beam.

For the $^7\text{Li}(p,\gamma_0)^8\text{Be}$ reaction, the cross section was determined using the program CALCXS with the overall normalization determined from the measured value of Cecil et al. [Cec92] at $E_p=70$ keV, which is $\sigma_T = 54.3$ nb. The error given by Cecil et al. for the ground state $S$-factor (at 100 keV) is 15%. Therefore we determine the astrophysical $S$-factor to be

$$S_{\gamma_0}(E) = (0.240 \pm 0.036)(1 + 0.0003561 E_p + 0.0000034128 E_p^2) \text{ keV} \cdot \text{barns.}$$

(4.21)

Note that Cecil et al. [Cec92] assume that $S$ does not vary with energy, so $S(E) = S(0 \text{ keV}) = 0.25 \text{ keV} \cdot \text{barns}$. It will be shown in Chapter 5 that the experimentally measured M1 strength is approximately four times larger than predicted by the direct capture plus M1 resonances model. Preliminary calculations based on this give an $S$-factor (at 0 keV) of 0.219 keV\cdot barns.

### 4.5.4 Calculation of $S(E)$: The First Excited State

The data obtained during the absolute cross section measurement for capture to the first excited state was previously displayed in Figure 3.4 on page 53. As discussed in section 3.3.2 and 4.5.1, the extraction of the yield, and the corrections to the yield, are quite simple. There are, however, a few problems which need to be addressed before calculating the astrophysical $S$-factor for this transition.

The first of these problems concerns the efficiency. Because the width of the state is so large (1500 keV) the efficiency of the HPGe detector changes as we sum over the energy gate. In order to examine the significance of this, we use the functional form for the
efficiency used in [Sch96] for the fit to the EGS4 calculation data:

\[ \varepsilon = a + c e x p \left[ b \ln \left( \frac{1.022}{E_{\gamma}} \right) + c \ln^2 \left( \frac{1.022}{E_{\gamma}} \right) \right] . \tag{4.22} \]

Although the constants are specific to the experimental conditions of that experiment [Sch96], this will give us a rough estimate of the effect. The gate used for summing the yield from the \( \gamma_1 \) transition spans the energy range 11.3-15.8 MeV. The efficiency changes from 2.13% to 1.60% over this energy regime. These values are 25% higher and 6% lower than the efficiency at 14.3 MeV, respectively, demonstrating a substantial change in the efficiency across the summing region.

Another problem exists which prevents an accurate measurement of the \( ^7 \text{Li}(p, \gamma_1)^8 \text{Be} \) cross section. Recall that in the previous section, a determination of the ground state cross section was performed. The yield used for this determination is derived from the number of observed counts in the full-energy peak. This specifically does not include the first and second escape peaks nor does it include any of the Compton background. Since the width of the \( \gamma_1 \) state is so large, the photopeak cannot be separated from the two escape peaks or the Compton background. The yield extracted (see section 3.3.2) therefore overestimates the true photopeak yield. Recall that the yield of the \( \gamma_0 \) photopeak is approximately a factor of four or five less than the yield which includes the two escape peaks and the Compton background between the photopeak and double-escape peak, even with the anticoincidence shield condition (it would be much greater had this requirement not been imposed). This factor is largely a function of the \( \gamma \) ray energy, and we can expect a similar contribution from these background sources in the \( \gamma_1 \) peak.

Because of these problems it is clear that a determination of the cross section based on the full-energy peak yield is not possible. Instead, we shall compare the relative cross section to that for the ground state by extracting the entire yield present, not just the full-energy peak. We expect the efficiencies for this measurement to be quite similar for both the ground state and first excited state transitions. The justification for this follows from the fact that the total absorption coefficient for \( \gamma \) rays between 10 and 20 MeV is
approximately constant (see [Mar68]), and from the fact that the efficiency is a function of this variable. The efficiency may be expressed as [Ros53]:

\[ \varepsilon(\beta) = 1 - e^{-\tau x(\beta)}, \]  

where \( x(\beta) \) is the distance traversed by the radiation in the crystal, incident at an angle \( \beta \) with respect to the detector axis, and \( \tau \) is the total absorption coefficient.

In order to determine the ratio of the \( \gamma_1 \) to \( \gamma_0 \) yield two procedures were followed. The first uses the HPGe data and the second uses an independent measurement using NaI detectors. In order to estimate the full response of the HPGe detector a background function was calculated and used to represent the Compton tail. This is shown in Figure 4.10. After subtracting the cosmic-ray background, which is known to be approximately constant at these energies [Wel96a], the full-response yield was extracted. Using the same energy gate, the full-response yield for capture to the first excited state was determined. This calculation gives the ratio of the total \( \gamma_1 \) yield to the total \( \gamma_0 \) yield to be 2.0, and so the cross section should also scale by this factor. This procedure is not expected to be a reliable method of determining the ratio of the total cross section for the two transitions and was performed only to see if the HPGe data gives approximately the "correct" value. A more detailed analysis of the HPGe data would provide a more accurate result, however, this was not pursued. Instead, the method we used for determining this ratio involves \( \gamma \)-ray detection with a NaI detector, and is described below.

An independent measurement was performed which determines the \( \gamma_1 \) to \( \gamma_0 \) ratio in a different manner. A large, anticoincidence shielded NaI detector was used to observe proton capture on \(^7\text{Li} \) [Spr96]. As Figure 4.11 shows, the yield for capture to the ground and first excite states are clearly resolved. A preliminary analysis of this data indicates that the ratio of these is 2.92 with a statistical error of 4.7\% (\( \tau = 2.92 \pm 0.14 \)). Any systematic errors (for example, choice of summing regions) will increase this error. This ratio is in fair agreement with the determination mentioned previously and in excellent agreement with earlier experimental results of Prior et al. [Pri95, Pri96]. Therefore, the ratio of the total,
angle-integrated cross section for proton capture to the first excited state of $^8\text{Be}$, compared to the ground state, at $E_p=70$ keV is $2.92 \pm 0.14$. Previous studies [Mai60, Cec92, Zah95a] have established that the astrophysical $S$-factor for proton capture to the first excited state of $^8\text{Be}$ is constant at the low energies of the present study. Furthermore, our direct capture plus M1 resonances calculations (see Chapter 5) also predict this behavior. Therefore we conclude that, based on a comparison to the ground state, the astrophysical $S$-factor for the $^7\text{Li}(p,\gamma_1)^8\text{Be}$ reaction below $\sim80$ keV is $S_{\gamma_1}(E) = (0.73 \pm 0.11)$ keV · barns.
Figure 4.11: NaI spectrum used for computing the $\gamma_1$ to $\gamma_0$ yield ratio. The two (full-response) peaks are well separated from each other. Cosmic-ray background is subtracted by normalizing to the yield above the $\gamma_0$ peak.

4.5.5 Calculation of $S(E)$: The Third Excited State

A typical scintillator TAC-gated energy spectrum for capture to the third excited state of $^8\text{Be}$ and a fit to the data was displayed in Figure 3.8 on page 59. Extracting the yield is quite easy, as explained in section 3.3.3. Correcting for the accidental rejection of true events, computer dead-time, and attenuation factors gives the yield to be used in equation 3.19. Since the data here show no signs of E1/M1 mixing, it is assumed that the reaction proceeds via pure s-wave capture. In that case, the astrophysical S-factor is a constant and may be factored out of the integral. The only other pieces of information needed are the efficiency and solid angle.
CHAPTER 4. RESULTS AND ANALYSIS

The value for the efficiency time solid angle was determined for this experimental setup using a mixed radioactive source. As explained in section 4.5.2, the quantity \( \varepsilon \Delta \Omega \) was determined at four energies and a curve following the functional form of equation 4.18 was fitted to these points. The value for \( \varepsilon \Delta \Omega \) at 698 keV is 0.1084. The error associated with this will be discussed in section 4.5.6.

The data for the \( ^7\text{Li}(p,\gamma)^8\text{Be} \) reaction was obtained by performing a coincidence experiment, detecting \( \gamma \) rays in the HPGe detector and alpha particles in the plastic scintillators. Therefore, the probability that a \( \gamma \) ray that enters the HPGe detector is tagged as a coincidence event must be accounted for. This in turn depends on the alpha particle detector efficiency and the fraction of alpha particles that are directed towards the detector array. The plastic scintillators used are essentially 100% efficient [Bic91]. Since the alpha particle distribution is approximately isotropic, the number of interest here is simply the fraction of space the detector covers (out of \( 2\pi \) steradians since two identical particles are released back-to-back in the center of mass reference frame).

Determination of this number was performed using a radioactive \( ^{241}\text{Am} \) source. The source was placed at the target location and the number of alpha particles detected (in a given time period) was recorded. Next the source was placed directly against one piece of scintillator, such that every alpha particle emitted (into one hemisphere of space) would be detected. The ratio of these two numbers is the fraction of space covered by the scintillator array. The value was determined to be 0.62 and the \( \gamma_3 \) yield has been corrected by this factor. This technique was performed several times using different scintillator pieces and with the source in different positions. The results agreed within 5% of the original measurement and the error is taken as such. Additionally, a mathematical calculation of the solid angle covered by the scintillator array was performed using MATHEMATICA [Wol91]. Assuming a point source for the \( \alpha \) particles, a value of 3.77–4.10 steradians was determined (allowing for an error in the measurement of the source to scintillator distance of one eighth of an inch), or equivalently, 60–65% of \( 2\pi \) steradians.
Table 4.6: The extracted yield for the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ reaction, and the parameters used for determining the angle-integrated cross section.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counts</td>
<td>1040.7</td>
</tr>
<tr>
<td>Accidental Correction</td>
<td>1.0058</td>
</tr>
<tr>
<td>Dead-Time Correction</td>
<td>1.0067</td>
</tr>
<tr>
<td>Attenuation Factor</td>
<td>0.9719</td>
</tr>
<tr>
<td>Corrected Counts</td>
<td>1156.7</td>
</tr>
<tr>
<td>Integrated Charge (Coul)</td>
<td>8.66</td>
</tr>
<tr>
<td>Efficiency \cdot solid angle</td>
<td>0.1084</td>
</tr>
<tr>
<td>Scintillator Factor</td>
<td>0.62</td>
</tr>
<tr>
<td>$S(E)$ Energy Dependence</td>
<td>constant</td>
</tr>
<tr>
<td>$\sigma(70 \text{ keV})$ (nb)</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Since the TME analysis of the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ data suggests a possible 100% E1 capture solution (with $0 \pm 0.1\%$ M1 admixture), the astrophysical $S$-factor is assumed to be a constant over the energy range of these studies. Using the program CALCXS and the parameters cataloged in Table 4.6 we find $S_{\gamma_3}(E) = 0.00645 \text{ keV}\cdot\text{barns}$ and the angle-integrated cross section at 70 keV is $\sigma(70 \text{ keV}) = 1.40 \text{ nanobarns}$.

4.5.6 Errors

In a perfect system, the error associated with the cross section would simply be a reflection of the statistical uncertainty in the measurement. These errors are easily accounted for and have been previously discussed (see sections 3.3.1 and 3.3.3). However, since it is implausible to acquire complete knowledge of all the experimental parameters at once, we must introduce systematic errors into our considerations. Possible sources of systematic errors include beam current integration, uncertainties in the correction factors, errors in the solid angle determination, uncertainty in the efficiency of the HPGe detector, and (for
\(\gamma_3\) error in the scintillator factor.

The computer dead-time and accidental correction factors were quite small and the associated errors have been neglected. The attenuation factor may be slightly altered due to the angle that the detected \(\gamma\) ray enters the crystal. The largest effect gives values \(\sim 1\%\) higher than the factors previously presented, and the errors are taken as this. The precision of the beam current integration, as discussed in section 2.3.3, is known to be better than 1%.

Recall that the data for capture to the third excited state is spread out (mostly) because of the width of the state and the energy spread due to the stopping of the beam. As Figure 4.8 displays, the efficiency of the HPGe detector changes over this width. Thus, a complete calculation would require determining the \(\gamma\)-ray energy associated with the beam energy (as it stops in the target) and then assuming a Gaussian distribution of \(\gamma\) rays, using the known width of the state, and adjusting the efficiency to the appropriate value in the program CALCXS. Since this is not expected to have a large effect, the efficiency was taken as a constant. The error associated with this may be estimated by comparing the experimentally determined values over the fitting range to the value used at 698 keV. The maximal difference is 8.86% and the error is taken as such.

The error associated with alpha detection by the scintillator (only necessary for the \(^7\text{Li}(p,\gamma_3)^8\text{Be}\) reaction) has been discussed in section 4.5.5 and was found to be 5%. To compute the total error all the sources of error, including statistical effects, are added in quadrature. These sources and the total error for the \(\gamma_3\) absolute cross section measurement are summarized in Table 4.7.

### 4.5.7 Final Results

To summarize the absolute cross section measurements performed, we list the obtained values here, along with the statistical and systematic errors. For the \(^7\text{Li}(p,\gamma_0)^8\text{Be}\)
CHAPTER 4. RESULTS AND ANALYSIS

Cross Section Calculation Errors

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current integration</td>
<td>1</td>
</tr>
<tr>
<td>Accidental Correction</td>
<td>0</td>
</tr>
<tr>
<td>Dead-time Correction</td>
<td>0</td>
</tr>
<tr>
<td>Attenuation Correction</td>
<td>1</td>
</tr>
<tr>
<td>Alpha detection by Scintillator</td>
<td>5</td>
</tr>
<tr>
<td>HPGe Solid Angle · Efficiency</td>
<td>8.86</td>
</tr>
<tr>
<td>Statistical Uncertainty</td>
<td>7.95</td>
</tr>
<tr>
<td>Total Error</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Table 4.7: Summary of the sources of error for the $^7\text{Li}(p,\gamma^3)^8\text{Be}$ absolute cross-section measurement. All values are given as a percentage. The total error is obtained by adding the individual errors in quadrature.

For the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction we find:

$$S_{\gamma^3}(E) = (0.240 \pm 0.036)(1 + 0.0003561 E_p + 0.0000034128 E_p^2) \text{ keV} \cdot \text{barns},$$

For the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction we find that the (relative) cross section is $2.92 \pm 0.14$ times greater than the ground state transition. Thus:

$$S_{\gamma}(E) = (0.73 \pm 0.11) \text{ keV} \cdot \text{barns},$$

$$\sigma_T(70\text{keV}) = 159 \pm 8 \text{ nanobarns}.$$

For the $^7\text{Li}(p,\gamma^3)^8\text{Be}$ reaction we find:

$$S_{\gamma^3}(E) = (6.45 \pm 0.84) \text{ eV} \cdot \text{barns},$$

$$\sigma_T(70\text{keV}) = 1.40 \pm 0.18 \text{ nanobarns}.$$
Chapter 5

Direct Capture Calculations

This chapter presents the theory of Direct Capture and the results of calculations for the $^7$Li($p,\gamma$)$^8$Be reaction. We will begin with a brief overview and explanation of the nuclear physics processes occurring, and then discuss calculations performed for capture to the ground, first, and third excited states of $^8$Be over the energy range 0–1500 keV. Some of the parameters of these calculations will be determined by comparing the predictions to the experimental data of Zahnow et al. [Zah95a]. Next we will use these results to predict the values of the measured observables ($\sigma(\theta)/A_0$ and $A_p(\theta)$ at $E_p$=80–0 keV) over the angular range $\theta, = 0^\circ - 180^\circ$ and compare this to the data presented in this dissertation. Lastly, these calculations will be extended to the $^7$Be($p,\gamma$)$^8$B system.

5.1 Direct Capture Theory

The Direct Capture (DC) model describes a reaction occurring between two particles, the projectile and the target, where both are assumed to be structureless. In this framework, radiative capture is considered a one-step process which occurs in a very short time ($\approx 10^{-22}$ seconds), thus the name direct capture. No intermediate, or compound, nuclear state is formed. Therefore, a non-resonant reaction may be described as a transition from the initial (continuum) state to the final (bound) state mediated by the electromagnetic
1. Incident channel | 2. $\gamma$-ray emission | 3. $\alpha$ decay

Figure 5.1: Classical picture of direct capture for the $^7\text{Li}(p,\gamma)^8\text{Be}^* \rightarrow 2\alpha$ reaction.

force. This is written as

$$T_{f,i} = \langle \Psi_f | H | \Psi_i \rangle,$$

where $|\Psi_i\rangle$ is the continuum initial state, $|\Psi_f\rangle$ is the final bound state, and $H$ is the Hamiltonian. In the continuum state the incoming nucleon is affected only by a nuclear potential and undergoes a radiative transition from this scattering state directly to the final state, which is viewed as a single-particle bound state. The end result of the reaction is the residual nucleus (target core plus single particle) and the emitted $\gamma$ ray. Figure 5.1 shows a representation of direct capture for the $^7\text{Li}(p,\gamma)^8\text{Be}$ experiment.

Next the Hamiltonian is separated into two parts such that

$$H = H_0 + H'.$$

Here $H_0$ will contain all the kinetic and potential energy terms of the projectile and target and also the free electromagnetic field and $H'$ describes the electromagnetic interaction [Rol73]. Since the latter of these two terms will be approximately 137 times smaller than the former, perturbation theory may be used to calculate the electromagnetic transition.
rate (and eventually, the cross section). The first step starts with Fermi’s Golden rule (number 2):

\[
W_{fi} = \frac{2\pi}{\hbar} |\langle \psi_i | H' | \psi_f \rangle|^2 \rho_f(k),
\]

(5.3)

which gives the transition rate (between the initial and final state) in terms of the unreduced transition matrix elements \( T_{fi} \), as given in equation 5.1. Thus the cross section is quite simply expressed as the rate divided by the flux of incoming particles:

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

(5.4)

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

\[
\frac{d\sigma}{d\Omega} = \frac{E_n}{2\pi \hbar^2 \epsilon^2 (2j_p + 1)(2j_f + 1) \sum_{m_{i,j}}} |\langle \psi_i | H' | \psi_f \rangle|^2.
\]

(5.5)

Here \( j_p \) and \( j_f \) 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. Alternatively, we may express the total direct capture cross section (on a spin zero target nucleus) for a particular electric transition of multipolarity \( L \) as [Wel80]

\[
\sigma_f = 4\pi e^2 \frac{197}{137} \frac{k_f}{E_a k_a} \frac{(2j + 1)}{(2x + 1)} B_L^2 \sum_{i,j} |T_{ji}^{L;ia;ia}|^2,
\]

(5.6)

where

\[
B_L^2 = \frac{L + 1}{(2L + 1)L} \frac{k_f^2 L}{[(2L - 1)!!]^2}.
\]

(5.7)

In this equation the transition matrix elements are

\[
T_{ij}^{L;ia;ia} = \epsilon^{ia-iL} C(jL;ja, 1/2, 0, -L) \sqrt{C^2 S_{ij}} \langle u_{ij}(r)|r^L|\chi_{ia;ia}^{(4)}(r) \rangle,
\]

(5.8)

where \( |u_{ij}(r)\rangle \) and \( |\chi_{ia;ia}^{(4)}(r)\rangle \) are the radial parts of the bound state and scattering state wave functions, respectively. Other specifics, including equations to relate this to targets with nonzero spin, are given in Weller and Roberson’s paper [Wel80].
CHAPTER 5. DIRECT CAPTURE CALCULATIONS

5.1.1 Wave Functions

In order to evaluate equation 5.5, 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:

\[
V(r) = V_0(r) + V_c(r),
\]

where \( V_c(r) \) is the coulomb potential and \( V_0(r) \) is the real central potential with the Woods-Saxon form factor:

\[
V_0(r, r_0, a_0) = \frac{V_0}{1 + e^{(r-r_0)/a_0}}.
\]

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. The same optical model parameters are used in these calculations, except for the real well depth, \( V_0 \), which is adjusted such that the calculated binding energies match the experimentally determined values (given in [AS88]).

5.1.2 The Electromagnetic Operator

The last piece of information needed to evaluate equation 5.5 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 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 magnetic dipole (M1) terms are necessary.

In calculating the electric multipole operators, Siegert’s theorem [Sie37] is used to replace the electric current density with the charge density. Also, the long wavelength approximation is evoked since $kr \ll 1$. Thus, electric multipoles possess the factor $(kr)^n$, and diminish rapidly for higher order multipoarities. The single-particle M1 operator is given in [Wel82] as

$$O_{M1} = \mu_0 (g_\alpha \vec{J}_\alpha + \mu \vec{\sigma} + \alpha \vec{L}),$$

(5.12)

where

$$\mu_0 = \frac{e\hbar}{2mc},$$

(5.13)

and

$$\alpha = \frac{Z + A^2 Z_n}{A + A^2}.$$  

(5.14)

In equation 5.12 $g_\alpha$ is the gyromagnetic ratio for the target of spin $\vec{J}_\alpha$, $\mu$ is the magnetic moment of the nucleon, $\vec{\sigma}$ is the Pauli spin matrix, and $\vec{L}$ is the operator for the relative angular momentum between the projectile and the target.

### 5.2 Direct Capture Calculations

Direct calculations have been performed by using the computer code HIKARI [Kin83], which has the ability to include direct capture terms and add in any desired resonances (in this case, two M1 resonances). This code first extracts the angular dependence from the integral (equations 5.5 and 5.11) in terms of angular coupling coefficients and Legendre polynomials. The equations that the code uses are those listed in equation 4.12, and a thorough discussion may be found in Seyler and Weller’s paper [Sey79]. Next, evaluation
CHAPTER 5. DIRECT CAPTURE CALCULATIONS

of the radial integrals are performed numerically, allowing the radius to vary from 0 to 100 fermi.

Direct capture is expected to be the prevailing mechanism at these low energies. However, as mentioned in section 1.6, the tails of the well known M1 resonances (at $E_p=441$ and 1030 keV in the laboratory frame) are expected to have an effect even at the low energies of this study. Therefore, in addition to direct E1 and M1 capture, our calculations also include these two M1 resonances. Although their contributions to the cross section are quite small, they may give rise to significant analyzing powers. Note that nonzero values for the analyzing power at 90° would be an indication of interference between electromagnetic transitions of different parity.

To better understand the effects of these resonances, the following procedure was followed. First direct capture calculations for the ground state transition were performed over the proton energy range 0–1500 keV, and included the known M1 resonances. The parameters for these resonances are well established, are taken from [AS88], and are listed in Table 4.1 on page 70. The strength was varied until the cross section data of Zahnow et al. [Zah95a] was reproduced. With this established, the calculations were performed at 70 keV and the analyzing power and angular distribution of the cross section as a function of $\gamma$-ray angle was examined and compared to the experimentally measured values. A similar procedure was followed for the $\gamma_1$ and $\gamma_3$ transitions. These calculations are discussed below.

5.2.1 The Ground State

The ground state of $^8$Be is known to be largely a proton single particle in the first $p_\frac{3}{2}$ shell. For the calculations, it shall be considered a pure single-particle state, with a spectroscopic factor of unity. Our first goal is to reproduce the extensive ground state data of Zahnow et al. [Zah95a]. Including the two known M1 resonances (using resonance parameters from the A=5–10 data compilations [AS88]) and adjusting the strengths of the resonances allowed us to fit the data fairly well, as shown in Figure 5.2. Note that when we
Figure 5.2: Direct capture plus M1 resonances calculation for the $^7\text{Li}(p,\gamma_0)^8\text{Be}$ reaction. The astrophysical $S$-factor is plotted against the proton lab energy. Also displayed is the data of Zahnow et al. [Zah95a].

required the two resonances to add constructively in the region between the two levels, the fit was much better. Barker [Bar95] has come to the same conclusion and points out that this contradicts findings from shell model calculations. The data and our fits are shown in Figure 5.2. Note that the calculations for the cross sections have been converted to astrophysical $S$-factors (using equation 1.8).

The data we have obtained are for proton energies of 80–0 keV. As explained in section 3.3, over 80% of the yield arises from protons of energy 80–60 keV and the "median energy" is ≈ 70 keV. Therefore we have performed calculations of the cross section and analyzing power at 70 keV, as a function of angle, and compared them with the experimen-
tally measured data. These results are shown in Figure 5.3. Note that the calculation does not reproduce fully the asymmetry in the \( ^7\text{Li}(p,\gamma_0)^8\text{Be} \) cross section reported by Chasteler et al. [Cha94]. The re-measured analyzing powers for this reaction reported in this dissertation (section 4.2.1) are also not predicted, although the calculation which requires destructive interference between the two levels is slightly better. The measured vector analyzing power \((\approx 0.4 \text{ at } \theta = 90^\circ)\) is about a factor of two greater than the calculations predicts. Thus the M1 amplitude needs to be doubled, and (since \( \sigma \sim \text{amplitude}^2 \)), we need four times as much M1 strength compared to what this direct capture calculation predicts!

The direct capture plus M1 resonances calculations find a \( \sim 6\% \sim 10\% \) M1 contribution to the cross section for the constructive (destructive) interference solution. Since the measured data imply that the M1 strength is under-predicted by a factor of four, a 24\% (40\%) M1 contribution would be required to fit our data. This is unsatisfying, but let us proceed.

5.2.2 The First Excited State

The unresolved S-factor for capture to both the ground and first excited states is reported in [Zah95a]. Following the same procedure as in the ground state, direct capture calculations are performed including terms added in for the two M1 resonances. Unlike the ground state, the first excited state is considered to be a mixture of \( p_{1/2} \) and \( p_{3/2} \) single-particle states. The spectroscopic factors have been previously determined [Man81, Swe69, Coh67] and are listed in Table 5.1, along with the spectroscopic factors used in the \( \gamma_0 \) and \( \gamma_3 \) calculations. In this situation, the direct capture calculations need to be performed twice, once for a \( p_{1/2} \) single-particle bound state and once for a \( p_{3/2} \) single-particle bound state. The HIKARI code includes the spectroscopic factors. The total cross section is determined by adding these two pieces together. The angular distribution of the cross section and analyzing power calculations use both sets of data weighted by the predicted value for \( A_0 \),
Figure 5.3: Angular distribution of the cross section and analyzing powers at $E_p=70$ keV for the $\gamma_0$ transition. The data represent integrated yields from 80 to 0 keV. The curves are direct capture plus M1 resonances calculations for constructive and destructive interference (referring to the energy regime between the two resonances). See the text for a further explanation.
CHAPTER 5. DIRECT CAPTURE CALCULATIONS

<table>
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<th>Spectroscopic Factors</th>
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Table 5.1: Spectroscopic factors used in the $^7\text{Li}(p,\gamma)^8\text{Be}$ direct capture calculations.

the absolute cross section normalization constant (given in equation 4.8). That is,

$$\sigma = \sigma^1 + \sigma^3,$$

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{[A_0^1 \sigma(\theta)^1] + [A_0^3 \sigma(\theta)^3]}{A_0^1 + A_0^3},$$

$$A_\nu(\theta) = \frac{[A_0^1 A_\nu(\theta)^1] + [A_0^3 A_\nu(\theta)^3]}{A_0^1 + A_0^3},$$ (5.15)

where the superscripts 1 and 3 represent the $p_{\frac{1}{2}}$ and $p_{\frac{3}{2}}$ single-particle states, respectively.

The overall normalization of the spectroscopic factors are allowed to vary until the direct capture only calculation agrees with the data of Zahnnow et al. [Zah95a]. Next, as in the $\gamma_0$ case, the strengths of the M1 resonances are allowed to vary until a suitable fit of the cross section (reported in [Zah95a]) is found. These data and our fits are shown in Figure 5.4. As can be seen, these direct capture plus M1 resonances calculations are in good agreement with the data.

Next the direct capture calculations are performed at $E_p=70$ keV over the angular range $\theta = 0^\circ - 180^\circ$. Figure 5.5 shows these calculations, the angular distribution of the cross section reported in [Cha94], and the analyzing powers of the present study. The data, which display an isotropic cross section and analyzing powers consistent with zero, are well represented by the direct capture plus M1 resonances calculations.
5.2.3 The Third Excited State

The direct capture calculations for the \( \gamma_0 \) and \( \gamma_1 \) transitions have been quite enlightening. A similar calculation has also been performed for the \( \gamma_3 \) state. Proton capture to the third excited state of \(^8\text{Be}\) has been studied previously and the spectroscopic factors determined [Man81, Swe69]. These are listed in Table 5.1. In the previous two sections the first step involved varying the strength of the M1 resonances until the cross section is fit over a large energy range. The extensive data of [Zah95a] has been used in those cases, but, unfortunately, Zahnow et al. [Zah95a] do not report cross section data for the \( \gamma_3 \) transition.

The data of Sweeney and Marion [Swe69] was used in order to estimate the strength of the M1 resonances in the \( \gamma_3 \) transition. In this paper, the differential cross section for
Figure 5.5: The angular distribution of the cross section and analyzing powers at $E_p = 70$ keV for the $\gamma_1$ transition. The data represent integrated yields from 80 to 0 keV.
$^7\text{Li}(p,\gamma_3)^8\text{Be}$ at $\theta = 120^\circ$ was given for proton energies between 441 and 1400 keV. Assuming an isotropic cross section the astrophysical $S$-factor was calculated, and the strength of the two M1 resonances were adjusted to match these values. The calculations for $S(E)$ are shown in Figure 5.6. The contributions of each single-particle state ($p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$) are shown along with the total direct capture calculation and the DC plus M1 resonances calculation. Note that our direct capture calculations match those in [Swe69] at $E_p=200$ keV.

The measured value for the absolute cross section has been discussed in section 4.5. Figure 5.7 examines the direct capture calculation below 200 keV, and the data measured for this experiment is shown. Again, the data represent an integrated yield from 80 to 0 keV! The astrophysical $S$-factor is extracted from the data by assuming no energy dependence
Figure 5.7: Experimental measurement of the $\gamma_3$ astrophysical $S$-factor shown with a direct capture calculation, which includes the M1 resonances. The vertical error bars represent statistical and systematic uncertainties.

in this region. The choice to display the data at 70 keV with an error ranging from 60 to 80 keV is made because most of the yield comes from this energy regime (as explained in section 3.3).

Continuing along the same lines as before, the angular distributions of the cross section and the analyzing power are calculated at $E_p=70$ keV as a function of $\gamma$-ray angle. These calculations along with the experimentally measured values are displayed in Figure 5.8. The data measured for the $^7\text{Li}(\vec{p},\gamma_3)^8\text{Be}$ reaction are well reproduced by the direct capture plus M1 resonances calculations. There is no evidence of any E1/M1 mixing in this data, since $A_\gamma(90^\circ)$ is nearly zero. The slightly anisotropic cross section and small analyzing powers predicted by the model arise from a mixing of $s$- and $d$-wave E1 amplitudes.
Figure 5.8: The angular distribution of the cross section and analyzing powers at $E_p=70$ keV for the $\gamma_3$ transition. The data represent integrated yields from $E_p=80-0$ keV.
CHAPTER 5. DIRECT CAPTURE CALCULATIONS

5.3 Summary and Discussion

The direct capture calculations for proton capture to the ground state of $^8$Be gave mixed results. The cross section data is well accounted for over a large energy range when both M1 resonances are added. However, contrary to shell model calculations, we required constructive interference of the two resonances between the levels. It has been argued ([Rol94, Bar95]) that the tails of these M1 resonances are providing the $p$-wave strength observed by Chasteler et al. [Cha94]. If this were true, the direct capture calculations at low energies would reproduce the observed effects. The most noticeable effects of E1/M1 mixing would be an anisotropic cross section and a nonzero analyzing power at 90°, where E1-M1 interference terms are significant.

The ground state data of [Cha94] and [God96] are presented in Figure 5.3 along with the direct capture calculations at 70 keV. Notice that these calculations predict an anisotropic cross section ($\sim 20\%$) and nonzero analyzing powers ($\sim 0.2$ at 90°). The effect of constructive versus destructive interference produces only a small change, since it is the first resonance (at $E_p=441$ keV) that has the biggest effect. Also note that calculations using only direct E1 and M1 radiation yield an isotropic cross section and analyzing powers consistent with zero. The tails of the M1 resonances produce noticeable effects in the cross section and analyzing powers even at these low energies, but do not give a quantitative account of the measured observables. We are left with the conclusion that the direct capture plus M1 resonances model does not completely predict the effects seen in the low-energy, ground state data. The measured cross section (anisotropic at $\approx 30\%$) and measured vector analyzing power ($\approx 0.4$ at 90°) are approximately a factor of two greater than the calculations predict. Thus the M1 amplitude needs to be doubled, and (since $\sigma \sim \text{amplitude}^2$) we need approximately four times as much M1 strength as predicted by this model.

On the other hand, both the first and third excited states data are well explained. The cross section data for the first excited state was constructed by including direct E1
and M1 capture to both the $p_{\frac{1}{2}}$ and $p_{\frac{3}{2}}$ states along with the two M1 resonances. The angular distribution of the cross section and analyzing power data do not exhibit any signs of mixing of opposite parity radiation, nor do the calculations show any. The third excited state is not as well studied and very little cross section data exists. However, using an estimate (section 5.2.3) of the resonance strengths the cross section predicted by the calculations disagreed (by a factor of 2) with the low-energy value presented in this dissertation (Figure 5.7). The measured angular distribution of the cross section and analyzing power data show no signature of opposite parity radiation mixing. In fact, the transition matrix element analysis (section 4.3.4) predicts either a pure E1 or pure M1 capture amplitude solution. The calculations show essentially the same effect.

These results are quite intriguing. Consider the ground state where M1 strength may be arising from a $p_{\frac{1}{2}} \to p_{\frac{3}{2}}$ transition. The first excited state is a mix of $p_{\frac{1}{2}}$ and $p_{\frac{3}{2}}$ single-particle states, with neither component presenting itself as dominant. Note also that the M1 resonances are weaker in the first excited state compared to the ground state. For example, at a proton energy of 441 keV, the ratio of the cross sections predicted by the direct capture plus M1 resonances calculation compared to the direct capture only calculation is 460 for the $\gamma_0$ transition but only 76 for the $\gamma_1$ transition. For these reasons, we might expect a smaller M1 strength here. The third excited state is also a combination of 2 single-particle states, but the $p_{\frac{3}{2}}$ component is clearly dominant (Figure 5.6). Why would the large $p$-wave, M1 strength seen in the ground state not be observed in the third excited state? The most important factor is the strength of the M1 resonances. The ratio of the cross sections at a proton energy of 441 keV with and without the resonance added is 24 (compared to 460 in the $\gamma_0$ reaction), showing that the M1 resonance is fairly weak here.

Another related subject that should be investigated is the bound-state wave functions. The radial part of the bound-state wave functions are shown in Figure 5.9. Note that the total radial wave function is plotted and that, where appropriate, the $p_{\frac{3}{2}}$ component
and the $p_{\frac{3}{2}}$ component have exactly the same radial dependence. Direct capture calculations of radiative proton capture assume a $\gamma$ ray is emitted during the proton's transition to this bound (single-particle) state. Riisager and Jensen [Rii93] argue that at low energies the main contribution to the cross section comes from the tail of the bound state wave function (especially if the proton is only weakly bound), which is certainly the case in this experiment. Simply, the large Coulomb barrier greatly suppresses the wave function of the incoming low-energy proton at small distances such that the cross section is very dependent on the final state wave function at large radii (i.e. the tail of this wave function). As the figure shows, the radial bound state wave function for capture to the third excited state is significantly different than that for capture to the ground state. It is broader and its
tail is much longer. In such a case p-wave capture strength might be expected to be very significant, compared to s-wave capture. This is another reason why the two reactions differ in terms of the M1 strength present. Although the spin of the ground and third excited states are different (J=0 and 2, respectively) the M1 partial waves involved in capture to the ground state are also involved in capture to the third excited state (see Table 4.2).

5.4 Boron-8

An important goal of this experiment is to compare these reactions with the \( ^7\text{Be}(p,\gamma)^8\text{B} \) reaction. Let us investigate the similarities and differences and continue our calculations.

In Chapter 1 the solar neutrino problem was introduced, which is a significant discrepancy between the experimentally measured and theoretically calculated flux of neutrinos produced in the sun and detected at the earth. Recall that several experiments are especially sensitive to the high energy neutrinos emitted from the decay of \( ^8\text{B} \) [Bah88], and that \( ^8\text{B} \) is produced in the sun from the \( ^7\text{Be}(p,\gamma)^8\text{B} \) reaction. Although an experiment that measures this cross section at low (astrophysical) energies would be quite useful, no direct measurement of the capture reaction has been performed. Besides the usual difficulties associated with capture reactions (low cross sections and inefficient detectors) this particular reaction uses a radioactive target with a half-life of 53 days. Therefore manufacturing and handling the targets presents problems. Additionally, the decay of the \( ^7\text{Be} \) target produces on the order of ten million background \( \gamma \) rays (\( E_\gamma = 478 \text{ keV} \)) for every \( \gamma \) ray of interest (\( E_\gamma = 207 \text{ keV} \) with an 80 keV proton beam) [Wul96a]. This rate is insurmountable, and makes an experimental detection of \( \gamma \) radiation implausible for this reaction. However, the \( ^7\text{Li}(p,\gamma)^8\text{Be} \) reaction is expected to be very similar to the \( ^7\text{Be}(p,\gamma)^8\text{B} \) reaction, for reasons detailed in section 1.5.

The cross section for the \( ^7\text{Be}(p,\gamma)^8\text{B} \) reaction has been studied by detecting the delayed \( \alpha \) particles coming from the decay of the \( ^8\text{B} \) residual nucleus. Some of the studies
include [Kav69], [Vau70], and [Fil83a, Fil83b]. The technique used for these experiments is to bombard a $^7$Be target with protons and produce $^8$B. The $^8$B nucleus will beta decay, leaving an excited $^8$Be nucleus which subsequently decays into two energetic alpha particles. These alpha particles are detected, and the $^7$Be($p,\gamma$)$^8$B cross section deduced. Unfortunately, the analyzing powers for this reaction can not be measured by the delayed alpha detection technique, and so the sensitivity of the polarized observables is lost. This is one advantage of the $^7$Li($p,\gamma$)$^8$Be experiment we have pursued. Another advantage is, of course, that we have performed a direct $\gamma$-ray detection measurement. Additionally, our measurements were performed at a lower energy than previous measurements [Fil83a] ($\sim$61 keV versus 117 keV, in the center of mass).

The goal now is to extend our direct capture calculations to the $^7$Be($p,\gamma$)$^8$B system. As in the previous section, the procedure followed was to use the direct capture model and add in the known M1 resonance. The strength of this was varied until the calculations agreed with the data. Figure 5.10 displays the data of Filippone et al. [Fil83b] and the low-energy data of Vaughn et al. [Vau70]. The calculations agree quite well with these data. In the case of $^7$Li($p,\gamma$)$^8$Be the next step involved performing these calculations at 70 keV to check for any noticeable signs of E1/M1 mixing. The results of these calculations for the present case for both the angular distribution of the cross section and of the analyzing power are plotted in Figure 5.11. As in the $\gamma_3$ case, the analyzing power at 90° is almost zero, a result of the fact that there is an insignificant amount of M1 radiation in this model calculation (0.05%) at these low energies. The anisotropy in the angular distribution of the cross section and the non-zero analyzing powers at other angles arise from interference between s- and d-wave E1 radiative capture. In fact, there is theoretical evidence (see [Rob73] and [Kim87]) that E1, d-wave capture makes significant contributions to the cross section at these low laboratory energies and must be included. Robertson [Rob73] also argues that M1 p-wave capture contributes (above 165 keV), however, according to our model, these effects are negligible below 100 keV and certainly in the true solar environment of $E_p \approx$ 20 keV. In
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Figure 5.10: Direct capture plus M1 resonance calculation for the $^7\text{Be}(p,\gamma)^8\text{B}$ astrophysical $S$-factor.

that paper the author renormalized his direct capture calculation to match the low energy ($E_p=165-500$ keV) data of Kavaaagh et al. [Kav69] by multiplying by a factor of 1.266, although the author states that "any reasonable prescription for the s-wave potential ... gives essentially the same results at low energies." This renormalization is accounted for by an adjustment in the radius and diffuseness, which the author claims is reasonable. A more thorough explanation is given in that paper [Rob73].

It has been asserted throughout this dissertation that proton capture to the third excited state of $^8\text{Be}$ is quite similar to proton capture to the ground state of $^8\text{B}$. The wave functions of the third excited state of $^8\text{Be}$ and the ground state of $^8\text{B}$ as calculated
Figure 5.11: Direct capture plus M1 resonance calculations of the angular distribution of the cross section and analyzing powers performed at $E_p=70$ keV for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction.
in our single-particle model are plotted in Figure 5.12. As expected the radial part of the wave functions are almost identical, with the $^8$B distribution being slightly more extended than the $^8$Be* one. This is yet another reason to believe the $^7$Li($p,\gamma_3$)$^8$Be and $^7$Be($p,\gamma_0$)$^8$B reactions will behave in similar fashions, at least within the framework of the direct capture model. A discussion of the implications follows in Chapter 6, where the isospin issue (T=0+1 for $^8$Be* but T=1 for $^8$B) will be addressed.
Chapter 6

Summary and Conclusions

The $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction has been studied in great detail over the energy range $E_p=80-0$ keV. In particular, we have examined polarized and unpolarized proton capture to the ground, first, and third excited states of $^8\text{Be}$. The measured observables include the vector analyzing power, $A_p(\theta)$, the angular distribution of the cross section, $\sigma(\theta)/A_0$, and the absolute cross section, $\sigma_T(E_p=80-0$ keV). From this information we deduced the $\gamma_3$ astrophysical $S$-factor, $S(E)$ for $E_p=80-0$ keV. We have formulated a new extrapolation of the $\gamma_0$ astrophysical $S$-factor and have measured the total angle-integrated cross section for capture to the first excited state relative to the ground state. Note that all measured quantities presented in this dissertation may be found in the tables of Appendix B. Transition matrix element analyses have been performed for both the ground state and the third excited state (Chapter 4). Extensive direct capture calculations have been performed (Chapter 5) for all three states and have been extended to the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction.

6.1 Summary of Results

As presented in this dissertation, the analyzing power data for the ground state transition show signatures of E1/M1 interference (namely, a value of $0.4 \pm 0.014$ at 90° with $E_p=80-0$ keV). The model independent transition matrix element analysis (Chapter 4)
quantifies this conclusion. However, both the first and third excited states do not show any evidence of E1/M1 radiation mixing at these low energies. The cross section is isotropic and the analyzing powers are consistent with being equal to zero for both cases. A TME analysis of the $^7\text{Li}(p,\gamma)^8\text{Be}^*\rightarrow 2\alpha$ data demonstrates that this reaction occurs by pure s-wave capture or pure p-wave capture. The traditional theory of direct capture prefers the pure E1, s-wave solution, but an experimental proof is desired. Such a proof may be obtained by measuring the linear polarization of the $\gamma$ rays emanating from the reaction. This experiment is being pursued vigorously by our group at TUNL [Spr96].

6.2 Comparison with the Literature

Prior to the experiments presented here, Chasteler et al. [Cha94] demonstrated that proton capture to the ground state of $^8\text{Be}$ proceeds not only via E1, s-wave capture (as previously assumed [Cec92] for this energy regime) but also by M1, p-wave capture. That result has stirred great interest, controversy, and indeed concern. As pointed out in [Cha94], this will affect the extrapolation of the astrophysical S-factor for the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction and, perhaps, the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. Chasteler et al. [Cha94] argue that, because of similarities in the ground states of $^8\text{Be}$ and $^8\text{B}$, evidence of p-wave capture strength might have a significant impact on the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, and thus, the solar neutrino problem. This dissertation project has pursued that idea.

An explanation of the results of [Cha94] has been offered by Rolfs et al. [Rol94] and Barker [Bar95]. In these papers the authors argue that the tails of the M1 resonances (at $E_p=441$ and 1030 keV) provide enough p-wave strength to explain the data. In response to the first paper, Weller and Chasteler [Wel95] show that the p-wave strength obtained in the analysis of Rolfs and Kavanagh [Rol94] (which considered only the cross section data) is at least an order of magnitude too small. Barker [Bar95] has performed extensive R matrix fits to the data of [Cha94], allowing for both resonances and allowing the relative sign of the reduced width resonance amplitudes to change. The best fit consisted of 9.2% M1 strength.
CHAPTER 6. SUMMARY AND CONCLUSIONS

However, it required the two resonances to destructively interfere in the region between the levels, contrary to shell model predictions and fits to higher-energy data [Bar79]. In Figure 4.5 we show the results of a complete TME analysis of the Chasteler et al. [Cha94] data and the Godwin et al. [God96] data, which gives the chi-squared value as a function of percent M1 strength. Each of these curves shows a local minimum around 10% M1 strength, which may be thought to agree with Barker’s solution. However, in light of these analyses, it is clear that the best (i.e. lowest chi-squared) solution contains on the order of 40–50% M1 strength. The chi-squared value here ($\chi^2 = 0.79$) represents approximately a 70% confidence level, whereas the solution containing 10% M1 strength ($\chi^2 = 1.11$) represents only a 40% confidence level (see [AB88]). Note that there are 14 degrees of freedom in this analysis.

Zahnow et al. [Zah95a] have recently published an extensive set of cross section data for the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction, spanning from $E_p \approx 100$–1500 keV. We have fit this data by performing direct capture calculations which include the two well-know M1 resonances. Calculations were then performed at $E_p = 70$ keV in order to investigate if this model predicts the asymmetry in the cross section and large analyzing powers for the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction observed in [Cha94] and [God96]. It does not. Allowing the M1 strength to arise solely from the tails of the two resonances, we find that the analyzing power data are noticeably under-predicted, regardless of the relative sign convention of the two levels.

Barker has continued his studies [Bar96] and includes the data of [Cha94] and [Zah95a]. This work attempted to fit the data allowing the E1 contribution to be given by either an R-matrix formalism or s-wave direct capture. Both fits use the accepted relative sign of the $1^+$ levels (in agreement with shell model calculations). Barker’s direct capture fit agrees with this cross section data, but under-predicts the analyzing power of Chasteler et al. [Cha94] and Godwin et al. [God96] by about a factor of two. On the other hand, the R-matrix results, which introduce 1$^-$ levels in a somewhat ad-hoc fashion, do agree with the analyzing power data, but under-predict the low-energy (< 200 keV) cross
section data measured by Zahnow et al. [Zah95a] by as much as a factor of two. Note that this R-matrix approach does, however, reproduce the cross section measured by Cecil et al. [Cec92] at approximately 125 keV and is in moderate agreement below 200 keV (recall that Cecil et al. report a constant $S$-factor whereas Barker's results have a noticeable energy dependence). Possibly there are errors in the data of Zahnow et al. below 200 keV. Barker's two different models (direct capture and R-matrix) lead to a factor of 2 difference in the cross section and thus the extrapolated zero-energy $S$-factor. In light of these findings a continued effort to study the cross section below 200 keV, both experimentally and theoretically, is called for and should be pursued.

To summarize our findings concerning proton capture to the ground state of $^8\text{Be}$, although the M1 resonances do make sizeable contributions, they do not account entirely for the $\gamma_0$ data, and the physical origin of the large M1 strength in the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction remains unresolved. Perhaps the direct capture plus M1 resonances model is insufficient, or at least incomplete, at these energies. Other studies [Wul96b] are being performed and analyzed which may help resolve this problem.

The M1 to E1 cross section strength ratio for the $\gamma_0$ transition is needed for the $S$-factor extrapolation (this is not true for the $\gamma_3$ transition, as will be discussed later). This ratio could not be determined from these dissertation data, so instead we have used the ratio of the M1 to E1 cross section given by the direct capture plus M1 resonances calculations, with the caveat that these calculations do not predict the strength seen in the analyzing power data presented here. In Chapter 4 an extrapolation of the astrophysical $S$-factor is given which uses the direct capture plus M1 resonances model. Using the calculated M1/E1 ratio, and normalizing to the value given in [Cec92] at 70 keV, a functional form of $S(E)$ is predicted in the energy regime below 80 keV:

$$ S_{\gamma_0}(E) = (0.240 \pm 0.036)(1 + 0.0003561 E_p + 0.0000034128 E_p^2) \text{ keV \cdot barns.} \quad (6.1) $$

The zero-energy value of $0.24 \pm 0.036 \text{ keV \cdot barns}$ is approximately 4% lower than the value at $E_p=70 \text{ keV}$ in this model, and therefore 4% lower than the value given by the constant
CHAPTER 6. SUMMARY AND CONCLUSIONS

S-factor (E1 only) extrapolation procedure followed by Cecil et al. [Cec92]. Again, it should be stressed that the new method does not reproduce the M1 effects observed in the data. In fact, the analyzing power data require roughly four times the calculated M1 strength. If we take the M1/E1 ratio to be four times greater than predicted by the model, the S-factor (at 0 keV) is calculated to be approximately 12% lower than the value obtained by an E1 only extrapolation. An experiment that is aimed at a more direct measurement of this S-factor is currently underway [Spr96].

The ratio of the $\gamma_{1}$ to $\gamma_{0}$ angle-integrated cross section has been determined (section 4.5.4) for the energy range $E_{p}=80-0$ keV. We have argued that observables measured over this energy range may be approximated as being measured at $E_{p}=70$ keV. Both an estimate based on the HPGe spectra and an independent measurement using a NaI detector yield a ratio of approximately three. Based on this we report the astrophysical S-factor for capture to the first excited state (below $E_{p}=80$ keV) to be:

$$S_{\gamma_{1}}(E) = 0.73 \pm 0.11 \text{ keV} \cdot \text{barns.}$$ (6.2)

The direct capture plus M1 resonances calculations (Chapter 5) predict a ratio near 2.2, but we have pointed out short-comings in this model's ability to predict the M1 strength present in capture to the ground state. Cecil et al. [Cec92] report constant values for the astrophysical S-factor for the $^7\text{Li}(p,\gamma_{0})^8\text{Be}$ and $^7\text{Li}(p,\gamma_{1})^8\text{Be}$ reactions below 200 keV. Although the ground state transition cross section data agree with the direct capture calculations of that paper [Cec92], no direct capture calculation is made by the Cecil et al. of the cross section for capture to the first excited state. The ratio of the S-factors in their report is 4.8 (thus implying the same ratio in the angle-integrated cross section) which is much higher than both our measurements and the direct capture plus M1 resonances model prediction. The data of Zahnow et al. [Zah95a] give ratios of 1.95, 2.425, and 2.15 at $E_{p}=98.3$, 147.6, and 198.3 keV, respectively.
6.3 Discussion: $^8\text{Be}^\ast$ and $^8\text{B}$

One of the main goals of this dissertation is to understand the mechanism of the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction and to consider its relationship to the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. Regardless of the explanations offered for the $\gamma_0$ data, it is clear that capture to the third excited state of $^8\text{Be}$ is much more closely related to capture to the ground state of $^8\text{B}$. Let us review the reasons for this and our findings.

First, recall the A=8 isobar diagram displayed in Figure 1.2 (page 11). We see that both the third and fourth excited states of $^8\text{Be}$ have the same spin-parity ($2^+$) as the ground state of $^8\text{B}$. In addition, the $\gamma$ rays from the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ and $^7\text{Be}(p,\gamma)^8\text{B}$ reactions will have energies much closer to each other than that for the $^7\text{Li}(p,\gamma_0)^8\text{Be}$ reaction ($\sim 700$ ($\gamma_3$) and $\sim 200$ ($^7\text{Be}$) keV, respectively, for a proton beam of energy $E_p=80$ keV, versus $\sim 17000$ keV for $\gamma_0$). The third and fourth excited states of $^8\text{Be}$ are known to be completely mixed in isospin, as demonstrated by Sweeney and Marion [Swe69]. Their best representation of these states has been given in equation 1.11 and is listed here:

$$|16.63\rangle = 0.772 \ |T = 0\rangle + 0.636 \ |T = 1\rangle,$$
$$|16.92\rangle = 0.636 \ |T = 0\rangle - 0.772 \ |T = 1\rangle.$$

Since the third excited state is essentially a pure proton single particle, whereas the fourth excited state is a neutron single particle, we expect that proton capture to the third excited state will be much stronger than to the fourth excited state. This was confirmed in this dissertation since we have detected a sizeable number of events from the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ reaction but not from the $^7\text{Li}(p,\gamma_4)^8\text{Be}$ reaction, and is also supported by higher energy studies [Man81].

The T=1 component of the two states (together) is the isobaric analog of the ground state of $^8\text{B}$. Therefore, we purport that the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction will be quite similar to the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ reaction. In the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, E1 or M1 capture will occur from an initial T=1 state to a final T=1 state. In the $^7\text{Li}(p,\gamma_3)^8\text{Be}$ reaction the initial state may be
either \( T=0 \) or \( T=1 \). The isospin selection rule for electromagnetic transitions is generally

\[
\Delta T = 0, \pm 1. \tag{6.3}
\]

However, for self-conjugate nuclei (where the number of protons equals the number of neutrons, as in \(^8\)Be) a further constraint is present. Specifically, \( \Delta T = 0 \) transitions are strongly suppressed for E1 radiation [Gam52, Tra52], so

\[
\Delta T = +1 \text{ (FJ, self-conjugate nuclei).} \tag{6.4}
\]

Morpurgo [Mor58] has shown that the same is true for M1 transitions. Therefore, any E1 or M1 capture must proceed from a \( T=1 \) to a \( T=0 \) state or from a \( T=0 \) to a \( T=1 \) state. In either case the system is left in the third excited state of \(^8\)Be, a completely isospin mixed state, which then decays into two alpha particles. It should be stressed that because of the isotopic spin mixing, isospin is not a good quantum number for the 16.6 MeV state in \(^8\)Be. Therefore the capture reaction can go to this state from both the \( T=0 \) and \( T=1 \) continua. Because of this, this reaction is closely related to the \(^7\)Be\((p,\gamma)^8\)B reaction even despite the different isospin situations. Namely, in the \(^7\)Li\((p,\gamma_3)^8\)Be case we see that all available continuum strength goes into the final (isospin mixed) state. For \(^7\)Be\((p,\gamma)^8\)B, the continuum state must have \( T=1 \), since \(^8\)B cannot have \( T=0 \) states (because \( T_3=1 \)) and goes to the \( T=1 \) ground state (as seen by equation 6.3). Hence, here too, all the available continuum strength is permitted to go to the final state by E1 and/or M1 transitions.

The direct capture calculations performed in Chapter 5 further support our postulate as to the similarities between the two reactions. The ground state wave function for \(^8\)B and the third excited state single-particle wave function for \(^8\)Be formed using Woods-Saxon potentials are plotted in Figure 5.12. The two wave functions are almost identical.

Our data for the \(^7\)Li\((p,\gamma_3)^8\)Be reaction show an isotropic cross section and analyzing powers consistent with zero. The TME analysis implies either a pure E1 (s-wave) or a pure M1 (p-wave) solution. The direct capture plus M1 resonances calculations of the cross section are about a factor of 2 larger than the measured value of the absolute cross section.
CHAPTER 6. SUMMARY AND CONCLUSIONS

(see Figure 5.7 on page 117), and do not show any signs of significant M1 radiation mixing. These calculations do, however, reproduce the angular distributions of the cross section and analyzing power that we have measured (see Figure 5.8 on page 118). Further, when these calculations are extended to the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, they show no evidence for $p$-wave strength. Based on this we conclude that the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction occurs via essentially pure $s$-wave capture, although a definitive experimental proof at low energies is desirable and is being planned [Wul96a].

The discrepancy between the measured cross section (for capture to the third excited state) and the direct capture plus M1 resonances model needs to be resolved. Until this is accounted for, no high level of confidence in the model (and therefore the $s$-wave, E1 only extrapolation of the astrophysical $S$-factor) can be drawn.

6.4 Concluding Remarks and Implications

The similarities between the $^7\text{Li}(p,\gamma)^8\text{Be}$ and $^7\text{Be}(p,\gamma)^8\text{B}$ reactions are quite apparent. Our study of the former reaction shows no evidence for mixing of E1 and M1 radiation, and we conclude that the reaction proceeds by pure E1 capture. Therefore it is highly unlikely that M1 radiation will play a role in proton capture to the ground state of $^8\text{B}$. Recall that this reaction produces the $^8\text{B}$ present in the sun. The solar neutrino detection experiments of Davis et al. [Dav68] are most sensitive to the neutrinos produced by the beta decay of boron in the sun. The discrepancy between these measurements and theoretical calculations using the standard solar model is quite drastic, so much so that this conundrum has been labeled the solar neutrino problem. In fact, the experimental measurements are two to three times fewer than theoretically calculated.

Clearly the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction proceeds by both $s$-wave and $p$-wave capture. Since previous measurements of the astrophysical $S$-factor and the extrapolation of this quantity to zero energy have assumed only $s$-wave capture occurs, these values require revision. Chasteler et al. [Cha94] calculate that they may be 7–38% too high. Our calculations, which
Astrophysical $S$-Factors at $E_p=70$ and 0 keV

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\gamma_0$ (70 keV) $\gamma_0$ (0 keV)</th>
<th>$\gamma_1$ (70 and 0 keV)</th>
<th>$\gamma_3$ (70 and 0 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>keV barns           keV barns      keV barns      eV barns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Godwin $^a$</td>
<td>0.25                0.24             0.73              6.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Godwin $^b$</td>
<td>0.25                0.219            –                 –</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cecil $^c$</td>
<td>0.25                0.25             1.2               –</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zahnow $^d$</td>
<td>0.4                 0.4              0.9               –</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ The M1/E1 strength ratio value given by the model is used.
$^b$ 4 x M1/E1 strength ratio value is used.
$^c$ Values given by Cecil et al. [Cec92].
$^d$ Values interpolated from the graphs of Zahnow et al. [Zah95a].

Table 6.1: Summary of the astrophysical $S$-factor measurements performed in this dissertation. The values given by Cecil et al. [Cec92] and Zahnow et al. [Zah95a] are also listed for comparison.

use the direct capture plus M1 resonances model in order to estimate values for the M1/E1 cross section ratio, predict a zero-energy value 4% lower than that which would be obtained assuming a pure E1 direct capture model. However, we estimate that the M1/E1 cross section ratio is four times greater than the model predicts, which in turn gives a zero-energy $S$-factor value 12% lower than a pure E1 extrapolation. A direct experimental measurement of the slope of the $S$-factor at energies between 40 and 100 keV is being attempted [Spr96] and should help resolve this problem. Values for the astrophysical $S$-factor at 70 keV and 0 keV for the $^7\text{Li}(p,\gamma_0)^8\text{Be}$, $^7\text{Li}(p,\gamma_1)^8\text{Be}$, and $^7\text{Li}(p,\gamma_3)^8\text{Be}$ reactions are summarized and compared with other measurements in Table 6.1. Despite these discrepancies in the $\gamma_0$ measurement, however, it appears as though the essentially pure s-wave assumption is correct in the $^7\text{Be}(p,\gamma)^8\text{B}$ case, and therefore, the extrapolation of the nuclear cross section to zero energy is not in error.

Many other theories attempt to explain the solar neutrino problem [Bah96]. One
such theory, which many physicists believe will provide “the answer”, proposes that neutrino oscillations occur, where the electron neutrinos produced in the sun may change flavor (to a muon neutrino or a tau neutrino) as they traverse the distance from the sun to the earth. There are many facilities (such as SNO, Super Kamiokande, and Borexino) being constructed specifically to study this and other ideas. Perhaps soon an answer to the 30 year old solar neutrino problem will be found.
Appendix A

Code Used for Fitting the Third Excited State

Description:

This appendix presents the program SGASS.FCN, used to analyze the data gathered from the $^7\text{Li}(p,\gamma)^8\text{Be}$ reaction. The program is a subroutine which is called by Minuit [Jam77] and is written by the user. As described in section 3.3.3, the routine fits the $\gamma$ peak by assuming a Breit-Wigner shaped resonance and an exponential background. See the text for a more complete description. Also included are sample input and output files.

Program:

```
SUBROUTINE FCN(NPAR, GG, FF, X, IFLAG)
  c
  c
  c
  c  THIS PROGRAM IS DESIGNED TO BE A FITTING PROGRAM THAT FITS
  c  MARK GODWIN'S LOW ENERGY COINCIDENCE DATA TO A BACKGROUND
  c  FUNCTION AND A BREIT-WIGNER RESONANCE USING THE MINUIT
```
APPENDIX A. CODE USED FOR FITTING THE THIRD EXCITED STATE

C
C CHI-SQUARED MINIMIZATION PACKAGE
C
C *** This subroutine is CALLED by minuit ***
C Mark Godwin March 1995
C
C Minuit subroutine
C Inputs: npar=no. of ADJUSTABLE parameters
C GG = derivative vector (not used here)
C FF = value of function to be minimized
C X = parameter values
C IFLAG = control value 1==> set up constants
C 2==> derivative vector (NOT used here)
C 3==> write out information
C 4==> calculate F (CHI-SQR)
C >4==> not used here
C
C **************************************************
C
C 1 2 3 4 5 6 7
C 23456789012345678901234567890123456789012345678901234567890123456789012
C
C **************************************************
C
C ***************
C *** Define Variables ***
C ***************

IMPLICIT DOUBLE PRECISION (A-Z)
DOUBLE PRECISION GG(50),X(50),XDATA(2000),YDATA(2000),W(50)
DOUBLE PRECISION FNCT,ERR(2000),AO,XP(50),EN
DOUBLE PRECISION UPB,LOWB,CUT
DOUBLE PRECISION LOWCHX,UPCHX,JL,JH,NFREE
DOUBLE PRECISION CEXP,ARG1EXP,ARG2EXP,CBW,ERES,WIDTH
DOUBLE PRECISION NEMIL
REAL*B U(50), WERR(50) ! Common block parameters
CHARACTER*80 CHAR(50),FILEIN

INTEGER I, INDEX, IFIX(50) ! Counters and flags
INTEGER IPFIX(50), NPFIX ! Common block parameters
CHARACTER*7 COMM(10) ! Comment string

COMMON /FIX/ IPFIX, XS, XTS, WTS, NPFIX
COMMON /KEEP/XDATA,YDATA,NDATA,ERR
COMMON /PARAMS/U, WERR

Set a variable to be one million. Will use in fitting to
make extremely big or small variables to a 'better' size

ONEMIL = 1000000.
C
APPENDIX A. CODE USED FOR FITTING THE THIRD EXCITED STATE

C
GO TO (10,20,30,40,20),IFLAG

C
C Initialize
C
10 CONTINUE
C

C ***********************************************
C *** Read in data from input file ***
C ***********************************************

C
C Reads in from FOR005, which is assigned in the sgass.com
C file to be CARDS.INFO
C Writes out to FOR006, which is assigned in the sgass.com
C file to be SGASS.LOG
C
WRITE(6,*) 'What is the data file to be fit? (in x,y format)'
READ(5,99)FILEIN
99 FORMAT(A80)

C Read in lower and upper bound of data to be fit.
WRITE(6,*) 'Enter upper and lower bound on data to be fit.'
READ(5,*)LOWB,UPB

C Read in lower and upper bound of the 511 peak to be ignored
WRITE(6,*) 'Enter channels NOT to be included in fit (511s)'
READ(5,*) LOWCHX,UPCHX

C Read in lineshape spectrum to be fit. Assign data file to unit 20
OPEN(UNIT=20, FILE=FILEIN,STATUS='OLD')
I = 1
100 READ(20,*,END=101)TEMPX,TEMPY
    !Read one line of data
    !If end-of-file goto 101
    !Data in x,y format
    IF(TEMPX.GE.LOWB.AND.TEMPX.LE.UPB) THEN  !Copy data to xdata, ydata
        XDATA(I)=TEMPX
        YDATA(I)=TEMPY
        IF (TEMPY.LE.0.) THEN
            ERR(I) = sqrt(1.0)
        ELSE
            ERR(I) = sqrt(tempy)
        ENDIF
        I=I+1
    ENDIF
GOTO 100
101 NDATA=I-1
    !NDATA IS NOW #OF DATA POINTS
The following will cut out (and not include in the fit) a specified section of the data. For MAG that's the 511 peak.

```plaintext
JL = LOWCHX - LOWB + 1.
JH = UPCHX - LOWB + 1.
CUT = (YDATA(JL-1)+YDATA(JH))/2.
WRITE(6,*) 'CUT = ',CUT
WRITE(6,*) 'JL,JH = ',JL,JH
DO I = JL,JH
   YDATA(I) = CUT
ENDDO
WRITE(6,*)'EXITED LOOP'
CLOSE(20)
WRITE(6,*)'CLOSED 20'
RETURN
```

--------- Derivative Function. Not Used ---------

---------

20 CONTINUE

---------

30 CONTINUE

THIS IS THE LAST CALL TO FCN -- THE FITTING IS FINISHED BY NOW

Function is quadratic exponential + Breit-Wigner Peak

\[ F = C \exp(ax+bx^2) + CB(1/x)(1/[(x-Eres)^2+(Gamma/2)^2]) \]

where \( x \) = energy or channel number

Define the constants in the fitting function:

```plaintext
CEXP = X(1)
ARG1EXP = X(2)
ARG2EXP = X(3)
CBW = X(4)
ERES = X(5)
WIDTH = X(6)
```

***** Write out info. to file FOR040.dat, assigned to be SGASS.OUT *****
```
WRITE(40,*) ','
```
WRITE(40,321) FILEIN
WRITE(40,322) LDWB,UPB
WRITE(40,323) ONEMIL
WRITE(40,324) ONEMIL

321 FORMAT(' **** The data file fit: ',A40,' ****')
322 FORMAT(' **** Fitting region: ',F6.0,' to ',F6.0,' ****')
323 FORMAT(' **** NOTE: X(3) has been multiplied by ',F8.0,' ****')
324 FORMAT(' **** NOTE: X(4) has been divided by ',F8.0,' ****')
WRITE(40,*), '

C
C *** This section will write out comment string ***
C
DO I = 1, 50
  IFIX(I) = 0
ENDDO
I = 1
299 IF (IFIX(I) .NE. 0) THEN
  IFIX(IFIX(I)) = 1
  I = I + 1
  GOTO 299
ENDIF

DO I = 1, 6
  IF ( IFIX(I) .EQ. 1 ) THEN
    COMM(I) = '*FIXED*
  ELSE
    COMM(I) = ',
  ENDIF
ENDDO

C
C *** Now write out the fitted values, errors and comments ***
C
DO I = 1, 6
  WRITE(40,330) I, X(I), WERR(I), COMM(I)
330 FORMAT(' X(',I1,') = ',E15.8,' +/- ',E15.8,2X,A7)
ENDDO

C
C ***** The following loop calculateds the final chi-squared *****
C Note that it does not include (cuts out) the 511 peak
C
DO I = 1, NDATA
  EN=XDATA(I)
  FNCT=CEXP*EXP(ARG1EXP*EN + ARG2EXP*EN*EN/ONEMIL)+
   ARG3EXP*EXP(-EN/ONEMIL)
  CHISQ = CHISQ + (X(I) - FNCT)**2/ERROR(I)**2
  ENDDO

C
C *** End of the fitting process ***
C
C *** Now write out the final chi-squared value ***
C
PRINT 330, CHISQ
330 FORMAT(' CHISQ = ',F15.8)
&
  CBW*ONEMIL*EN/((EN-ERES)**2+WIDTH**2/4.)
  IF (I.LT.JL .OR. I.GT.JR) THEN
    FF = FF + ((YDATA(I)-FNCT)/ERR(I))**2  !Calculate chi^2
  ENDF
ENDDO

CHISQR = FF
NFREE = NDATA - 6. -(UPCHX-LOWCHX+1)  !**** CHECK THIS OUT***
CHIPE=CHISQR/NFREE

WRITE(40,167) CHISQR
WRITE(40,168) NFREE
WRITE(40,169) CHIPE

167 FORMAT ('/,' Total chi-squared = ',F9.3)
168 FORMAT (' Degrees of freedom = ',F7.2)
169 FORMAT (' Chi-squared/degree of freedom = ',F7.5)

C
C ***** Write out the fits (real*4) to data files:
C
C ***** Put the fitted spectra into FOR045, assigned to be SGASS.FIT
C ***** Put the fitted background into FOR046, assigned to be BAKC.FIT
C ***** Put the fitted breit-wigner into FOR047, assigned to be PEAK.FIT
C
DO I=LGWB,UPB
  EN=DFLOAT(I)

  FIT1=CEXP*EXP(ARG1EXP*EN + ARG2EXP*EN/ONEMIL)
  WRITE(46,*),I,FIT1

  FIT2 = CBW*ONEMIL*EN/((EN-ERES)**2+WIDTH**2/4.)
  WRITE(47,*),I,FIT2

  FIT = FIT1 + FIT2
  WRITE(45,*),FIT
ENDDO

RETURN

C***********************************************************************

40 CONTINUE

C***********************************************************************
APPENDIX A. Code Used for Fitting the Third Excited State

FF = 0.

C
C Note: Minuit minimizes the array X(npar)
C Define the constants in the function X to be a more descriptive name
C Function is quadratic exponential + Breit-Wigner Peak
C
CEXP = X(1)
ARG1EXP = X(2)
ARG2EXP = X(3)
CBW = X(4)
ERES = X(5)
WIDTH = X(6)

DO I = 1, NDATA
   EN=XDATA(I)
   FNCT=CEXP*EXP(ARG1EXP*EN + ARG2EXP*EN/EN/ONEMIL) +
   & CBW*ONEMIL/EN/((EN-ERES)**2+WIDTH**2/4.)
   IF (I.LT.JL .OR. I.GT.JH) THEN
      FF = FF + ((YDATA(I)-FNCT)/ERR(I))**2       !Calculate chi^2
   ENDIF
ENDDO

CHISQR = FF

C*******************************************************************************
C
RETURN
END
Sample Input File:

Run2106/SP1/511subtractedII
CEXP 100. 1.
ARG1EXP -0.004 0.0001
ARG2EXP 0.0 0.1
CBW 20. 0.1
ERES 630. 1.
WIDTH 101. 4.

Sample Output File:

**** The data file fit: [off14.li.fit.data]r2106sp415_xy.dat  ****
**** Fitting region:  350. to 1000.  ****
**** NOTE: X(3) has been multiplied by 1000000.  ****
**** NOTE: X(4) has been divided by 1000000.  ****

\begin{align*}
X(1) &= 0.11238419E+03 \pm 0.23817300E+02 \\
K(2) &= -0.39756197E-02 \pm 0.75311333E-03 \\
X(3) &= 0.44146659E+00 \pm 0.58887111E+00 \\
X(4) &= 0.21997818E+02 \pm 0.13785288E+01 \\
X(5) &= 0.62665766E+03 \pm 0.26124681E+01 \\
X(6) &= 0.10100000E+03 \pm 0.40000000E+01 \quad \ast \text{FIXED}\ast \\
\end{align*}

Total chi-squared = 797.910
Degrees of freedom = 636.00
Chi-squared/degree of freedom = 1.25457
Appendix B

Data Tables

All of the experimentally determined data presented in this dissertation are given below. Unless otherwise noted, the errors include only statistical uncertainty. In the first table, the γ-ray angle is given in both the laboratory and center of mass frame (at 80keV). Note that the data represent measurements over the beam energy 80–0 keV, and the center of mass angle changes over this range (at 0 keV θ_{Lab} = θ_{CM}).

<table>
<thead>
<tr>
<th>θ_{Lab} (θ_{CM})</th>
<th>γ₀</th>
<th>Δγ₀ (θ)</th>
<th>γ₁</th>
<th>Δγ₁ (θ)</th>
<th>γ₃</th>
<th>Δγ₃ (θ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 (0.0)</td>
<td>0.0105 0.0239</td>
<td>-0.0117 0.0089</td>
<td>-0.0479 0.091</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0 (15.024)</td>
<td>0.1075 0.0238</td>
<td>-0.1404 0.0078</td>
<td>-0.0135 0.051</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.0 (30.047)</td>
<td>0.2398 0.0265</td>
<td>-0.0156 0.0107</td>
<td>-0.0309 0.062</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60.0 (60.081)</td>
<td>0.3171 0.0211</td>
<td>-0.0017 0.0078</td>
<td>0.0029 0.092</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61.26 (61.342)</td>
<td>0.3619 0.0155</td>
<td>0.0285 0.0047</td>
<td>-0.0843 0.095</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90.0 (90.094)</td>
<td>0.3976 0.0138</td>
<td>0.0250 0.0062</td>
<td>0.0373 0.084</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97.0 (97.093)</td>
<td>0.3851 0.0230</td>
<td>-0.0170 0.0073</td>
<td>-0.0272 0.052</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>112.5 (112.587)</td>
<td>0.3962 0.0239</td>
<td>0.0062 0.0060</td>
<td>-0.1165 0.091</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table B.1: Analyzing powers for the \(^7\text{Li}(\vec{p},\gamma)^8\text{Be}\) reaction.
Table B.2: Angular distribution of the cross section measurements for the \(^{7}\text{Li}(\vec{p},\gamma_3)^{8}\text{Be}\) reaction.

<table>
<thead>
<tr>
<th>Angle</th>
<th>(\gamma_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_{\text{Lab}})</td>
<td>(\sigma(\theta))</td>
</tr>
<tr>
<td>15.0</td>
<td>1.014</td>
</tr>
<tr>
<td>30.0</td>
<td>1.087</td>
</tr>
<tr>
<td>90.0</td>
<td>1.000</td>
</tr>
<tr>
<td>97.0</td>
<td>1.083</td>
</tr>
</tbody>
</table>

Table B.3: Binned analyzing power data for the \(^{7}\text{Li}(\vec{p},\gamma_0)^{8}\text{Be}\) reaction.

<table>
<thead>
<tr>
<th>Angle</th>
<th>80–0 keV</th>
<th>85–65 keV</th>
<th>65–0 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_{\text{Lab}})</td>
<td>(A_y(\theta))</td>
<td>(\Delta A_y(\theta))</td>
<td>(A_y(\theta))</td>
</tr>
<tr>
<td>30.0</td>
<td>0.3381</td>
<td>0.0537</td>
<td>0.3855</td>
</tr>
<tr>
<td>61.26</td>
<td>0.3877</td>
<td>0.0469</td>
<td>0.4358</td>
</tr>
<tr>
<td>90.0</td>
<td>0.3927</td>
<td>0.0321</td>
<td>0.4068</td>
</tr>
</tbody>
</table>

Table B.4: The astrophysical S-factors determined for the \(^{7}\text{Li}(p,\gamma_0)^{8}\text{Be}\), \(^{7}\text{Li}(p,\gamma_1)^{8}\text{Be}\), and \(^{7}\text{Li}(p,\gamma_3)^{8}\text{Be}\) reactions.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Astrophysical S-Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_0)</td>
<td>(S(E)=0.240(1 + 0.0003561 E_p + 0.0000034128 E_p^2)) keV barns</td>
</tr>
<tr>
<td>(\gamma_0^a)</td>
<td>(S(E)=0.219(1 + 0.0012109 E_p + 0.0000116225 E_p^2)) keV barns</td>
</tr>
<tr>
<td>(\gamma_1)</td>
<td>(S(E) = 0.73 \pm 0.11) keV barns (constant)</td>
</tr>
<tr>
<td>(\gamma_2)</td>
<td>(S(E) = 6.45 \pm 0.84) eV barns (constant)</td>
</tr>
</tbody>
</table>

\(^a\) 4 \times M1/E1 ratio used.
<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>$\gamma_0$</th>
<th>$\gamma_1^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{Lab}}$</td>
<td>$\sigma(\theta)$</td>
<td>$\Delta\sigma(\theta)$</td>
</tr>
<tr>
<td>0.0</td>
<td>0.8093</td>
<td>0.0277</td>
</tr>
<tr>
<td>15.0</td>
<td>0.8321</td>
<td>0.0262</td>
</tr>
<tr>
<td>30.0</td>
<td>0.8473</td>
<td>0.0267</td>
</tr>
<tr>
<td>45.0</td>
<td>0.8749</td>
<td>0.0313</td>
</tr>
<tr>
<td>60.0</td>
<td>0.9088</td>
<td>0.0265</td>
</tr>
<tr>
<td>75.0</td>
<td>0.9372</td>
<td>0.0285</td>
</tr>
<tr>
<td>90.0</td>
<td>1.0000</td>
<td>0.0196</td>
</tr>
<tr>
<td>105.0</td>
<td>1.1040</td>
<td>0.0542</td>
</tr>
<tr>
<td>120.0</td>
<td>1.1823</td>
<td>0.0574</td>
</tr>
</tbody>
</table>

$^a$ This data is unpublished.

$^b$ No data available.

Table B.5: Analyzing power and cross section angular distribution data of Chasteler et al. [Cha94].
Appendix C

Code Used for Calculating $S(E)$

Description:

This appendix presents the program CALCXS, used to calculated the astrophysical $S$-factor based on the experimentally measured yield. See section 4.5.3 for more detail. Also included are sample input and output data files.

Program:

```c
C       CALCXS   -  Calculate cross section for 7Li(p,g)8Be reactions
C
C       Mark Godwin
C       22 August 1996
C
C       HOW IT WORKS:
C       The user will input everything, including the corrected yield
C       and a guess at the $S$-factor. The program calculates the
C       expected yield based on this value, compares it to the real
C       yield observed, modifies the $S$-factor, and then reports the
C       real value.
C
C       $S(E) = \sigma(E) \times E \times \exp\left(\frac{-b}{E^{0.5}}\right)$  \( E = \text{Ecm} \)
```
APPENDIX C. CODE USED FOR CALCULATING $S(E)$

C

```fortran
PROGRAM CALCXS

IMPLICIT NONE
double precision S0,S1,REAL(S0),Soq,S2
double precision MP,MT,zt,EB
double precision EFF,Y,DOMEGA,Q,slice,yperslice,scin
double precision E,DE,Ecm
double precision A1,A2,A3,A4,A5
double precision stp,xsec,calcY,dedx,sig80
double precision qe,Na,pi,cnt,btocm2,btonb,gtoug
double precision cmfact,redumass,b

data qe /1.602E-19/ !Charge of one proton
data Na /6.02252E23/ !Avagadro’s Number
data pi /3.14159265359/ !Pi
data cnt /0.08683/ !Converts STP to DEDX for 7Li
data btocm2 /1.00E-24/ !Conversion from barns to cm$^{-2}$
data btonb /1.00E+09/ !Conversion from barns to nanobarns
data gtoug /1.00E-06/ !Conversion from grams to ug

open(unit=8, name='calcxs.out', type='new', disp='save')

C
C 1 2 3 4 5 6 7
C23456789012345678901234567890123456789012345678901234567890123456789012
C ***** Fortran *****
C
C *********************
C *** Main Program ***
C ********************
C
CALL PROLOGUE
CALL RXNDATA(eb,mp,mt,zt)
CALL EXPDATA(Q,domega,eff,Y,scin)
CALL SDATA(s0,s1,s2)
CALL CALCPARAM(mp,mt,zt,cmfact,redumass,b)

de = 0.01
do 10 e = eb,.010,-de

ecm = e*cmfact

CALL STOPPING(e,stp)
CALL SFACtor(s0,s1,s2,cmfact,Ecm,sofe)

```

C
\texttt{dedx = stp*cnt} \\
\texttt{xsec = \exp(-b/sqrt(Ecm))*(1/Ecm)*SofE} \\
\texttt{slice = (xsec*btocm2) * de * (Na/mt)*gtoug / (dedx)} \\
\texttt{yperslice = slice*sft*(q/qe)*(domego/(4*pi))*sin} \\
\texttt{C *** NOTE: The 4*pi assumes isotropy to calculate the yield ***} \\
\texttt{calcy = calcy + yperslice} \\
\texttt{10 continue} \\
\texttt{CALL DATAOUT(calcy,Y,s0,s1,s2,reals0,sig80,cfact,b,eb,btonb)} \\
\texttt{999 close(8)} \\
\texttt{stop} \\
\texttt{end} \\
\texttt{C******************************************************************************} \\
\texttt{C END MAIN PROGRAM (ABOVE)} \\
\texttt{C******************************************************************************} \\
\texttt{C BEGIN SUBROUTINES (BELOW)} \\
\texttt{C******************************************************************************} \\
\texttt{subroutine calcparam(mp,mt,zt,cmfact,redumass,b)} \\
\texttt{\hspace{1cm} IMPLICIT NONE} \\
\texttt{\hspace{2cm} double precision \hspace{1cm} mp,mt,zt} \\
\texttt{\hspace{2cm} double precision \hspace{1cm} cmfact,redumass,b} \\
\texttt{\hspace{1cm} cmfact = mt/(mp+mt)} \\
\texttt{\hspace{1cm} redumass = mt*mp/(mp+mt)} \\
\texttt{\hspace{1cm} b = 31.28*(1)*zt*sqrt(redumass)} \\
\texttt{\hspace{1cm} return} \\
\texttt{\hspace{1cm} end} \\
\texttt{C******************************************************************************} \\
\texttt{subroutine stopping(e,stp)} \\
\texttt{\hspace{1cm} IMPLICIT NONE} \\
\texttt{\hspace{2cm} double precision \hspace{1cm} E} \\
\texttt{\hspace{2cm} double precision \hspace{1cm} A1,A2,A3,A4,A5} \\
\texttt{\hspace{2cm} double precision \hspace{1cm} stp} \\
\texttt{\hspace{2cm} double precision \hspace{1cm} SH,SL,S}
C*** Ziegler's Values for protons stopping in Lithium ***
C Reference: Hydrogen Stopping Powers and Ranges in all Elements
             H.R. Anderson and J.F. Ziegler (1977)
C
a1 = 1.411
a2 = 1.600
a3 = 725.6
a4 = 3013.
a5 = 0.04578

C*** Ziegler's equation for stopping power ***

IF(E .LT. 10.0) THEN
    S = A1*SQR(T(E))
ELSE
    SL = A2*E**(0.45)
    SH = (A3/E)*DLOG(1.0 + (A4/E) + (A5*E))
    S = 1.0/(1.0/SL + 1.0/SH)
ENDIF

stp = S

return
end

C*****************************************************
subroutine sfactor(s0,s1,s2,cmfact,ecm,sofe)

IMPLICIT NONE
    double precision     S0,S1,sofe,s2,cmfact
    double precision     ecm,ep

Ep = Ecm/cmfact
sofe = S0*(1 + S1*Ep + S2*Ep*Ep)

return
end

C*****************************************************
subroutine prologue

C*** WRITE TO SCREEN ***
write(*,*)
write(*,*)'==============================================='
write(*,*)'======== Program CALCIS ========' write(*,*)'===================================' write(*,*) write(*,*)'*** At present this reaction only works for p+7Li ***' write(*,*)' If you want to use this program for other reactions' write(*,*)' you must change the coefficients in the program.' write(*,*)

C*** WRITE TO DATA FILE ***
write(8,*)
write(8,*)'==================================='
write(8,*)'======== Program CALCXS ========' write(8,*)'===================================' write(8,*) write(8,*)'*** At present this reaction only works for p+7Li ***' write(8,*)' If you want to use this program for other reactions' write(8,*)' you must change the coefficients in the program.' write(8,*)

return
end

C***************************************************************************** subroutine rxndata(eb,mp,mt,zt)

IMPLICIT NONE
double precision MP,MT,zt,EB

C*** WRITE TO SCREEN ***
write(*,*)
write(*,*)'===== Enter Specifics About the Reaction =====>' write(*,*)

write(*,*)' Enter charge of target: '
read(*,*) zt
write(*,*)' Enter mass of target (in amu): '
read(*,*) mt
write(*,*)' Enter mass of projectile (in amu): '
read(*,*) mp
WRITE(*,*)' Enter the beams LAB-FRAME energy (in keV): '
READ(*,*) EB
write(*,*)
APPENDIX C. CODE USED FOR CALCULATING $S(E)$

C*** WRITE TO DATA FILE ***
   write(8,*),'**** Enter Specifics About the Reaction =====>,'
   write(8,*)

   write(8,*)' Enter charge of target: '
   write(8,*) zt
   write(8,*)' Enter mass of target (in amu): '
   write(8,*) mt
   write(8,*)' Enter mass of projectile (in amu): '
   write(8,*) mp
   write(8,*)' Enter the beams LAB-FRAME energy (in keV): '
   write(8,*) E8
   write(8,*)

return
end

C**************************
subroutine expdata(Q,domega,eff,Y,scin)

IMPLICIT NONE
   double precision   EFF,Y,DOMEGA,calcy,Q,scin

C*** WRITE TO SCREEN ***
   write(*,*)
   write(*,*)'**** Enter Experimental Conditions =====>,'
   write(*,*)

   write(*,*)' Enter Total Charge Collected (in coulombs): '
   read(*,*) Q
   write(*,*)' Enter Solid Angle of HPGe (in steradians): '
   read(*,*) domega
   write(*,*)' Enter Detector Efficiency (eff <= 1.00): '
   read(*,*) eff
   write(*,*)' Enter Corrected Detector Yield: '
   read(*,*) Y
   write(*,*)' Enter Scintillator Factor (1.0 if not needed): '
   read(*,*) scin
   write(*,*)

C*** WRITE TO DATA FILE ***
   write(8,*)
   write(8,*),'**** Enter Experimental Conditions ======>,'
   write(8,*)
APPENDIX C. CODE USED FOR CALCULATING S(E)

write(8,'') Enter Total Charge Collected (in coulombs): 
write(8,'') Q
write(8,'') Enter Solid Angle of HPGe (in steradians): 
write(8,'') domega
write(8,'') Enter Detector Efficiency (eff <= 1.00): 
write(8,'') eff
write(8,'') Enter Corrected Detector Yield: 
write(8,'') Y
write(8,'') Enter Scintillator Factor (1.0 if not needed): 
write(8,'') scin
write(8,'')
return
end

C***********************************************************************************************************************************************

subroutine sdata(s0,s1,s2)

IMPLICIT NONE

double precision s0, s1, s2

C*** WRITE TO SCREEN ***

write(*,*)
write(*,*)'===== Input S-Factor Parameters =====>'
write(*,*)
write(*,*)' Sfactor = S0(1 + S1*E + S2*E^2)'
write(*,*)' Enter GUESS for S0 (in keV b), S1, and S2: '
write(*,*)' Note that program will adjust the normalization '
write(*,*)' factor S0, but NOT S1 or S2, at the end'
read(*,*) S0, S1, S2
write(*,*)
write(*,*)'.....hold your horses Im calculating......'
write(*,*)

C*** WRITE TO DATA FILE ***

write(8,*)
write(8,*)'===== Input S-Factor Parameters =====>'
write(8,*)
write(8,*)' Sfactor = S0(1 + S1*E + S2*E^2)'
write(8,*)' Enter GUESS for S0 (in keV barns), S1, and S2: '
write(8,*)' Note that program will adjust the normalization '
write(8,*)' factor S0, but NOT S1 or S2, at the end'
write(8,*) S0, S1, S2
return
dend

C*************************************************************************
subroutine dataout(calcy,Y,s0,s1,s2,reals0,sig80,cmfact,b,eb,btonb)

IMPLICIT NONE
        double precision          S0, S1, REALS0, S2, SofE, eb
        double precision          Y, calcy, sig80, sig80_nb, cmfact, b, btonb

C*** WRITE TO SCREEN ***
write(*,*)
write(*,*)'=====================================================================
write(*,*)'===== Output of Program ======
write(*,*)'=====================================================================
write(*,*)

write(*,*)' If we assumes S(E) = ', S0, '(1 + ', S1, '*E + ', S2, '*E^2'
write(*,*)' Assuming isotropy (sigma_total=4piA0) then '
write(*,*)' The calculated yield is', calcy
write(*,*)
write(*,*)' The detected yield is ', Y

reals0 = S0*(Y/calcy)
CALL SFACTOR(realS0,S1,S2,cmfact,eb,SofE)
sig80 = SofE * exp(-b/sqrt(eb*cmfact))/(eb*cmfact)
sig80_nb = sig80*btonb

write(*,*)' Therefore the value for S0 = ', realS0, ' keV barns'
write(*,*)
write(*,*)' The total cross section at ', eb, ' keV = ', sig80_nb, &
write(*,*)
write(*,*)

C*** WRITE TO DATA FILE ***
write(8,*)
write(8,*)'=====================================================================
write(8,*)'===== Output of Program ======
write(8,*)'=====================================================================
write(8,*)

write(8,*)' If we assumes S(E) = ', S0, '(1 + ', S1, '*E + ', S2, '*E^2'
write(8,*)' Assuming isotropy (sigma_total=4piA0) then '
write(8,*)' The calculated yield is', calcy
write(8,*)
write(8,*)' The detected yield is ', Y
write(8,*)
write(8,*)' Therefore the value for S0 = ', realS0, ' keV barns'
write(8,*)
write(8,*)' The total cross section at ', eb, ' keV = ', sig80_nb, ' nanobarns'

return
end
Sample Input File:

=====================================================================
======== Program CALCXS =======
=====================================================================

*** At present this reaction only works for p+7Li ***
If you want to use this program for other reactions
you must change the coefficients in the program.

==== Enter Specifics About the Reaction ====>

Enter charge of target: 3.00
Enter mass of target (in amu): 7.016
Enter mass of projectile (in amu): 1.007825
Enter the beams LAB-FRAME energy (in keV): 80.0

==== Enter Experimental Conditions ====>

Enter Total Charge Collected (in coulombs): 8.66
Enter Solid Angle of HPGe (in steradians): 0.1084
Enter Detector Efficiency (eff <= 1.00): 1.000
Enter Corrected Detector Yield: 1156.7
Enter Scintillator Factor (1.0 if not needed): 0.6197

==== Input S-Factor Parameters ====>

Sfactor = S0(1 + S1*E + S2*E^2)
Enter GUESS for S0 (in keV barns), S1, and S2:
Note that program will adjust the normalization
factor S0, but NOT S1 or S2, at the end
1.000E-02 0.00E+00 0.00E+00
Sample Output File:

=================================
======= Output of Program =======
=================================

If we assume $S(3) = 1.0 \times 10^{-2} (1 + 0.05 \times 10^5 \times E + 0.05 \times 10^5 \times E^-2)$
Assuming isotropy (sigma_total=4piA0) then
The calculated yield is 1793.07282295925

The detected yield is 1156.7

Therefore the value for $S0 = 6.45 \times 10^{-3}$ keV barns

The total cross section at 80.0 keV = 2.4498 nanobarns
Bibliography


Biography

Mark Allen Godwin

Personal
- Born in Plainfield, New Jersey, 12 June 1967

Education
- B.S. Engineering Physics, Grove City College, Grove City, Pennsylvania, 1989
- A.M. Physics, Duke University, Durham, North Carolina, 1991

Academic Positions
- President, GCC Society of Physics Students, 1988-1989
- Teaching Assistant, Duke University, 1989-1991
- Research Assistant, Duke University, 1991-1996

Memberships
- American Physical Society
- Division of Nuclear Physics
- Sigma Pi Sigma

Journal Publications


**Oral Presentations**


2. *The $^7Li(\bar{p},\gamma)^8Be$ Reaction to the $2^+$ T=0,1 States for $E_p = 80-0$ keV*. Given at the APS meeting, Washington, D.C. (April 1995).

3. *Polarized Capture and the Isovector Giant Quadrupole Resonance in $^{90}Zr$*. Given at the DNP meeting, Pacific Grove, CA (October 1993).